NASA/CR—2015-218844

Identification and Analysis of Future Aeronautical Communications Candidates

A Study of Concepts and Technologies to Support the Aeronautical Communications Needs in the NextGen and Beyond National Airspace System

Joel M. Wichgers and James P. Mitchell
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August 2015

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Prepared under Contract NNA12AB82C

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

August 2015

Acknowledgments

The authors would like to acknowledge the funding and support of the NASA Aeronautics Research Mission Directorate's Airspace Systems Program Office at NASA Headquarters and NASA Ames Research Center; specifically: Dr. John A. Cavolowsky, Dr. Parimal H. Kopardekar, Mr. Rudy A. Aquilina, and Ms. Nazaret C. Galeon. The authors would also like to acknowledge the technical monitoring and review for this NRA research provided by Ms. Denise S. Ponchak and Mr. Rafael D. Apaza from the NASA Glenn Research Center.

This report contains preliminary findings,
subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by NASA technical management OR expert reviewer(s).

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Abstract

This report describes the results of future aeronautical communications research conducted by Rockwell Collins employees under NRA contract to NASA. The overall goal of this research was to identify and begin to evaluate communication technology candidates expected to meet the long-term aircraft-to-aircraft and aircraft-to-ground data communications needs of Air Traffic Management in the NextGen and beyond National Airspace System (NAS), considering how the NAS and communications technologies will evolve during a 50-year modernization time horizon.

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1 EXECUTIVE SUMMARY

Title: Identification and Analysis of Future Aeronautical Communications Candidates

A Study of Concepts and Technologies to Support the Aeronautical Communications Needs in the NextGen and Beyond National Airspace System

This report describes the results of future aeronautical communications research conducted by Rockwell Collins employees under NRA contract to NASA associated with the statement of work entitled: "The Development of NextGen Concepts for Air-to-Air and Air-to-Ground Data Exchange." The overall goal of this research was to identify and evaluate communication technology candidates expected to meet the long-term aircraft-to-aircraft (A-A) and aircraft-to-ground (A-G) data communications needs of Air Traffic Management (ATM) in the NextGen and beyond National Airspace System (NAS), considering how the NAS and communications technologies will evolve during a 50-year modernization time horizon (see Figure 1).

Figure 1 – NAS will Evolve During Study's 50 Year Modernization Time Horizon

Today's NAS has served the community well in meeting past operational and safety needs. It has made effective and prudent use of air-routes, procedures, and traditional Communication, Navigation, and Surveillance (CNS) systems to provide a level of capacity that was sufficient for the demand while maintaining a strong safety record. However, without change, the NAS will be unable to realize the capacity, efficiency, safety, security, and environmental improvements that are being demanded for the Next Generation Air Transportation System (NextGen) and beyond. To realize these improvements, the long term NextGen and beyond infrastructure is envisioned to be built on better, more capable, and optimally integrated communications, navigation, surveillance, information management, decision support, and automation systems.

Today's NAS ATM communications are mostly voice and are nearing capacity/saturation limits in the United States and Europe. The legacy voice communications are ill-suited to support the NAS evolution that is anticipated over the next 50 years. The data communications that exist today in the NAS and those that are emerging, while more capable than legacy voice communications are not even close to meeting the expected NAS communications needs over the study's 50 year time horizon. During this time, the NAS will need to accommodate significant growth in air traffic, integrate a wide range of new aircraft vehicles like Unmanned Aircraft Systems (UAS), have additional robustness against security threats, and support enhanced operations that are enabled with more capable communications.

One of the first steps in the research to identify and evaluate communication technology candidates to fill the NAS long-term communications needs gaps was to characterize existing and emerging aeronautical communication links as well as non-aeronautical communication links (e.g., cellular) that may become relevant to aeronautical communications. Then, communication relevant trends and technologies were identified and a spectrum investigation was launched to identify spectrum potentially suitable for NAS communications considering the entire electromagnetic spectrum. This investigation looked at spectrum both inside and outside the traditional radio frequency spectrum and considered the expected maturation of communications technologies and potential spectrum availability over the study period.

A next step included identifying and describing a set of potentially feasible A-A and A-G NAS communications candidates. Candidates were selected for further investigation that passed an initial feasibility screening with traits that included:

a) compliance with the fundamental physics of electromagnetic propagation;

b) expectation that the candidate would be able to meet the current and anticipated future operational, performance, safety, and security requirements associated with NAS ATM-relevant communications;

c) technology that is mature today or has a reasonable expectation that the technology could be matured during the modernization time horizon of the study;

d) expectation that the spectrum is available or could potentially become available for aviation use during the modernization time horizon; and

e) have a plausible transition path from today's communications.

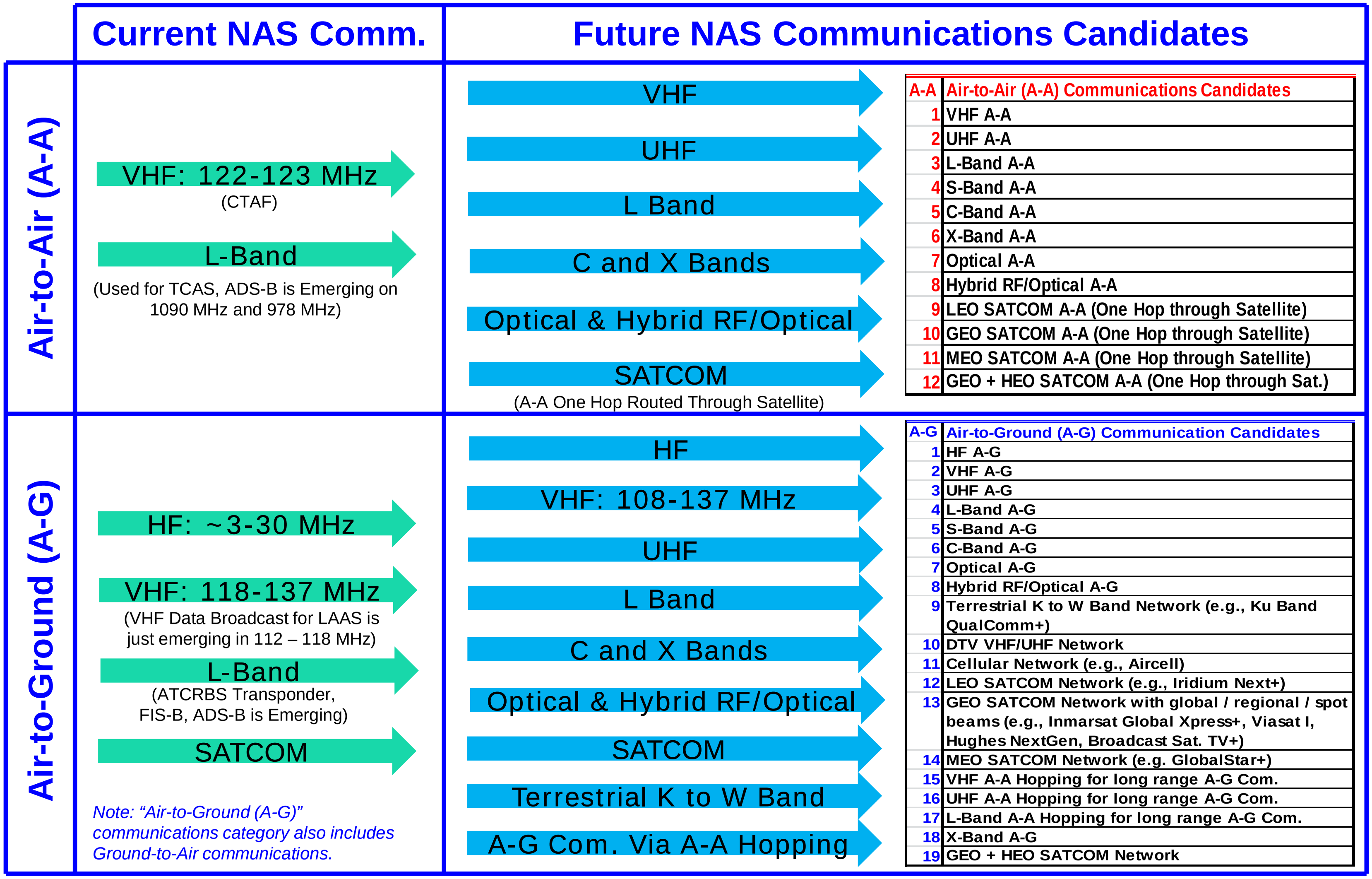
Twelve A-A and nineteen A-G communications candidates were identified (see Figure 2) and are described in the body of this report. The A-A candidates consisted of line-of-sight (LOS) candidates including VHF, UHF, L-band, S-band, C-band, X-band, optical, and hybrid RF/optical as well as one hop routing through future SATCOM systems that include satellites in Geosynchronous (GEO) as well as in Low, Medium, or High Earth Orbits (referred to as LEO, MEO, and HEO, respectively). The A-G candidates consisted of LOS candidates from VHF to optical and beyond line-of-sight candidates that included HF, SATCOM, and long range A-G communications enabled by A-A LOS communications hopping to one or more intermediate aircraft. Note that the hopping candidates are not expected to become a primary mode of long-range A-G communications, but they may provide a backup means of communicating with aircraft in oceanic, remote, and polar airspace when the primary means of communications (likely SATCOM) is not available. Having such a backup may allow significant aircraft cost and weight savings by removing the need for HF communications equipment. Also note that waveforms for the communications candidates were intentionally not selected at this time as it was deemed premature to select waveforms for communication systems that will not be fielded for decades.

Analyses to characterize and evaluate the identified candidates were completed. These analyses included:

- Quantifying the characteristics and attributes of each candidate including the communication bandwidth, latency, communications range, coverage, expected user data rates, spectral efficiency, technology readiness level (TRL), capacity, availability, vulnerabilities, etc. as a means to characterize the Actual Communications Performance (ACP) provided by each of the candidates;

- Identifying and prioritizing a representative set of ATM uses or applications that are expected to be utilized in the future NAS and are enabled by A-A and/or A-G communications;

- Identifying straw man initial Required Communications Performance (RCP) levels expected to support the identified set of ATM uses / applications;



A-A	Air-to-Air (A-A) Communications Candidates
1	VHF A-A
2	UHF A-A
3	L-Band A-A
4	S-Band A-A
5	C-Band A-A
6	X-Band A-A
7	Optical A-A
8	Hybrid RF/Optical A-A
9	LEO SATCOM A-A (One Hop through Satellite)
10	GEO SATCOM A-A (One Hop through Satellite)
11	MEO SATCOM A-A (One Hop through Satellite)
12	GEO + HEO SATCOM A-A (One Hop through Sat.)

A-G	Air-to-Ground (A-G) Communication Candidates
1	HF A-G
2	VHF A-G
3	UHF A-G
4	L-Band A-G
5	S-Band A-G
6	C-Band A-G
7	Optical A-G
8	Hybrid RF/Optical A-G
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)
10	DTV VHF/UHF Network
11	Cellular Network (e.g., Aircell)
12	LEO SATCOM Network (e.g., Iridium Next+)
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)
14	MEO SATCOM Network (e.g. GlobalStar+)
15	VHF A-A Hopping for long range A-G Com.
16	UHF A-A Hopping for long range A-G Com.
17	L-Band A-A Hopping for long range A-G Com.
18	X-Band A-G
19	GEO + HEO SATCOM Network

Figure 2 – Twelve Air-to-Air and Nineteen Air-to-Ground Comm. Candidates

- Mapping each candidate's actual communications performance to the ATM uses (or applications) based upon their ability to support the RCP of the intended use;
- Identifying the infrastructure and architecture needed to implement each candidate;
- Performing an initial security assessment of the candidates by identifying threats, vulnerabilities, and risk mitigation strategies relevant to the NAS data exchanges;
- Characterizing the relative costs associated with each candidate;
- Performing use case analyses for a subset of potential future airspace applications including Delegated Interval (DI) [also known as Interval Management (IM)], Delegated Separation (DS), and Airborne Self-Separation (ASS); and
- Prioritizing the communications candidates from most promising to least promising.

This report documents the results from all of these analyses. While a description of the results from each of these analyses would result in an excessively long executive summary, a high level description of the results from prioritizing the candidates is provided below followed by a list of the most important study findings.

Most Promising Communications Candidates

The A-A and A-G communication candidates were all evaluated for their ability to support the anticipated long-term NAS ATM future communication needs in all of the various flight domains, including surface, terminal area, enroute, oceanic/remote, and polar as well as for several combinations of flight domains.

Twenty five (25) evaluation criteria were identified for the purposes of evaluating and prioritizing the communication candidates to meet the long-term NAS communication needs. The criteria are traceable to the necessary elements of future aeronautical communications systems as articulated in various documents developed by the FAA, NASA, Eurocontrol, and ICAO. The set of evaluation criteria encompass a broad range of factors that can be grouped into three categories including technical performance, cost, and risk as given in Figure 3.

The results from evaluating the communications candidates by flight domain are provided in Figure 4 for A-A and Figure 5 for A-G and are summarized below.

- A-A Communications Candidates Prioritization:
    - The top tier of A-A candidates include L-band, VHF, and C-band. These candidates scored well in terms of high technical performance, low cost, and low risk across all flight domains. These candidates are capable of providing an actual communications performance quality of service (QoS) commensurate with meeting the RCP for most of the identified long-term NAS ATM applications that require A-A communications.
    - The middle tier of A-A candidates include UHF, S-band, LEO SATCOM, and X-band. The candidates in this tier generally have high scores for some of the evaluation criteria, but have at least one category of performance, cost, or risk that were not evaluated as well as the highest tier of candidates.
    - The lowest tier of A-A candidates include MEO SATCOM, GEO-SATCOM, GEO + HEO SATCOM, hybrid RF/Optical, and Optical. The candidates in this lowest tier generally scored low in at least two evaluation categories of performance, cost, or risk. The performance of the candidates in this tier typically only meets the RCP for a subset of the identified long-term ATM applications.

Category	Evaluation Category Description	#	Criteria
Technical Performance	Technical performance of candidate capabilities needed to support future NextGen and beyond ATM communication services.	1	Coverage Volume / Communications Range
		2	Data Rate
		3	Spectral Efficiency
		4	Capacity
		5	Number of Users
		6	Availability & Continuity
		7	Integrity
		8	Latency
		9	Scaleability / Flexibility / Ability to Incorporate New Technologies
		10	Security / Vulnerabilities
		11	Robustness to Interference / Environment
		12	Installable on Range of Air Vehicles
		13	Ability to Support Broadcast Communications
		14	Satisfy Requirements for Aviation Safety Services
		15	Satisfy Requirements for Aviation Advisory Services
Cost	Costs associated with candidate including airborne/ ground/ satellite infrastructure, and maturation & standards.	16	Airborne Infrastructure Cost
		17	Ground / Satellite Infrastructure Cost
		18	Technology Maturation & Standards Cost
Risk	Risks associated with candidate in the areas of spectrum availability, technology readiness, global acceptance, standards, certification, and transition.	19	Spectrum Availability & Compatibility
		20	Technical Maturity / Readiness Level (TRL)
		21	Standardization Status
		22	Global Harmonization Risk
		23	Certification Complexity
		24	Susceptible to Wide Outage / Long MTTR
		25	Ease of Transition

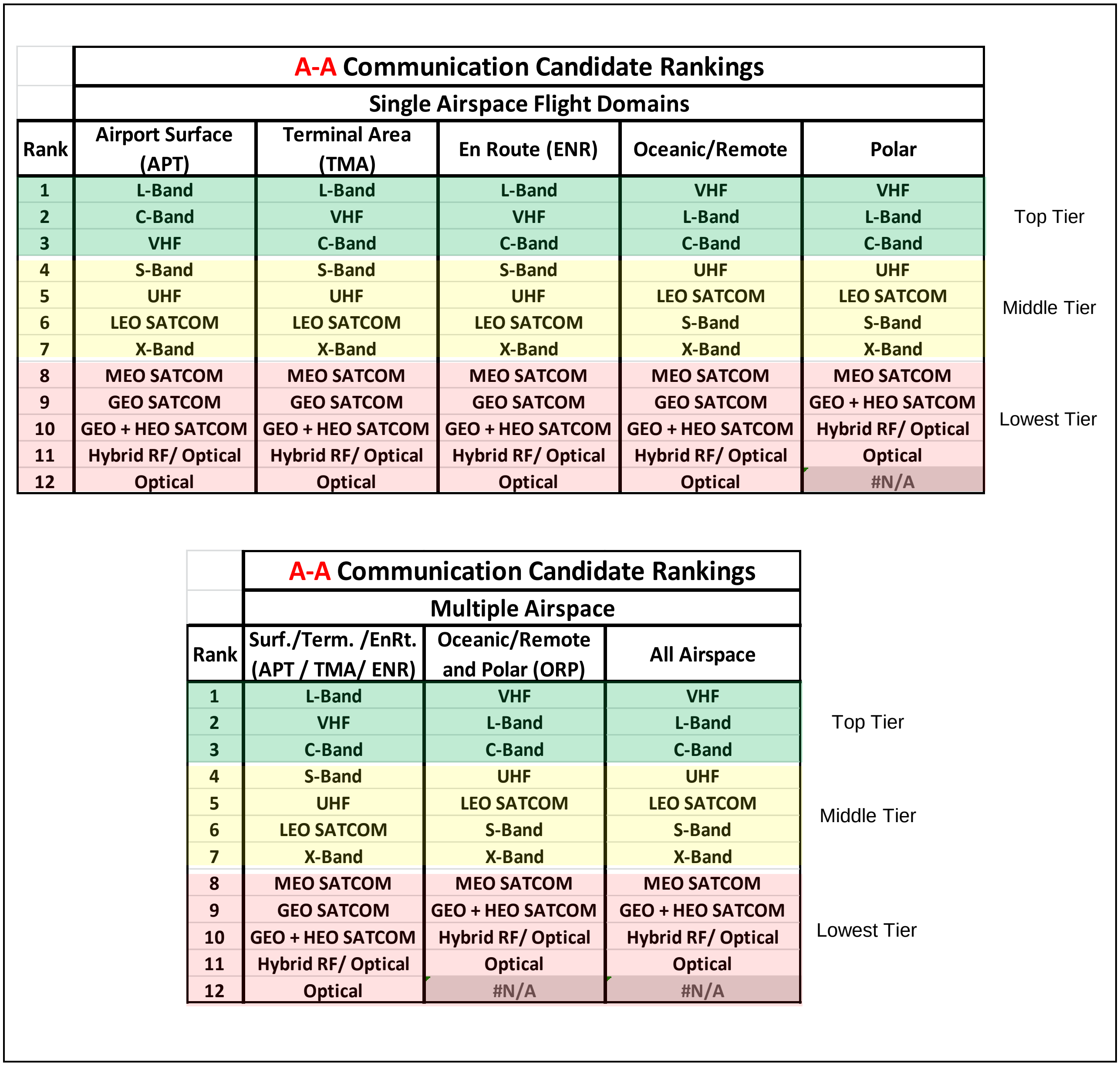
Figure 3 – Criteria Used to Evaluate / Prioritize Communications Candidates

- A-G Prioritization for Surface, Terminal Area, and Enroute Flight Domains:
  - The top tier of A-G candidates applicable to the airport surface, terminal area, and enroute flight domains include VHF, L-band, LEO SATCOM, and cellular candidates. These A-G candidates scored well in terms of high technical performance, low cost, and low risk. These candidates (evaluated with expected improvements over the study 50-year time horizon) tend to be capable of providing a QoS commensurate with meeting the RCP for most of the envisioned ATM applications.
  - The middle tier of A-G candidates applicable to the airport surface, terminal area, and enroute flight domains include UHF, S-band, and C-band. This tier of candidates has some of the desirable characteristics of the top tier, but these candidates generally have at least one area of performance, cost, or risk that was not evaluated as well as the highest tier of candidates.
  - The lower tier of candidates applicable to the airport surface, terminal area, and enroute flight domains include X-band, MEO SATCOM, GEO SATCOM, GEO + HEO SATCOM, DTV VHF/UHF, Terrestrial K to W band, Hybrid RF/Optical, and Optical. The candidates in this lowest tier usually evaluated low in at least two evaluation categories of performance, cost, or risk. The actual communication performances of these lowest tier candidates typically only meet the RCP for a small subset of the envisioned long-term ATM applications.

- A-G Prioritization for Oceanic, Remote, and Polar Flight Domains:
    - The top tier of A-G candidates applicable to the oceanic, remote, and polar flight domains include LEO and MEO SATCOM. These candidates were evaluated very high relative to the other alternatives against the measures of high technical performance, low cost, and low risk. They also could meet the A-G communications RCP to enable a broad range of identified ATM long-term safety and advisory applications.
    - The middle tier of A-G candidates include the GEO SATCOM (for oceanic/ remote not including polar) or GEO + HEO SATCOM (when including polar coverage) and HF. These candidates could meet the ATM application RCP, but have shortfalls primarily in a number of areas [e.g., capacity for HF, and cost for GEO and GEO + HEO SATCOM].
    - The lowest tier of A-G candidates include those that achieve long range A-G communications using aircraft-to-aircraft LOS communications that hop between intervening aircraft. These candidates include VHF, UHF, and L-band A-A hopping. They ranked low in a number of performance areas.
    - While HF and the hopping candidates tended to be evaluated with lower priority than the SATCOM alternatives to support ATM applications in oceanic, remote, and polar flight domains, it will likely remain important from safety and security perspectives to maintain a backup / alternate means of A-G communications to the primary means of communications (likely SATCOM) in these flight domains. HF or the hopping alternatives provide a diverse technical means to SATCOM for achieving long range A-G communications.

Note that in the context of this report, A-G communications are meant to also imply the reciprocal capability of Ground-to-Aircraft (G-A) communications.

While this study has attempted to appropriately prioritize the communication candidates in a manner consistent with the expected long-term NAS communication needs while balancing the collective interests of all the aviation stakeholders, it should be noted that the candidate prioritizations are subject to change when different evaluation criteria, assumptions, communications requirements, or weighting factors (all of which are described in the body of this report) are used in the assessment process.



A-A Communication Candidate Rankings

Single Airspace Flight Domains

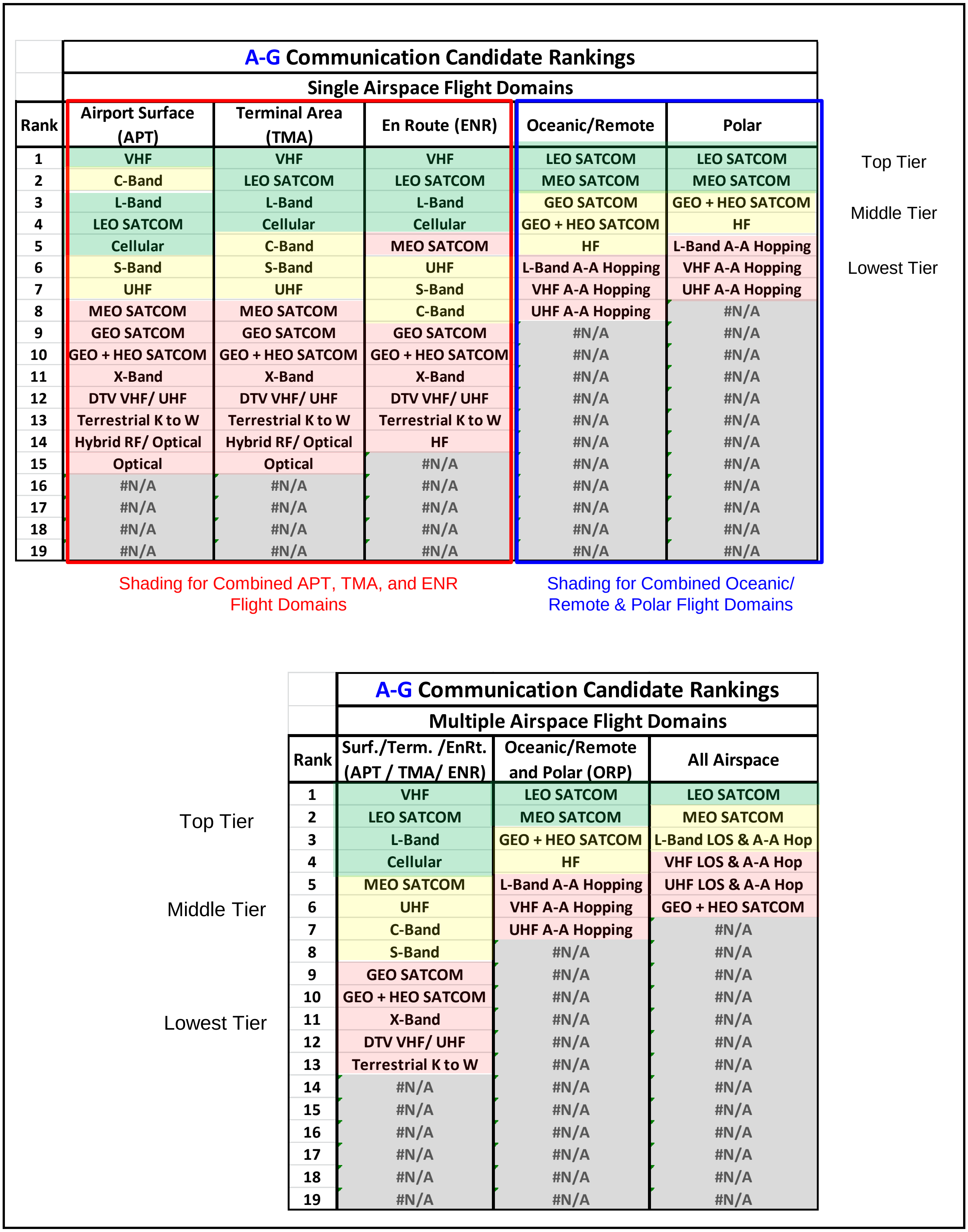
Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar	
1	L-Band	L-Band	L-Band	VHF	VHF	
2	C-Band	VHF	VHF	L-Band	L-Band	Top Tier
3	VHF	C-Band	C-Band	C-Band	C-Band	
4	S-Band	S-Band	S-Band	UHF	UHF	
5	UHF	UHF	UHF	LEO SATCOM	LEO SATCOM	Middle Tier
6	LEO SATCOM	LEO SATCOM	LEO SATCOM	S-Band	S-Band	
7	X-Band	X-Band	X-Band	X-Band	X-Band	
8	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO + HEO SATCOM	
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	Hybrid RF/ Optical	Lowest Tier
11	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Optical	
12	Optical	Optical	Optical	Optical	#N/A	

A-A Communication Candidate Rankings

Multiple Airspace

Rank	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace	
1	L-Band	VHF	VHF	
2	VHF	L-Band	L-Band	Top Tier
3	C-Band	C-Band	C-Band	
4	S-Band	UHF	UHF	
5	UHF	LEO SATCOM	LEO SATCOM	Middle Tier
6	LEO SATCOM	S-Band	S-Band	
7	X-Band	X-Band	X-Band	
8	MEO SATCOM	MEO SATCOM	MEO SATCOM	
9	GEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	
10	GEO + HEO SATCOM	Hybrid RF/ Optical	Hybrid RF/ Optical	Lowest Tier
11	Hybrid RF/ Optical	Optical	Optical	
12	Optical	#N/A	#N/A	

Figure 4 – Prioritized List of A-A Candidates by Flight Domain



A-G Communication Candidate Rankings

Single Airspace Flight Domains

Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar
1	VHF	VHF	VHF	LEO SATCOM	LEO SATCOM
2	C-Band	LEO SATCOM	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	L-Band	L-Band	GEO SATCOM	GEO + HEO SATCOM
4	LEO SATCOM	Cellular	Cellular	GEO + HEO SATCOM	HF
5	Cellular	C-Band	MEO SATCOM	HF	L-Band A-A Hopping
6	S-Band	S-Band	UHF	L-Band A-A Hopping	VHF A-A Hopping
7	UHF	UHF	S-Band	VHF A-A Hopping	UHF A-A Hopping
8	MEO SATCOM	MEO SATCOM	C-Band	UHF A-A Hopping	#N/A
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	X-Band	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	DTV VHF/ UHF	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	Terrestrial K to W	Terrestrial K to W	#N/A	#N/A
14	Hybrid RF/ Optical	Hybrid RF/ Optical	HF	#N/A	#N/A
15	Optical	Optical	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A

Top Tier

Middle Tier

Lowest Tier

Shading for Combined APT, TMA, and ENR Flight Domains

Shading for Combined Oceanic/ Remote & Polar Flight Domains

A-G Communication Candidate Rankings

Multiple Airspace Flight Domains

Rank	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace
1	VHF	LEO SATCOM	LEO SATCOM
2	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	GEO + HEO SATCOM	L-Band LOS & A-A Hop
4	Cellular	HF	VHF LOS & A-A Hop
5	MEO SATCOM	L-Band A-A Hopping	UHF LOS & A-A Hop
6	UHF	VHF A-A Hopping	GEO + HEO SATCOM
7	C-Band	UHF A-A Hopping	#N/A
8	S-Band	#N/A	#N/A
9	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	#N/A	#N/A
14	#N/A	#N/A	#N/A
15	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A

Top Tier

Middle Tier

Lowest Tier

Figure 5 – Prioritized List of A-G Candidates by Flight Domain

Summary of Study Findings

There are numerous study findings that have resulted from this future aeronautical communications study. A few of the more important findings include:

- Current and evolving NAS communications are insufficient to meet the anticipated future needs of the NAS.
- Current spectrum efficiency of today's NAS A-A and A-G communications is inefficient by today's state of the practice for wireless communications.
- The current state of the art for wireless communications achieves ~60% of Shannon's channel capacity theorem limit. 60% to 70% of Shannon's channel capacity limit will likely become the state of the practice for wireless communications systems during the study's 50-year modernization time horizon.
- Wireless communications technologies are advancing in a number of areas that will lead to significant increases in the spectral efficiency (e.g., bits/Hz).
- Spectrum is a very limited (finite) resource. Allocation of it among all those who desire to use the spectrum is becoming increasingly more difficult. Obtaining significantly more spectrum allocations dedicated to support NAS communications will become increasingly challenging. Existing users of the spectrum (including aviation) will need to modernize their systems to improve their spectral efficiency to meet the future demands.
- It is envisioned that commercial broadband communications networks will expand beyond what is offered today and be capable of further supporting NAS communications.
- Technology will advance over the study modernization time horizon that will enable:
  - the use of spectrum in the K, V, W, and G bands (up to ~200 GHz not including around 60 GHz) for SATCOM and/or airport surface/terminal area communications;
  - the use of free space optical communications for ground-to-satellite, satellite-to-aircraft, aircraft-to-ground, and aircraft-to-aircraft communications; and
  - future SATCOM communication systems that are capable of allocating communication bandwidth (BW) and quality of service (QOS) on demand to support a wide range of applications, including those in civil aviation.
- Future Aviation CNS needs will evolve during the 50 year NAS study time horizon. NAS data communications can potentially reuse aviation spectrum that is decommissioned by other NAS services. The primary opportunities identified over the study period include:
  - the MLS band (C-band), [already planned for the airport surface data link (AeroMACS) and UAS Control Non-payload Communications (CNPC) data link];
  - portions of the VHF VOR/ILS Localizer bands (including at least 112 to 118 MHz and possibly part of 108 to 112 MHz band);
    - VOR is expected to be decommissioned over the study period.
    - ILS is expected to be retained in a reduced service configuration (backup to GNSS) with greater emergence of GBAS VHF Data Broadcasts (VDB).
  - portions of the DME (L-band).
    - The DME spectrum is predicted over the long term to transition to support a highly capable Alternative Position / Navigation / Timing (APNT) terrestrial-based navigation aid and NAS A-A and A-G communications.

- Five fundamental strategic approaches have been identified for addressing the long term NAS communication needs including:
  1) Reducing the need for communications bandwidth (e.g., using techniques such as advanced data compression, data acceleration, and data bases);
  2) More efficiently using the existing aviation communications spectrum (e.g., using higher order modulations);
  3) Leveraging commercial communications networks to support NAS communications needs;
  4) Identifying and reusing "aviation" spectrum to support NAS communications [e.g., MLS (C-Band), VOR (VHF), and DME (L-band)]; and
  5) Identifying and obtaining new spectrum allocations for NAS communications.

  A combination of the above strategies will be used to meet the long-term NAS needs.
- As NAS communication and information systems become more networked, there is the potential for increased cyber-attacks.
- Understanding of the specific threats and operational constraints is key to identifying and implementing appropriate A-A and A-G communication systems security mitigations and controls. Simply applying information security controls used by the computer industry may not be appropriate or sufficient for NAS information and communication systems.
- The successful implementation of NAS communications information security will require coordination and collaboration between the traditional aeronautical stakeholders and information security and information technology experts.
- NAS modernization architects and planners should be very conscious of the cost impact of CNS infrastructure elements including future A-A and A-G communication systems.
  - Airborne system costs are a very substantial portion of the entire system infrastructure cost for future communications systems resulting from the large number of aircraft that need equipment built, installed, operated, and maintained to broadly implement a given communications candidate.
  - It is typically cost beneficial for reducing the total system costs to increase ground and satellite system costs if it results in a reduction in airborne system costs.
  - Future NAS communications costs can be substantially reduced by taking advantage of commercial communications networks (e.g., cellular, SATCOM, potential future terrestrial broadband networks), rather than building custom aviation-only communications networks.
  - The operational improvements enabled by future NAS CNS systems improvements or upgrades must have their schedules aligned to when the users can expect to receive benefits or else they will be resisted because of the very substantial costs being borne by the aircraft operators.
- Future air-to-air and air-to-ground communication systems should be architected to much more easily incorporate new technologies to meet the evolving future NAS needs.
- No one single communications data link technology can meet all the expected future A-A and A-G communications requirements for the NAS. A combination of various communication technologies are needed to address the diverse aeronautical communications requirements across all the operational flight domains.

- The emerging and the predicted future communication technologies are envisioned to be able to meet the NextGen and beyond NAS air-to-air and air-to-ground communication needs.

Conclusion to Executive Summary

A more in-depth study summary that provides additional description of the investigations described in this report is provided in Section 2.2. Additional R&D is planned and recommended to more comprehensively evaluate aircraft-to-aircraft and aircraft-to-ground communication candidates to meet the evolving long-term needs of the NAS. Unmanned Aircraft Systems will likely have a far-reaching effect on future CNS and ATM systems. It is therefore recommended that a detailed study be initiated as soon as possible to further assess the impact of low (below ≈1200 feet) and very low (below ≈400 feet) altitude UAS operations on future CNS and ATM systems. Such a study should consider a range of possible UAS concepts of operation and operational environments. Specific recommendations for further study are provided in Section 33.2.

Rockwell Collins appreciates the confidence that NASA has entrusted in us to support this important research to begin to identify and evaluate communication candidates to meet the long-term needs of the NextGen and beyond NAS.

2 INTRODUCTION AND STUDY SUMMARY

2.1 Background and Introduction

This report describes the results of future aeronautical communications research conducted by employees of Rockwell Collins under NRA contract to NASA regarding the statement of work entitled: "The Development of NextGen Concepts for Air-to-Air and Air-to-Ground Data Exchange." This research supports NASA's work in the Aeronautics Research Mission Directorate and the Concepts, Technology, and Development Project of the Airspace Systems Program. This research was contracted from the NASA Ames Research Center with representatives from the NASA Glenn Research Center providing technical monitoring for the contract.

The purpose of this research effort was to identify and evaluate communication technology candidates expected to meet the long-term aircraft-to-aircraft (A-A) and aircraft-to-ground (A-G) data communication needs and requirements for the future national air transportation system. *Note that in the context of this report, A-G communications are meant to also imply the reciprocal capability of Ground-to-Aircraft (G-A) communications.*

This comprehensive report contains the results of five interim study reports that were developed by employees of Rockwell Collins Advanced Technology Center and Commercial Systems groups during FY2013 and FY2014 to document the results of the research conducted under NRA contract to NASA. The specific overall research objectives stated by NASA included:

1) identifying long-term communication technology candidates that allow aircraft-to-aircraft and aircraft-to-ground data exchange for the future air transportation system,
2) characterizing the candidates, and
3) investigating how the candidates could serve the evolution of airspace applications over a National Airspace System (NAS) modernization time horizon of 50 years.

Today's NAS has served the community well in meeting past operational and safety needs. It has made effective and prudent use of air-routes, procedures, and traditional Communication, Navigation, and Surveillance (CNS) systems to provide a level of capacity that was sufficient for the demand while maintaining a strong safety record. However, without change, the NAS will be unable to realize the capacity, efficiency, safety, security, and environmental improvements that are being demanded for the Next Generation Air Transportation System (NextGen) and beyond. To realize these improvements, the NextGen and beyond infrastructure is envisioned to be built on better, more capable, and optimally integrated communications, navigation, surveillance, information management, decision support, and automation systems.

Today's NAS ATM communications are mostly voice and are nearing capacity/saturation limits in the United States and Europe. The legacy voice communications are ill-suited to support the NAS evolution that is anticipated over the next 50 years. The data communications that exist today in the NAS and those that are emerging or soon to emerge, while more capable than legacy voice communications are not even close to meeting the expected NAS communications needs over the study's 50 year NAS modernization time horizon. During this time, the NAS will need to accommodate significant growth in air traffic, integrate a wide range of new aircraft vehicles including UAS that will need significantly more and better communications, have additional robustness to security threats, and support greatly enhanced applications and operations that are enabled with more capable communications. Communications is a key infrastructure element necessary to realize the future NAS vision such that the appropriate information is available at the required quality of service to enable Air Traffic Management (ATM) systems to better utilize the airspace through enhanced operational procedures and applications.

To address the gap in NAS communications needs, this study was launched. During the execution of the study, five interim reports were written to document the investigations and analyses completed in the five study phases as defined in the NRA contract's statement of work. Phase 1 of the study resulted in the completion of an interim report entitled "Data Communications Technologies Candidates." This first interim report described the investigations to characterize existing and emerging aeronautical and non-aeronautical communication links, identify communication relevant trends and technologies, complete a spectrum investigation to identify spectrum potentially suitable for A-A and A-G NAS communications considering the entire electromagnetic spectrum, and identify and characterize twelve A-A and nineteen A-G candidates that could potentially serve the evolution of airspace applications in the NAS during the study's modernization time horizon of 50 years.

Phase 2 of the study concluded with the completion of a second interim report, entitled "Infrastructure and Architecture Needs of Candidate Technologies" that built on the results of Phase 1. This second interim report described the investigations to identify the aircraft-based, ground-based, and satellite-based infrastructure and architecture needs of all the candidates. It also described the results of an initial security assessment that has identified and evaluated potential threats, vulnerabilities, and security challenges relevant to future NAS communications.

During Phase 3 of the study, a third interim study report was developed to document an initial cost assessment of all the communications candidates that have been identified and analyzed in the preceding two phases. A cost estimation methodology was developed to enable comparative assessments to be made between the various A-A and A-G communication candidates. A parametric cost model was developed that leveraged historical and predicted costs associated with a number of relevant benchmark CNS systems that are in use today or are in the process of being fielded, and modified these historical/predicted costs by applying relevant cost adjustment factors based on the characteristics of the various communications candidates and predictions for how costs will change over the study's 50 year time horizon.

During Phase 4 of the study, a fourth interim study report was completed that identified, described, and prioritized a broad set of ATM applications/capabilities enabled by communications that are expected to be used in the NextGen or beyond NextGen NAS. A defensible prioritization process was developed. For each application, an assessment of the communication candidates that would be capable of meeting the Required Communications Performance (RCP) to enable the application was made. Use case analyses were completed for three of the highest priority applications including: 1) Delegated Interval (DI) / Interval Management (IM), 2) Delegated Separation (DS), and Airborne Self-Separation (ASS). The use case analyses identified the specific activities and information that needed to be communicated in the context of the application where A-A, A-G, and Ground-to-Aircraft (G-A) communications take place.

During Phase 5 of the study, a fifth interim study report was completed that described the findings from:

- identifying criteria for prioritizing the list of communication technology candidates from most promising to least promising,
- using the criteria to identify the most promising communication candidates, and
- identifying which of the applications are feasible with the most promising communication candidates.

This report is a comprehensive document that has combined the results from each of the five phases of the study that each resulted in interim reports developed during the execution of the FY2013 and FY2014 study.

2.2 Study Summary

A high-level and relatively brief study summary is provided in the "Executive Summary" of this report (see Section 1).

The subsections below provide a more in-depth study summary of the investigations and findings documented in this comprehensive report. This more in-depth summary is partitioned into five subsections corresponding to the five phases of investigations that were documented in the five interim reports developed during the course of the study.

2.2.1 Phase 1: Data Communication Technologies, Trends, and Candidates

Today's A-A and A-G NAS communications are rather limited as documented in Section 7 of this report and consist primarily of VHF, HF, and SATCOM to support the traditional communications services, plus the use of L-band (978, 1030, and 1090 MHz) to support a number of surveillance and flight information services [e.g., Secondary Surveillance Radar (SSR), TCAS, and FIS-B].

Emerging is the use of 1090 MHz Extended Squitter and 978 MHz Universal Access Transceiver (UAT) for A-A and A-G Automatic Dependent Surveillance – Broadcast (ADS-B) and the A-G communications of companion traffic surveillance systems including ADS-Rebroadcast (ADS-R) and Traffic Information Services – Broadcast (TIS-B). Also, emerging or soon to emerge is the use of VHF data link (VDL) to support data communications between air traffic controllers and aircraft (FAA Data Comm. program) and the use of VHF Data Broadcast (VDB) to support GPS/Local Area Augmentation System (LAAS) Category I precision approaches.

A number of A-A and A-G communications technology candidates have been identified based upon an initial technical feasibility assessment considering at least the following factors:

- the fundamental physics of electromagnetic wave propagation through the earth's atmosphere and the suitability of various frequencies to support A-A and A-G communications in the NAS,
- wireless communications being used or developed for other applications (e.g., cellular, military, commercial broadband),
- communications technologies currently in various stages of R&D [e.g., free space optical communications, UAS Control Non-Payload Communications (CNPC) data link],
- communication relevant trends,
- technologies relevant to significantly improving wireless communications that are anticipated to mature during the study time horizon (e.g., directional and conformal antennas, software defined radios, advances in signal and general purpose processing, adaptive/cognitive radios),
- potential availability of spectrum,
- ability to meet the anticipated NAS operational, performance, safety, and security requirements,
- potential transition path between today's NAS communications and the future, and
- positions being taken by relevant regulatory (e.g., FAA, FCC, ITU) and industry standards groups (e.g., ICAO, RTCA, EUROCAE).

It should be noted that in addition to the initial technical feasibility assessment provided as part of the identification of candidates in this report, there are many other factors that will ultimately influence the final selection of the preferred candidates including more comprehensive operational / technical / performance / safety / security assessments of each candidate’s ability to meet the future NAS needs, securing the spectrum allocation at both the national and international levels, cost/benefit assessment of each candidate relative to the other alternatives, additional analyses of the NAS communications transition path from operations today to operations in the future, and the willingness of the candidate to be accepted by all the stakeholders impacted.

There are a number of communication relevant technologies that are expected to mature during the next 50 years that will enable significant improvements in A-A and A-G communications in the NAS. Such technologies are described in Section 8 of this report. Examples of such technologies include:

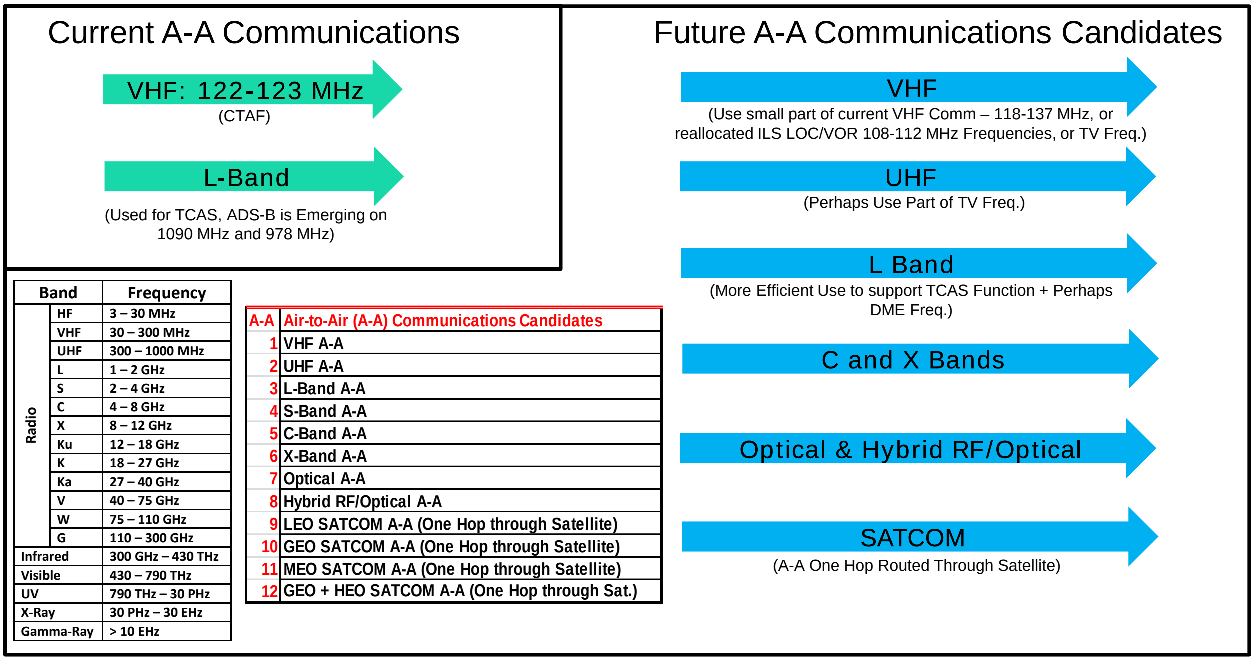
a. antennas (e.g., low cost directional / conformal / electronically scanned arrays, and other smart antenna technologies will enable significantly improved link margins),

b. radio and processing technologies (e.g., including software defined radios and advances in signal and general purpose processing),

c. algorithms (e.g., data compression, data acceleration, and information security), and

d. free space optical communications.

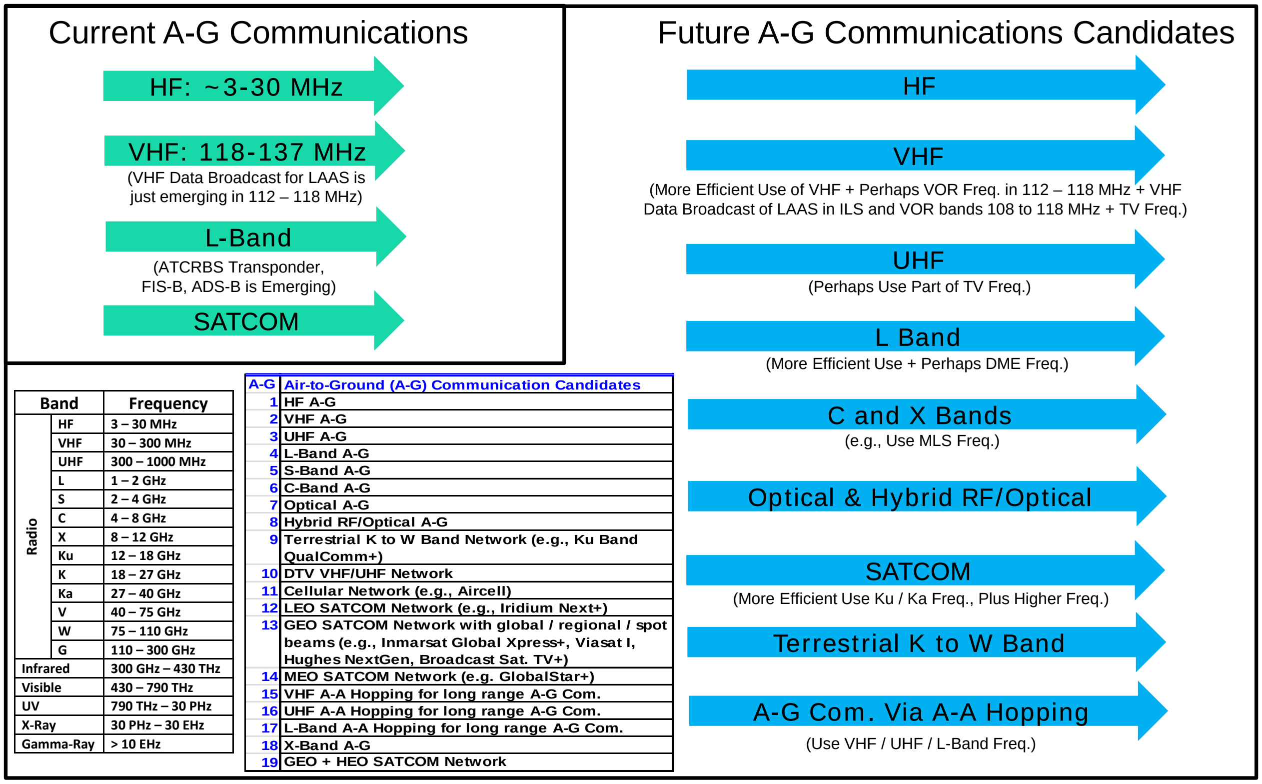
Figure 6 and Figure 7 below provide a high level summary of current and the identified future Air-to-Air and Air-to-Ground communication candidates, respectively. Waveforms for the communications candidates were intentionally not selected at this time as it was deemed premature to select waveforms for communication systems that will not be fielded for decades. Note that the communication candidates are described in greater detail in this report along with the key technology enablers that are needed to be matured for the low Technology Readiness Level (TRL) candidates, including, for example, antenna technologies like low cost conformal electronically scanned arrays, wireless optical technologies, software defined radio technologies, on satellite IP switching and processing, and split proxy communications.



Band		Frequency
Radio	HF	3 – 30 MHz
	VHF	30 – 300 MHz
	UHF	300 – 1000 MHz
	L	1 – 2 GHz
	S	2 – 4 GHz
	C	4 – 8 GHz
	X	8 – 12 GHz
	Ku	12 – 18 GHz
	K	18 – 27 GHz
	Ka	27 – 40 GHz
	V	40 – 75 GHz
	W	75 – 110 GHz
	G	110 – 300 GHz
Infrared		300 GHz – 430 THz
Visible		430 – 790 THz
UV		790 THz – 30 PHz
X-Ray		30 PHz – 30 EHz
Gamma-Ray		> 10 EHz

A-A	Air-to-Air (A-A) Communications Candidates
1	VHF A-A
2	UHF A-A
3	L-Band A-A
4	S-Band A-A
5	C-Band A-A
6	X-Band A-A
7	Optical A-A
8	Hybrid RF/Optical A-A
9	LEO SATCOM A-A (One Hop through Satellite)
10	GEO SATCOM A-A (One Hop through Satellite)
11	MEO SATCOM A-A (One Hop through Satellite)
12	GEO + HEO SATCOM A-A (One Hop through Sat.)

Figure 6 – Twelve Air-to-Air Communications Candidates



Band		Frequency
Radio	HF	3 – 30 MHz
	VHF	30 – 300 MHz
	UHF	300 – 1000 MHz
	L	1 – 2 GHz
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	C	4 – 8 GHz
	X	8 – 12 GHz
	Ku	12 – 18 GHz
	K	18 – 27 GHz
	Ka	27 – 40 GHz
	V	40 – 75 GHz
	W	75 – 110 GHz
	G	110 – 300 GHz
Infrared		300 GHz – 430 THz
Visible		430 – 790 THz
UV		790 THz – 30 PHz
X-Ray		30 PHz – 30 EHz
Gamma-Ray		> 10 EHz

A-G	Air-to-Ground (A-G) Communication Candidates
1	HF A-G
2	VHF A-G
3	UHF A-G
4	L-Band A-G
5	S-Band A-G
6	C-Band A-G
7	Optical A-G
8	Hybrid RF/Optical A-G
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)
10	DTV VHF/UHF Network
11	Cellular Network (e.g., Aircell)
12	LEO SATCOM Network (e.g., Iridium Next+)
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)
14	MEO SATCOM Network (e.g. GlobalStar+)
15	VHF A-A Hopping for long range A-G Com.
16	UHF A-A Hopping for long range A-G Com.
17	L-Band A-A Hopping for long range A-G Com.
18	X-Band A-G
19	GEO + HEO SATCOM Network

Figure 7 – Nineteen Air-to-Ground Communications Candidates

The functional attributes and characteristics relevant for quantifying the Actual Communications Performance (ACP) for these candidates were assessed and are provided in Section 10 of this report.

A number of current and future potential NextGen and beyond ATM applications have been identified for surface, terminal area, domestic enroute, oceanic/remote, and polar airspaces. Required Communication Performance (RCP) values have been identified for current applications and initial RCP values have been established for supporting future applications. See Section 13 for additional information. Based upon this work, an initial assessment has been made as to each communication technology candidate's ability to support ATM applications in all of the various airspaces. The good news is that there are many potential candidates that are emerging or predicted to mature and become available to meet the NextGen and beyond A-A and A-G communication needs of the NAS.

The study findings for the analyses completed in Phase 1 of the study are summarized as follows:

- The future NAS will require significantly more A-A and A-G communications to support the envisioned NAS NextGen and beyond operations as envisioned in the JPDO Concept of Operations.
- Current A-A and A-G NAS communications links are insufficient to meet the anticipated future needs of the NAS.
- Traffic is expected to increase 3X to 10X of today's NAS traffic levels over the 50 year study time horizon, assuming a yearly nominal growth rate between 2.2% and 4.7%.
- Current spectrum efficiency of today's NAS A-A and A-G communications is inefficient by today's state of the practice for wireless communications.
- The current state of the art for wireless communications achieves ~60% of Shannon's channel capacity theorem limit. 60% to 70% of Shannon's channel capacity limit will likely become the state of the practice for wireless communications systems during the modernization time horizon.
- Wireless communications technologies are advancing in a number of areas that will lead to significant increases in the spectral efficiency (e.g., bits/Hz).
- Spectrum is a very limited (finite) resource. Allocation of it among all those who desire to use the spectrum is becoming increasingly more difficult. Many existing users of the spectrum (including aviation) will over time need to modernize their systems to improve their spectral efficiency to enable the spectrum to meet the future demands.
- Obtaining significantly more spectrum allocations dedicated to support NAS A-A and/or A-G communications will become increasingly challenging.
- It is envisioned that commercial broadband communication networks will expand beyond what is offered today to further support ATM communications (primarily A-G, but also A-A).
- Technology will advance over the study modernization time horizon that will enable:
  - the use of spectrum in the K, V, W, and G bands (up to ~200 GHz not including around 60 GHz) for SATCOM and/or airport surface/terminal area communications;
  - the use of free space optical communications for ground-to-satellite, satellite-to-aircraft, aircraft-to-ground, and aircraft-to-aircraft communications; and

  - future SATCOM communication systems that are capable of allocating communication bandwidth (BW) and quality of service (QOS) on demand to support a wide range of applications, including those in civil aviation.

- Future Aviation CNS needs will evolve during the 50 year NAS study time horizon. NAS data communications can potentially reuse aviation spectrum that is decommissioned by other NAS services. The primary opportunities identified over the study period include:
  - the MLS band (C-band), [already being planned with use for airport surface data link (AeroMACS) and UAS Control Non-payload Communications (CNPC) data link]
    - Currently the MLS (C-band) spectrum is not being used in the NAS.
  - portions of the VHF VOR/ILS Localizer bands (including at least 112 to 118 MHz and possibly part of 108 to 112 MHz band)
    - VOR is expected to be decommissioned over the study period.
    - ILS is expected to be retained in a reduced service configuration as a backup to GNSS-based approach and landing systems.
    - GBAS VHF Data Broadcast systems are just emerging and are anticipated to be more widely fielded in portions of the 108 to 118 MHz spectrum as the NAS is modernized.
  - portions of the DME (L-band)
    - The DME spectrum is predicted over the long term to transition to support a highly capable Alternative Position / Navigation / Timing (APNT) terrestrial-based navigation aid in a small percentage of the existing DME allocated spectrum (e.g., ~10%), and remainder could be allocated to support NAS A-A and A-G communications.
- Five fundamental strategic approaches have been identified for addressing the long term NAS communication needs including:
  1) Reducing the need for communications bandwidth (e.g., using techniques such as advanced data compression, data acceleration, and data bases);
  2) More efficiently using existing aviation communications spectrum (e.g., using higher order modulations);
  3) Leveraging commercial communications networks to support NAS communications needs;
  4) Identifying and reusing “aviation” spectrum to support NAS communications [e.g., MLS (C-Band), VOR (VHF), and DME (L-band)]; and
  5) Identifying and obtaining new spectrum allocations for NAS communications.

  A combination of the above strategies will be used to meet the long-term NAS needs
- Future air-to-air and air-to-ground communication systems should be architected to much more easily incorporate new technologies to meet the evolving future NAS needs.
- No one single communications data link technology can meet all the expected future A-A and A-G communications requirements for the NAS. A combination of various communication technologies will be needed to address the diverse aeronautical communications requirements across all the operational flight domains.

- The emerging and the predicted future communication technologies are envisioned to be able to meet the NextGen and beyond NAS air-to-air and air-to-ground communication needs.

2.2.2 Phase 2: Communication Systems Infrastructure and Architecture Needs, and Initial Communications Security Assessment

Phase 2 of the study built on the work completed in Phase 1. The aircraft-based, ground-based, and satellite-based infrastructure and architecture needs of the twelve A-A and nineteen A-G candidates were identified as is documented in Sections 17 and 18. This information was utilized in analyses completed during Phase 3 of the study to support estimating the costs to implement the candidate technologies.

During Phase 2, an initial security assessment (as presented in Section 19) was completed that has identified and evaluated potential threats, vulnerabilities, and security challenges relevant to the future NAS communication candidates. This initial security analysis as documented in this report has followed the available industry standards and guidelines used to perform such risk assessments. There are a number of documents developed by the National Institute of Standards and Technologies (NIST) and published by the United States Department of Commerce that are relevant for assessing the security of Federal Communication and Information Systems that were utilized in this assessment including, for example:

- NIST Special Publication 800-30, “Information Security Guide for Conducting Risk Assessments,”
- NIST Special Publication 800-53, “Security and Privacy Controls for Federal Information Systems and Organizations,” and
- NIST Federal Information and Processing Standards (FIPS) Publication 199, “Standards for Security Categorization of Federal Information and Information Systems.”

In addition, other relevant industry guidance and standards were also utilized in the security assessment, including documents from ARINC, EUROCAE, RTCA, and SAE, as well as other NIST standards.

The general risk assessment process as documented in NIST Special Publication (SP) 800-30 was followed to identify and evaluate threats and vulnerabilities, and to identify appropriate mitigations. As part of the initial security assessment, over 60 potential threat sources were identified from 6 different threat types, and over 30 vulnerabilities were identified from 8 different vulnerability categories. Methods to mitigate many of the vulnerabilities have been identified with consideration given to the 18 security control mitigation groups defined in NIST SP-800-53. Mitigations were identified that strategically result in: a) decreasing the threat level by eliminating or intercepting the threat source before it can attack, b) blocking the vulnerability through enhanced security controls, or c) reducing the impact of the potential consequences should a threat be successful in exploiting a vulnerability.

A summary of the findings for the analyses conducted during Phase 2 of the study are summarized as follows:

- While the focus of this study is on the long range future A-A and A-G data communication technology candidates (including their relevant infrastructure and architectural elements needed to address the NAS communication needs for NextGen and beyond), it is important to also consider the infrastructure and architecture of other functional elements of the NAS such that the overall NAS infrastructure and architecture can be optimized. Thus, this report has documented at a high level relevant other areas of the NAS infrastructure, especially the CNS infrastructure, since integration with or leveraging other infrastructure elements might yield significant cost savings.

- Today's A-A and A-G communication systems are largely implemented using federated systems.
- As NAS communication and information systems become more networked, there is the potential for increased cyber-attacks, similar to those experienced by corporate communication and information systems.
- Understanding of the specific threats and operational constraints is key to identifying and implementing appropriate A-A and A-G communication systems security mitigations and controls. Simply applying information security controls used by the computer industry may not be appropriate or sufficient for NAS information and communication systems.
- The successful implementation of NAS communications information security will require coordination and collaboration between traditional aeronautical stakeholders (e.g., airlines, aircraft manufacturers, avionics suppliers, ground systems suppliers, aeronautical service providers, FAA/civil aviation authorities, military aviation authorities) and information security and information technology experts.
- There are several activities underway trying to address the aviation security challenges for the NAS elements, including the A-A and A-G communication systems. Finding security solutions that will be viable for all stakeholders will be a challenge. Additional research and development into aviation security issues and mitigations that take into account the full set of stakeholder issues and holistically address the NAS security challenges is needed.

2.2.3 Phase 3: Relative Cost Comparison of the Communications Candidates

Phase 3 of the study contains the results from an initial cost assessment of the A-A and A-G communications candidates that have been identified in Phase 1 of the study and analyzed throughout the study.

A cost estimation methodology was developed to enable comparative assessments between the various A-A and A-G communication candidates. A parametric cost model was developed that leveraged historical costs associated with a number of relevant benchmark CNS systems that are in use today. The model applied cost factors based on the characteristics of the various A-A and A-G candidates that influence costs and predictions for how the costs of these candidates will change over the study's 50 year time horizon.

Total system cost "scores" were formulated based upon estimating the costs from four cost elements including: 1) Technology Maturation & Standards, 2) Equipment, 3) Deployment, and 4) Operation & Maintenance. This is depicted in Figure 8 below.

The technology maturation and standards costs included an estimate of the incremental costs that would need to be borne by the aviation community to adapt and standardize a given technology candidate to meet the needs of the NAS assuming that the technology has been matured by other entities (e.g., academia, military, government, or other commercial industry) for non-civil aviation use.

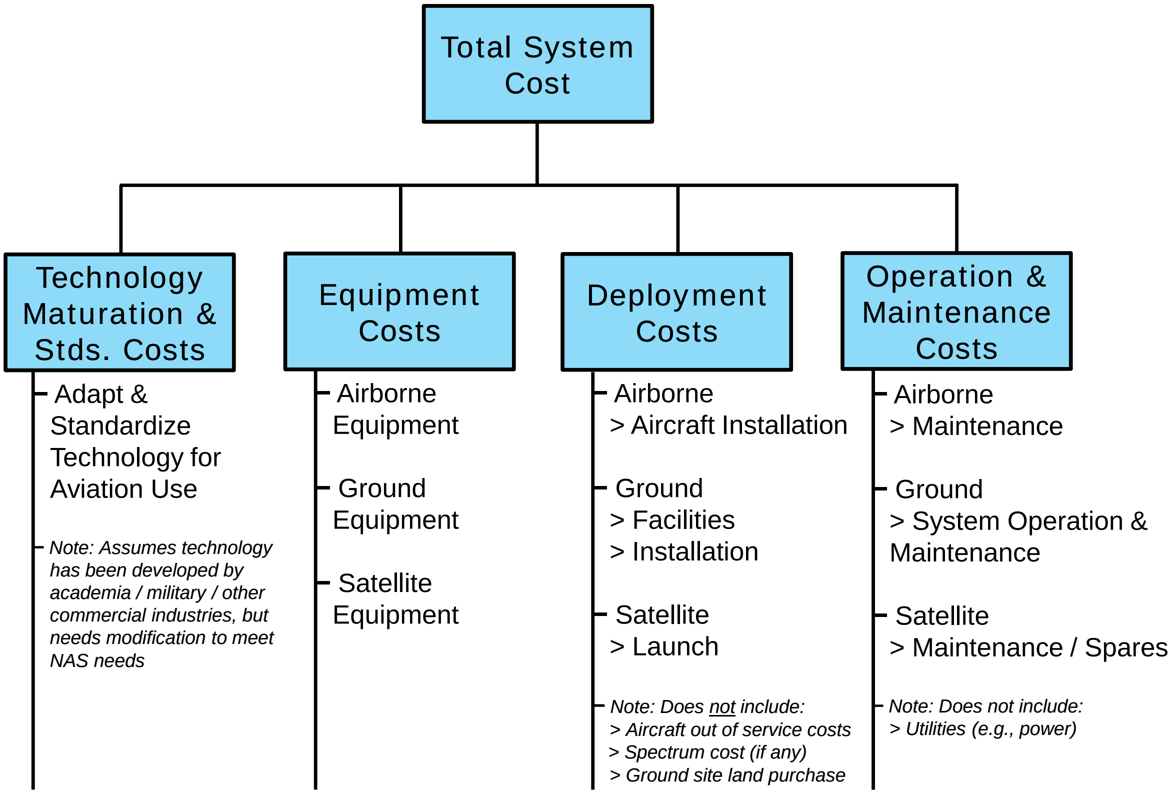


Figure 8 – Total System Cost Model Summary

Equipment costs included all the costs associated with designing, developing, manufacturing the communications equipment and having the equipment approved or certified for use in the NAS. The cost estimates have incorporated the non-recurring costs (e.g., design, development, and certification/approval) into the cost of the equipment.

Deployment costs include the cost of taking the equipment and installing it in a deployed state. For airborne deployment costs, the cost estimates include installation of the equipment on the aircraft, but have not included any lost revenue or lost opportunity costs for taking aircraft out of service to perform the installations.

The operation and maintenance costs include the costs associated with using the system in a manner that supports providing the intended function of the system (i.e., operational use of the system) and maintaining the equipment to be able to continue to perform its intended function.

Additional information on the cost estimation method, model, and assumptions can be found in Sections 21 and 22.

Figure 9 and Figure 10 contain plots of the relative cost scores for the twelve A-A and nineteen A-G candidates, respectively based upon a 25-year system life-cycle-cost model for aircraft fleet model #1, which is described in Section 22.3.4.1. These plots should not be misinterpreted to be the total system costs and should be interpreted as relative cost "scores" for relative comparison of the communication candidates. For relative comparison purposes among the candidates, the entire aircraft fleet was assumed to be upgraded with the candidate communication system to simplify relative cost comparisons between candidates as is described in Section 23.1. Clearly, some of the candidates will only be utilized by a small subset of the entire aircraft fleet (e.g., HF communications), which was taken into account when estimating the costs for the eight integration alternatives as described in Section 23.3.

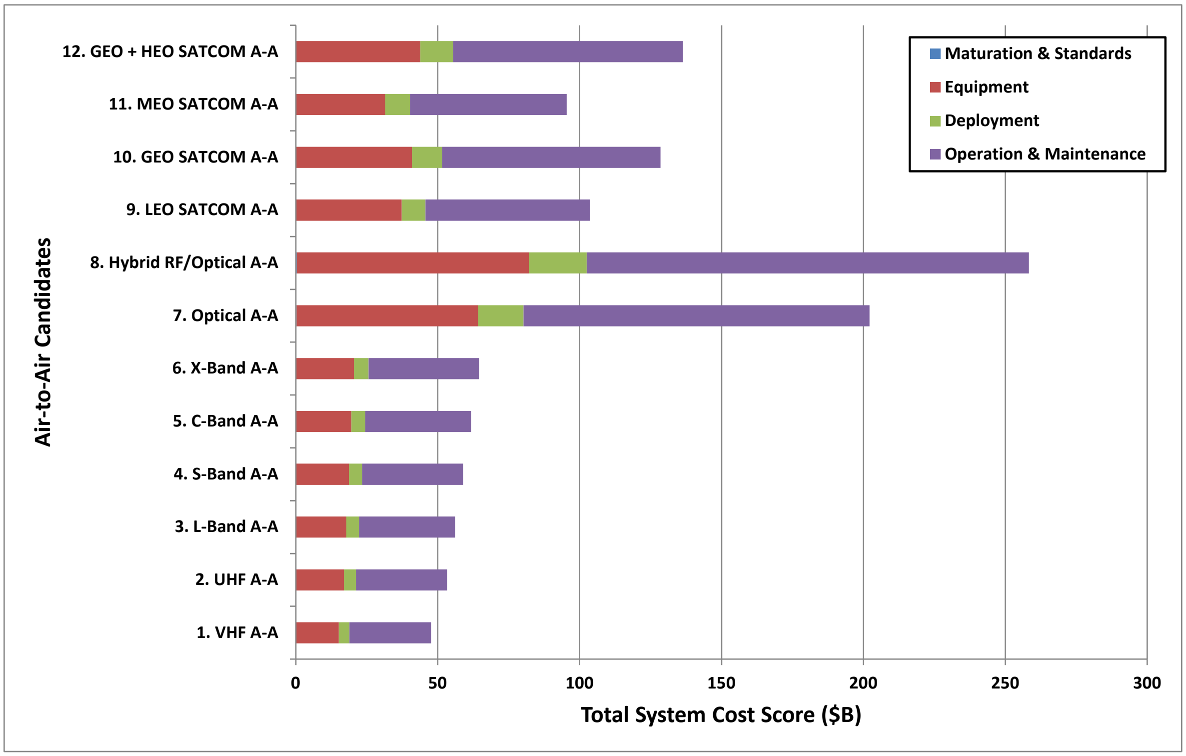


Figure 9 – Summary of A-A Candidates Relative Cost Scores (AC Fleet Model #1)

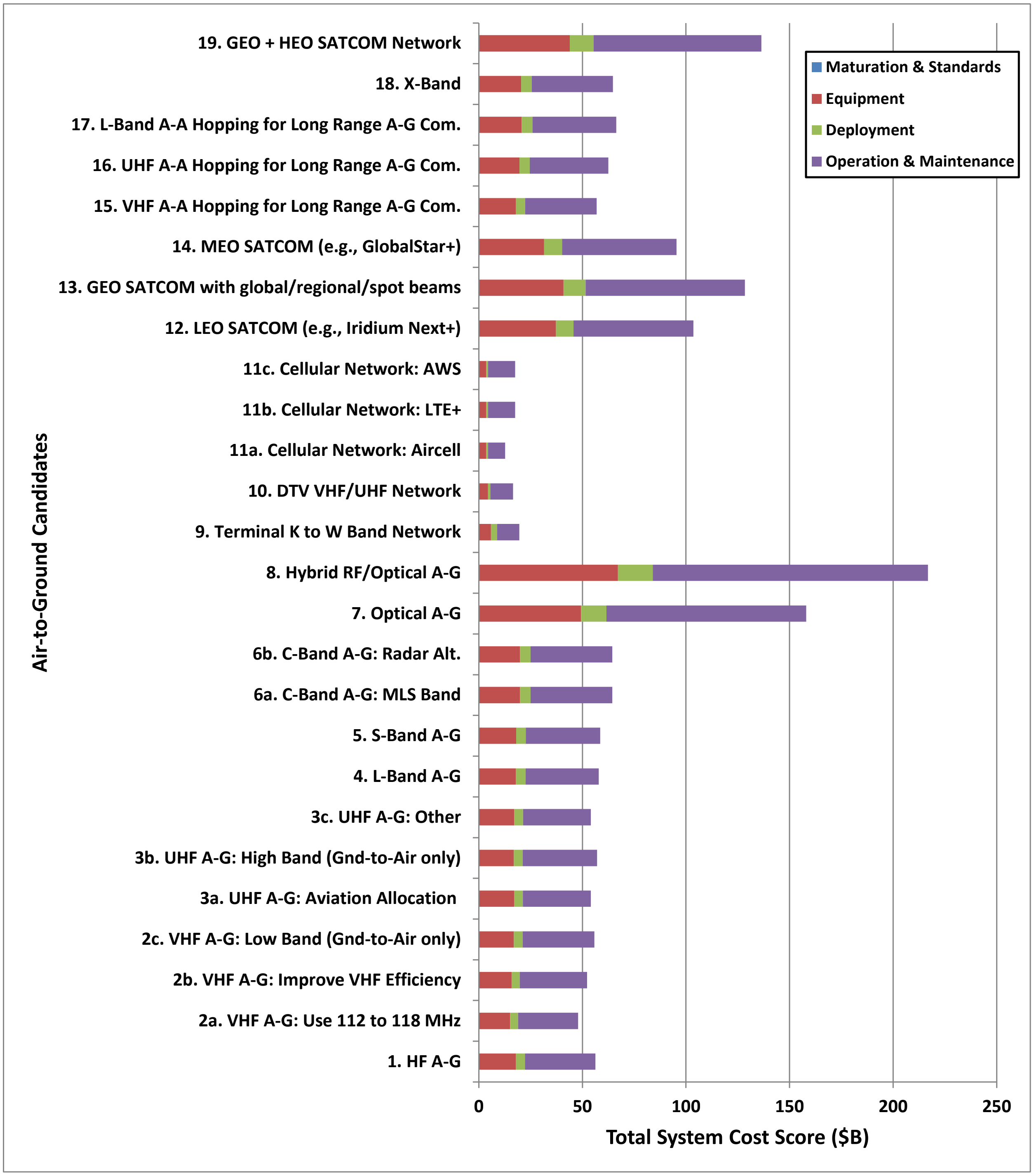


Figure 10 – Summary of A-G Candidates Relative Cost Scores (AC Fleet Model #1)

Note that there are actually twenty six A-G candidates when including several sub-candidates [e.g., candidate #2 actually has three sub-candidates (#2a, #2b, and #2c), candidate #3 has three sub-candidates (#3a, #3b, and #3c), etc., as described in the body of the report].

The findings for the analyses competed in Phase 3 of the study are summarized as follows:

- NAS modernization architects and planners should be very conscious of the cost impact of CNS infrastructure elements including future A-A and A-G communication systems.
- Airborne system costs are a very substantial portion of the entire system infrastructure cost for future communications systems resulting from the large number of aircraft that need equipment built, installed, operated, and maintained to broadly implement a given communications candidate.
- It is typically cost beneficial for reducing the total system costs to increase ground and satellite system costs if it results in a reduction in airborne system costs. This is normally the case because of the large number of aircraft that need to be equipped, operated, and maintained versus the relatively small number of ground and satellite systems.
- Future NAS communications costs can be substantially reduced by taking advantage of commercial communications networks (e.g., cellular, SATCOM, and possible future terrestrial broadband network), rather than building custom aviation-only communications networks.
- The operational improvements enabled by various future NAS CNS systems improvements or upgrades must have their schedules aligned to when the users can expect to receive benefits or else they will be resisted because of the very substantial costs being borne by the aircraft operators.
  - An aligned schedule synchronizes the different avionics modifications programs (e.g., CNS) to reduce the number of installations, thereby minimizing aircraft out-of-service costs, and achieving synergy between related programs needed to achieve operational objectives.
  - Multiple installations are almost always more expensive than a single installation because the labor required for one larger installation is typically less expensive than the labor for two or more smaller installations and other associated costs (e.g., aircraft out of service cost for retrofit aircraft).

2.2.4 Phase 4: NextGen and Beyond ATM Applications, Priority, and Use Case Analyses for Three High Priority Applications

Phase 4 has identified and described a representative set of applications that are enabled by communications and are expected to be utilized in the long-term NextGen and beyond NAS, prioritized the applications, and performed use case analyses for three of the highest priority applications.

A defensible prioritization process was developed that leverages the prioritization process developed by the RTCA NextGen Advisory Committee (NAC). The NAC prioritization process was modified as described herein to de-weight the relative importance of today's "implementation readiness" evaluation metric given the longer term nature of this study than the applications the NAC committee was evaluating and to incorporate a specific individual cost assessment evaluation metric. The application prioritization assessment evaluated each of the identified long-term ATM applications according to five evaluation criteria that included:

1) Benefits (Monetizable) [45%] *[i.e., benefits that readily can be estimated to have a monetary (or cash) value, including, for example, capacity and efficiency]*;

2) Benefits (Non-Monetizable) [15%] *[i.e., benefits difficult to estimate the monetary (or cash) value, including, for example, safety and security]*;
3) Cost [25%] *[i.e., cost of elements needed to enable the application]*;
4) Implementation Readiness [5%] *[i.e., assessment of whether the needed elements are in place to achieve a given operational capability, including, for example standards, policy, and systems]*; and
5) Other Considerations [10%] *[i.e., factors including global harmonization, confidence that the benefits will be realized, and whether the capability is a critical element for a broad set of NextGen and beyond improvements]*.

The individual scores from the five evaluations were multiplied by the weighting factors for each evaluation criterion as identified above (percentages) and summed to obtain a total relative score for each application. The total scores for all applications were ranked to establish a relative prioritization of the applications such that Delegated Interval (DI), Delegated Separation (DS), and Airborne Self-Separation (ASS) applications were in the top tier of applications. Other applications, including In-Trail Procedures (ITP), Optimized Profile Descent (OPD), and Airborne Access to SWIM (AAtS) were ranked in the middle tier, and applications including GNSS/GBAS Category I/II/III Precision Approach, Surface Situational Awareness with Indications and Alerts (SURF IA), and Ground-based Interval Management (GIM) (without Flight Deck IM) were ranked in the lowest tier.

For each of the 52 long-term ATM applications, an assessment of the A-A and A-G communication candidates that would be capable of meeting the application's Required Communications Performance (RCP) was made. This assessment was made by comparing the RCP needed to enable each of the long-term ATM applications with the Actual Communications Performance (ACP) provided by each of the communications candidates.

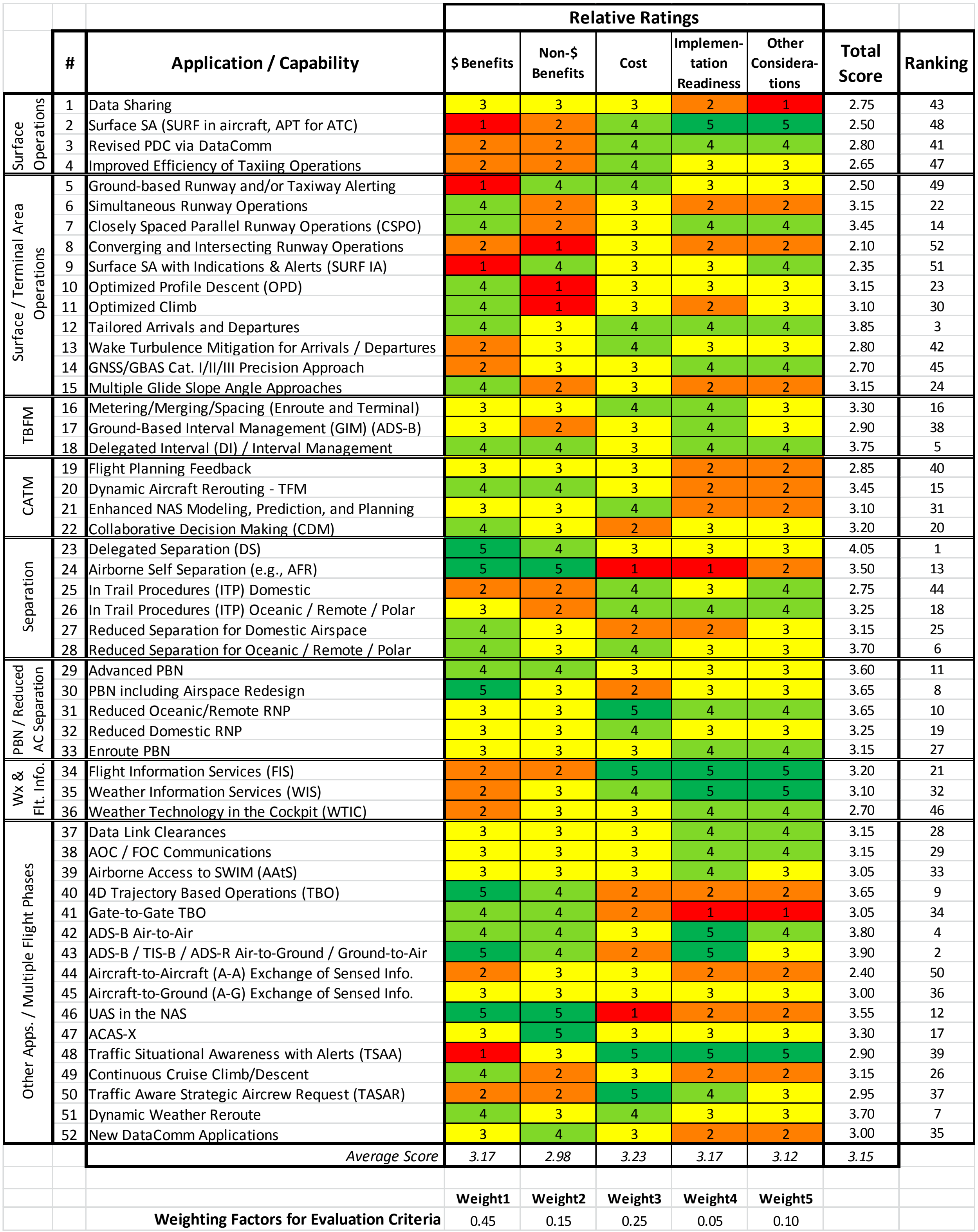
Use case analyses were completed for three of the highest priority applications including: 1) Delegated Interval (DI) / Interval Management (IM), 2) Delegated Separation (DS), and Airborne Self-Separation (ASS).

Each of the use case analysis included the following: a) a description of the concept of operations, b) an identification of a representative set of example operational scenarios used as the basis for the analyses, c) a partitioning of the application into its constituent phases of operation (e.g., pre-initiation, initiation, execution, and termination), d) the development of use case activity diagrams that identify the specific activities in the context of the application where A-A, A-G, and Ground-to-Aircraft (G-A) communications take place, and e) a description of the specific communications needed during each phase of the application.

<u>The study findings for the analyses completed in Phase 4 of the study are summarized as follows:</u>

- A broad set of 52 NextGen and beyond long-term NAS ATM applications were identified, described, and subjectively assessed relative to each other using the evaluation process described in Section 21 of this report. A results summary table that ranks all of these applications is provided in Figure 11 (page 27). *Note that the color scoring legend for this table is given in Figure 305 (page 430).* Individual ratings were provided for each of the 5 evaluation criteria, which were then multiplied by the weighting factors associated with each criterion and summed to yield a total relative score for each application. This evaluation has led to prioritizing the applications into 3 prioritized tiers as given in Figure 12 (page 28) with "Tier 1" being the highest priority application grouping, "Tier 2" being the middle priority grouping, and "Tier 3" being the lowest priority grouping.

- No one single communications data link technology can meet the needs of all the future NAS operations in all airspaces. A combination of various communication technologies are needed to address the diverse aeronautical communications requirements across all the operational flight domains.
- At least one of the communication candidates identified is able to meet the communication requirements needed enable each of the long-term ATM applications. In other words, no application has been identified for which there is no communication data link technology capable of satisfying the application's RCP.



	#	Application / Capability	Relative Ratings					Total Score	Ranking
			$ Benefits	Non-$ Benefits	Cost	Implemen-tation Readiness	Other Considera-tions		
Surface Operations	1	Data Sharing	3	3	3	2	1	2.75	43
	2	Surface SA (SURF in aircraft, APT for ATC)	1	2	4	5	5	2.50	48
	3	Revised PDC via DataComm	2	2	4	4	4	2.80	41
	4	Improved Efficiency of Taxiing Operations	2	2	4	3	3	2.65	47
Surface / Terminal Area Operations	5	Ground-based Runway and/or Taxiway Alerting	1	4	4	3	3	2.50	49
	6	Simultaneous Runway Operations	4	2	3	2	2	3.15	22
	7	Closely Spaced Parallel Runway Operations (CSPO)	4	2	3	4	4	3.45	14
	8	Converging and Intersecting Runway Operations	2	1	3	2	2	2.10	52
	9	Surface SA with Indications & Alerts (SURF IA)	1	4	3	3	4	2.35	51
	10	Optimized Profile Descent (OPD)	4	1	3	3	3	3.15	23
	11	Optimized Climb	4	1	3	2	3	3.10	30
	12	Tailored Arrivals and Departures	4	3	4	4	4	3.85	3
	13	Wake Turbulence Mitigation for Arrivals / Departures	2	3	4	3	3	2.80	42
	14	GNSS/GBAS Cat. I/II/III Precision Approach	2	3	3	4	4	2.70	45
	15	Multiple Glide Slope Angle Approaches	4	2	3	2	2	3.15	24
TBFM	16	Metering/Merging/Spacing (Enroute and Terminal)	3	3	4	4	3	3.30	16
	17	Ground-Based Interval Management (GIM) (ADS-B)	3	2	3	4	3	2.90	38
	18	Delegated Interval (DI) / Interval Management	4	4	3	4	4	3.75	5
CATM	19	Flight Planning Feedback	3	3	3	2	2	2.85	40
	20	Dynamic Aircraft Rerouting - TFM	4	4	3	2	2	3.45	15
	21	Enhanced NAS Modeling, Prediction, and Planning	3	3	4	2	2	3.10	31
	22	Collaborative Decision Making (CDM)	4	3	2	3	3	3.20	20
Separation	23	Delegated Separation (DS)	5	4	3	3	3	4.05	1
	24	Airborne Self Separation (e.g., AFR)	5	5	1	1	2	3.50	13
	25	In Trail Procedures (ITP) Domestic	2	2	4	3	4	2.75	44
	26	In Trail Procedures (ITP) Oceanic / Remote / Polar	3	2	4	4	4	3.25	18
	27	Reduced Separation for Domestic Airspace	4	3	2	2	3	3.15	25
	28	Reduced Separation for Oceanic / Remote / Polar	4	3	4	3	3	3.70	6
PBN / Reduced AC Separation	29	Advanced PBN	4	4	3	3	3	3.60	11
	30	PBN including Airspace Redesign	5	3	2	3	3	3.65	8
	31	Reduced Oceanic/Remote RNP	3	3	5	4	4	3.65	10
	32	Reduced Domestic RNP	3	3	4	3	3	3.25	19
	33	Enroute PBN	3	3	3	4	4	3.15	27
Wx & Flt. Info.	34	Flight Information Services (FIS)	2	2	5	5	5	3.20	21
	35	Weather Information Services (WIS)	2	3	4	5	5	3.10	32
	36	Weather Technology in the Cockpit (WTIC)	2	3	3	4	4	2.70	46
Other Apps. / Multiple Flight Phases	37	Data Link Clearances	3	3	3	4	4	3.15	28
	38	AOC / FOC Communications	3	3	3	4	4	3.15	29
	39	Airborne Access to SWIM (AAtS)	3	3	3	4	3	3.05	33
	40	4D Trajectory Based Operations (TBO)	5	4	2	2	2	3.65	9
	41	Gate-to-Gate TBO	4	4	2	1	1	3.05	34
	42	ADS-B Air-to-Air	4	4	3	5	4	3.80	4
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	5	4	2	5	3	3.90	2
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	2	3	3	2	2	2.40	50
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	3	3	3	3	3	3.00	36
	46	UAS in the NAS	5	5	1	2	2	3.55	12
	47	ACAS-X	3	5	3	3	3	3.30	17
	48	Traffic Situational Awareness with Alerts (TSAA)	1	3	5	5	5	2.90	39
	49	Continuous Cruise Climb/Descent	4	2	3	2	2	3.15	26
	50	Traffic Aware Strategic Aircrew Request (TASAR)	2	2	5	4	3	2.95	37
	51	Dynamic Weather Reroute	4	3	4	3	3	3.70	7
	52	New DataComm Applications	3	4	3	2	2	3.00	35
		Average Score	*3.17*	*2.98*	*3.23*	*3.17*	*3.12*	*3.15*	
			Weight1	**Weight2**	**Weight3**	**Weight4**	**Weight5**		
		Weighting Factors for Evaluation Criteria	0.45	0.15	0.25	0.05	0.10		

Figure 11 – Summary: Priority Assessment of Long-term ATM Applications

			Relative Ratings						
	#	Application / Capability	$ Benefits	Non-$ Benefits	Cost	Implemen-tation Readiness	Other Considera-tions	Total Score	Ranking
Tier 1	23	Delegated Separation (DS)	5	4	3	3	3	4.05	1
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	5	4	2	5	3	3.90	2
	12	Tailored Arrivals and Departures	4	3	4	4	4	3.85	3
	42	ADS-B Air-to-Air	4	4	3	5	4	3.80	4
	18	Delegated Interval (DI) / Interval Management	4	4	3	4	4	3.75	5
	28	Reduced Separation for Oceanic / Remote / Polar	4	3	4	3	3	3.70	6
	51	Dynamic Weather Reroute	4	3	4	3	3	3.70	7
	30	PBN including Airspace Redesign	5	3	2	3	3	3.65	8
	40	4D Trajectory Based Operations (TBO)	5	4	2	2	2	3.65	9
	31	Reduced Oceanic/Remote RNP	3	3	5	4	4	3.65	10
	29	Advanced PBN	4	4	3	3	3	3.60	11
	46	UAS in the NAS	5	5	1	2	2	3.55	12
	24	Airborne Self Separation (e.g., AFR)	5	5	1	1	2	3.50	13
	7	Closely Spaced Parallel Runway Operations (CSPO)	4	2	3	4	4	3.45	14
	20	Dynamic Aircraft Rerouting - TFM	4	4	3	2	2	3.45	15
Tier 2	16	Metering/Merging/Spacing (Enroute and Terminal)	3	3	4	4	3	3.30	16
	47	ACAS-X	3	5	3	3	3	3.30	17
	26	In Trail Procedures (ITP) Oceanic / Remote / Polar	3	2	4	4	4	3.25	18
	32	Reduced Domestic RNP	3	3	4	3	3	3.25	19
	22	Collaborative Decision Making (CDM)	4	3	2	3	3	3.20	20
	34	Flight Information Services (FIS)	2	2	5	5	5	3.20	21
	6	Simultaneous Runway Operations	4	2	3	2	2	3.15	22
	10	Optimized Profile Descent (OPD)	4	1	3	3	3	3.15	23
	15	Multiple Glide Slope Angle Approaches	4	2	3	2	2	3.15	24
	27	Reduced Separation for Domestic Airspace	4	3	2	2	3	3.15	25
	49	Continuous Cruise Climb/Descent	4	2	3	2	2	3.15	26
	33	Enroute PBN	3	3	3	4	4	3.15	27
	37	Data Link Clearances	3	3	3	4	4	3.15	28
	38	AOC / FOC Communications	3	3	3	4	4	3.15	29
	11	Optimized Climb	4	1	3	2	3	3.10	30
	21	Enhanced NAS Modeling, Prediction, and Planning	3	3	4	2	2	3.10	31
	35	Weather Information Services (WIS)	2	3	4	5	5	3.10	32
	39	Airborne Access to SWIM (AAtS)	3	3	3	4	3	3.05	33
	41	Gate-to-Gate TBO	4	4	2	1	1	3.05	34
	52	New DataComm Applications	3	4	3	2	2	3.00	35
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	3	3	3	3	3	3.00	36
Tier 3	50	Traffic Aware Strategic Aircrew Request (TASAR)	2	2	5	4	3	2.95	37
	17	Ground-Based Interval Management (GIM) (ADS-B)	3	2	3	4	3	2.90	38
	48	Traffic Situational Awareness with Alerts (TSAA)	1	3	5	5	5	2.90	39
	19	Flight Planning Feedback	3	3	3	2	2	2.85	40
	3	Revised PDC via DataComm	2	2	4	4	4	2.80	41
	13	Wake Turbulence Mitigation for Arrivals / Departures	2	3	4	3	3	2.80	42
	1	Data Sharing	3	3	3	2	1	2.75	43
	25	In Trail Procedures (ITP) Domestic	2	2	4	3	4	2.75	44
	14	GNSS/GBAS Cat. I/II/III Precision Approach	2	3	3	4	4	2.70	45
	36	Weather Technology in the Cockpit (WTIC)	2	3	3	4	4	2.70	46
	4	Improved Efficiency of Taxiing Operations	2	2	4	3	3	2.65	47
	2	Surface SA (SURF in aircraft, APT for ATC)	1	2	4	5	5	2.50	48
	5	Ground-based Runway and/or Taxiway Alerting	1	4	4	3	3	2.50	49
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	2	3	3	2	2	2.40	50
	9	Surface SA with Indications & Alerts (SURF IA)	1	4	3	3	4	2.35	51
	8	Converging and Intersecting Runway Operations	2	1	3	2	2	2.10	52
		Average Score	*3.17*	*2.98*	*3.23*	*3.17*	*3.12*	*3.15*	
			Weight1	**Weight2**	**Weight3**	**Weight4**	**Weight5**		
		Weighting Factors for Evaluation Criteria	0.45	0.15	0.25	0.05	0.10		

Figure 12 – Summary: Prioritized Tiers of Long-term ATM Applications

2.2.5 *Phase 5: Most Promising Long-Term NAS Communications Technologies*

Phase 5 of the study has completed analyses to identify the most promising long-term NAS communications candidate technologies by phase of flight.

Twenty five (25) evaluation criteria as given in Figure 13 have been identified for the purposes of evaluating and prioritizing the communication candidates. These 25 criteria encompass a broad range of factors that have been used to evaluate the technical performance, cost, and risk of the various candidates. The identified evaluation criteria are traceable to the necessary elements of future aeronautical communications systems as articulated in a number of documents developed by the FAA, NASA, Eurocontrol, and ICAO. A rating scale (from 1 to 5) was defined for each of the evaluation criteria whereby a rating of "1" is "poor" (i.e., very low technical performance, very high cost, or very high risk) and a rating of "5" is "very good" (i.e., very high technical performance, very low cost, or very low risk). Similarly, the intermediate ratings of 2, 3, and 4 incrementally improve from "fair," to "medium," to "good" (respectively) assessments for the evaluation criteria. For a few of the criteria in addition to numerical ratings from 1 to 5, there is an additional rating of "showstopper" (SS). Such a rating indicates that a candidate's performance against the criterion relevant to meeting the ATM communication services needs is completely unacceptable (i.e., a "showstopper") in the flight domain(s) being assessed. When a showstopper rating is given for a particular communication candidate, further assessment of that candidate is stopped for the flight domain(s) under investigation since the candidate's rating for the criterion is determined to be completely unacceptable (i.e., a "showstopper" to selection as a viable candidate).

Category	Evaluation Category Description	#	Criteria
Technical Performance	Technical performance of candidate capabilities needed to support future NextGen and beyond ATM communication services.	1	Coverage Volume / Communications Range
		2	Data Rate
		3	Spectral Efficiency
		4	Capacity
		5	Number of Users
		6	Availability & Continuity
		7	Integrity
		8	Latency
		9	Scaleability / Flexibility / Ability to Incorporate New Technologies
		10	Security / Vulnerabilities
		11	Robustness to Interference / Environment
		12	Installable on Range of Air Vehicles
		13	Ability to Support Broadcast Communications
		14	Satisfy Requirements for Aviation Safety Services
		15	Satisfy Requirements for Aviation Advisory Services
Cost	Costs associated with candidate including airborne/ ground/ satellite infrastructure, and maturation & standards.	16	Airborne Infrastructure Cost
		17	Ground / Satellite Infrastructure Cost
		18	Technology Maturation & Standards Cost
Risk	Risks associated with candidate in the areas of spectrum availability, technology readiness, global acceptance, standards, certification, and transition.	19	Spectrum Availability & Compatibility
		20	Technical Maturity / Readiness Level (TRL)
		21	Standardization Status
		22	Global Harmonization Risk
		23	Certification Complexity
		24	Susceptible to Wide Outage / Long MTTR
		25	Ease of Transition

Figure 13 – Criteria Used to Evaluate / Prioritize Communications Candidates

While all evaluation criteria are important, in the candidate evaluation process it was deemed appropriate to more heavily weight the relative importance of some criteria over other criteria. As such, weighting factors that characterize the relative importance of each evaluation criterion were assigned values that attempted to balance the collective interests of all the aviation stakeholders. The weighting factors were assigned as percentages, such that the sum of the weighting factors for all criteria totaled 100%. These weighting factors were used in the communication candidate prioritization process to determine a total score that is used to rank the candidates, whereby a higher weighted “total score” for a given candidate represents a higher priority candidate.

A summary description of the evaluation criteria, rating scale, and weighting factors used to evaluate and prioritize the candidates in this report is provided in Figure 14 (on page 32).

The A-A and A-G communication candidates were all evaluated for their ability to support the ATM communication needs in all the various flight domains, including surface, terminal area, enroute, oceanic/remote, and polar. The assessments were done for each individual flight domain, as well as for several combinations of flight domains.

An example evaluation matrix is provided in Figure 15 (on page 33), which is the evaluation matrix of the twelve A-A communication candidates in the airport surface flight domain. Similar evaluation matrices were completed for all the flight domains and are provided in Section 30 of this report. Figure 16 (on page 34) summarizes the results of the evaluations with the identification of the prioritized rankings of the A-A communications candidates by flight domains. Similarly, Figure 17 (on page 35) summarizes the prioritizations for the A-G communication candidates by flight domain.

The results of the evaluation are summarized as follows.

- A-A Prioritization:
  - The top tier of A-A candidates include L-band, VHF, and C-band. These candidates scored well in terms of high technical performance, low cost, and low risk across all flight domains. These candidates are capable of providing an actual communications performance quality of service (QoS) commensurate with meeting the RCP for most of the identified long-term NAS ATM safety and advisory applications that require A-A communications.
  - The middle tier of A-A candidates include UHF, S-band, LEO SATCOM, and X-band. The candidates in this tier generally have high scores for some of the evaluation criteria, but have at least one category of performance, cost, or risk that were not evaluated as well as the highest tier of candidates.
  - The lowest tier of A-A candidates include MEO SATCOM, GEO-SATCOM, GEO + HEO SATCOM, hybrid RF/Optical, and Optical. The candidates in this lowest tier generally scored low in at least two evaluation categories of performance, cost, or risk. The performance of the candidates in this tier typically only meets the RCP for a subset of the long-term ATM applications.
- A-G Prioritization for Surface, Terminal Area, and Enroute Flight Domains:
  - The top tier of A-G candidates applicable to the airport surface, terminal area, and enroute flight domains include VHF, L-band, LEO SATCOM, and cellular candidates. These A-G candidates scored well in terms of high technical performance, low cost, and low risk. These candidates (evaluated with expected future improvements and maturation over the study 50-year time horizon) tend to be capable of providing a QoS commensurate with meeting the RCP for most of the envisioned long-term ATM applications. Evaluating these candidates as they

are today would result in higher cost associated with LEO SATCOM and higher risk associated with using cellular systems for safety services. It is envisioned that over time that LEO SATCOM will become very high performance and very low cost with Teledesic-style LEO constellations containing hundreds to thousands of pico-satellites and cellular networks will become robust for aviation safety services.

  - The middle tier of A-G candidates applicable to the airport surface, terminal area, and enroute flight domains include UHF, S-band, and C-band. This tier of candidates has some of the desirable characteristics of the top tier, but these candidates generally have at least one area of performance, cost, or risk that was not evaluated as well as the highest tier of candidates.
  - The lowest tier of candidates applicable to the airport surface, terminal area, and enroute flight domains include X-band, MEO SATCOM, GEO SATCOM, GEO + HEO SATCOM, DTV VHF/UHF, Terrestrial K to W band, Hybrid RF/Optical, and Optical. The candidates in this lowest tier usually evaluated low in at least two evaluation categories of performance, cost, or risk. The actual communication performances of these lowest tier candidates typically only meet the RCP for a small subset of the envisioned long-term ATM applications.

- A-G Prioritization for Oceanic, Remote, and Polar Flight Domains:
  - The top tier of A-G candidates applicable to the oceanic, remote, and polar flight domains include LEO and MEO SATCOM. These candidates were evaluated very high relative to the other alternatives against the measures of high technical performance, low cost, and low risk. They also could meet the A-G communications RCP to enable a broad range of identified ATM long-term safety and advisory applications.
  - The middle tier of A-G candidates include the GEO SATCOM (for oceanic/ remote not including polar) or GEO + HEO SATCOM (when including polar coverage) and HF. These candidates could meet the ATM application RCP, but have shortfalls primarily in a number of areas [e.g., capacity for HF, and cost for GEO and GEO + HEO SATCOM].
  - The lowest tier of A-G candidates include those that achieve long range A-G communications using aircraft-to-aircraft LOS communications that hop between intervening aircraft. These candidates include VHF A-A hopping, UHF A-A hopping, and L-band A-A hopping. They ranked low in a number of performance areas.
  - While HF and the hopping candidates tended to be evaluated with lower priority than the SATCOM alternatives to support ATM applications that require A-G communications in oceanic, remote, and polar flight domains, it will likely remain important from safety and security perspectives to maintain a backup / alternate means of A-G communications to the primary means of communications (likely SATCOM) in these flight domains. HF or the hopping alternatives provide a diverse technical means to SATCOM for achieving long range A-G communications.

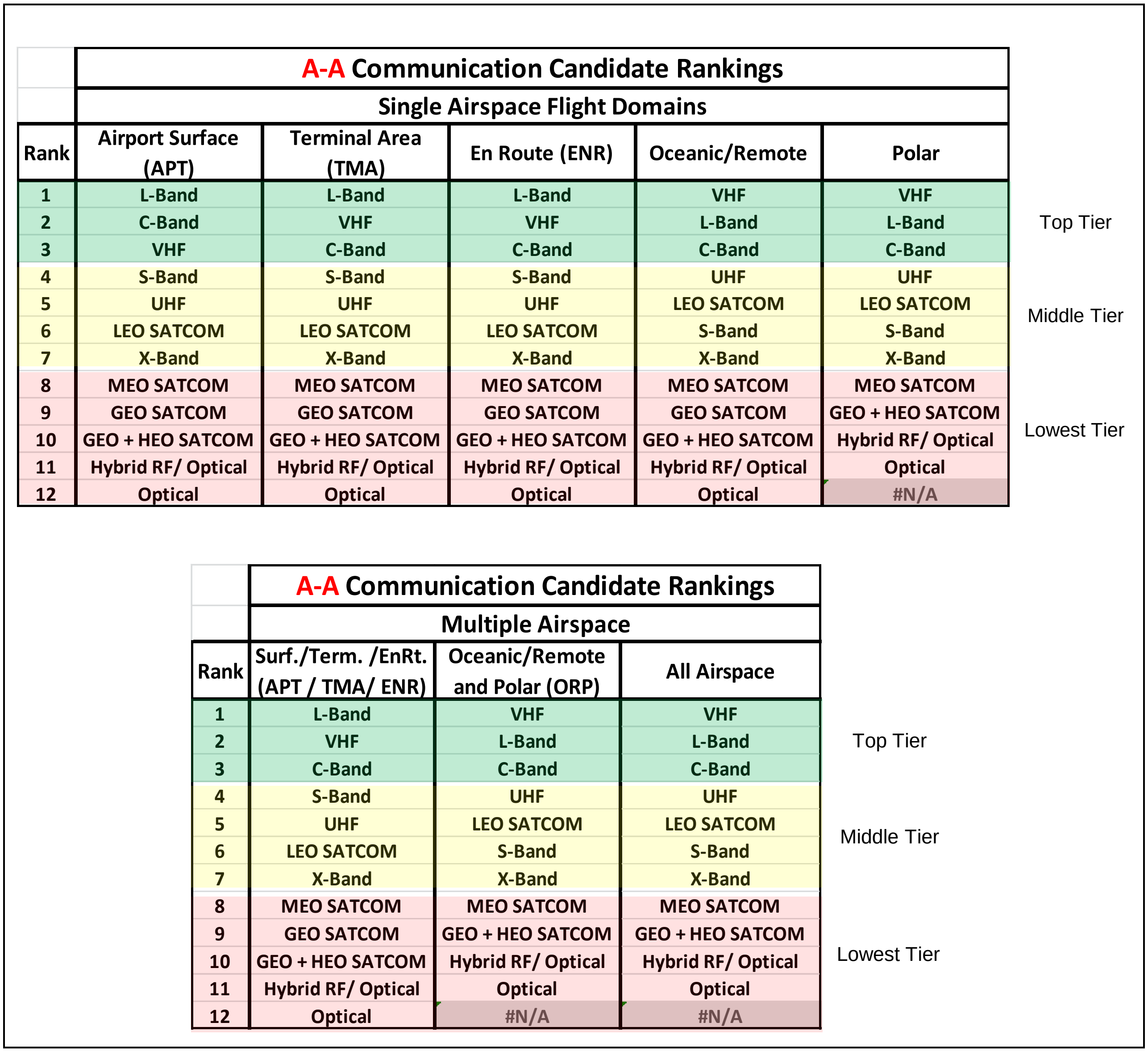
While this study has attempted to appropriately prioritize the communication candidates in a manner consistent with the expected long-term NAS communication needs while balancing the collective interests of all the aviation stakeholders, it should be noted that the candidate prioritizations are subject to change when different evaluation criteria, assumptions, communications requirements, or weighting factors are used in the assessment process.

	#	Criteria Weight (%)	Evaluation Criteria	Brief Description	Ratings Scale Summary					
					5	4	3	2	1	SS
					Very Good	Good	Medium	Fair	Poor	Showstoper for Candidate
Technical Performance	1	6	Coverage Volume/ Comm. Range	Coverage in flight domain(s)	100% Coverage	Nearly 100%	A few gaps	Some gaps	Many gaps	No service in at least one Flight Domain
	2	5	Data Rate	Data rate expected to be achieved by the candidate	> 1000 MBPS	< 1000 MBPS	< 200 MBPS	< 1 MBPS	< 0.01 MBPS	---
	3	3	Spectral Efficiency	bit rate/BW	> 15	< 15	< 5	< 2.5	< 0.5	---
	4	5	Capacity	Relative comparison of the total communication BW of candidate	Very High	High	Medium	Low	Very Low	---
	5	3	Number of Users	Relative comparison of the total number of simultaneous users	Very High	High	Medium	Low	Very Low	---
	6	3	Availability & Continuity	Availability & continuity assessment	Very High (>0.999995)	High (> 0.99995)	Medium (> 0.9999)	Low (> 0.999)	Very Low (< 0.999)	---
	7	3	Integrity	Relative comparison to meet aviation services integrity requirements	Very High	High	Medium	Low	Very Low	---
	8	3	Latency	Communication system latency (sec)	< 0.2	< 1.0	Threshold for adequate voice com.	< 5	> 5	---
	9	2	Scaleability /Flexibility /Incorp. New Tech.	Candidate Scaleability, Flexibility, & Ability to incorporate new technology	Very High	High	Average	Low	Very Low	---
	10	3	Security /Vulnerabilities	Robustness against 6 data security measures	Very Highly Robust to Security Measures	Highly Robust to Security Measures	Moderately Robust to Security Measures	Low Robustness to Security Measures	Very Low Robustness to Security Measures	---
	11	3	Robustness to Interference /Environment	Robustness against environmental interference	Very Highly Robust to Interference	Highly Robust to Interference	Moderately Robust to Interference	Low Robustness to Interference	Very Low Robustness to Interference	---
	12	3	Installable on Range of Air Vehicles	East of incorporating on range of aircraft types	Easy for all air vehicles	Easy for most air vehicles	Medium	Hard or impractical for some air vehicles	Hard or impractical for many air vehicles	---
	13	5	Ability to Support Broadcast Comms.	Candidates ability to support broadcast communications	Very Good	Good	Medium	Very limited broadcast capability	No practical broadcast capability	---
	14	8	Satisfy RCP for Safety Services (QoS)	Ability to satisfy safety services RCP for identified ATM applications	Easilty Meets	Meets	Meets most	Meets many	No safety service	---
	15	8	Satisfy RCP for Advisory Services (QoS)	Ability to satisfy advisory services RCP for identified ATM applications	Easilty Meets	Meets	Meets most	Meets many	Meets some	Does not meet QoS for Advisory Services
Cost	16	9	Airborne Infrastructure Cost	Relative airbonre cost	Very Low	Low	Average	High	Very High	Cost Showstoper
	17	4	Ground / Satellite Infrastructure Cost	Relative cost of ground/satellite infrastructure to civil aviation	Very Low	Low	Average	High	Very High	Cost Showstoper
	18	1	Technology Maturation & Stds. Cost	Relative civil aviation cost to mature and standardize candidate	Very Low	Low	Average	High	Very High	---
Risk	19	9	Spectrum Availability & Compatibility	Risk of spectrum availability & compatibility with AMCS	AMCS Band Unused	Aeronautical Band Under Use	Aero. Allocation of Spectrum Expected	Spectrum Available, but not Allocated	Spectrum in use non-civil aviation users	Spectrum not Avail. nor AMCS compatible
	20	1	Technical Maturity /Readiness Level	Predicted TRL in 15 years	TRL >= 7	TRL = 6	TRL 4 or 5	TRL = 3	TRL 1 or 2	---
	21	1	Standization Status	Existance of standards (Stds.)	Aeronautical Stds. - Minor Mod.	Aeronautical Stds. - Major Mod.	Commercial/Military Stds. - Minor Mod.	Commercial/Military Stds. - Major Mod.	No Current Stds.	---
	22	3	Global Harmonization Risk	Risk in global acceptance of candidate for ATM applications	Very Low	Low	Medium	High	Very High	---
	23	3	Certification Complexity	Risk in certification of candidate for Aviation Services Applications	Similar Aviation Products Certified	Plan to Certify within 15 years	Used in Non-Aviation Safety Service	Used for Non-Safety Services	Technology is Not Currently Used	Impractical Relative to Other Alternatives
	24	3	Susceptible to Wide Outage / Long MTTR	Candidate susceptability to large coverage area outages / long MTTR	Very Low	Low	Medium	High	Very High	---
	25	3	Ease of Transition	Ease of transitioning NAS to the new candidate	Very Easy	Easy	Moderately Easy	Hard	Very Hard	---

Figure 14 – Summary of Evaluation Criteria, Rating Scale, and Weighting Factors

	#	Criteria Weight (%)	Evaluation Criteria	Ratings for Air-to-Air Candidates											
			Airport Surface Flight Domain	1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
				VHF	**UHF**	**L-Band**	**S-Band**	**C-Band**	**X-Band**	**Optical**	**Hybrid RF/ Optical**	**LEO SATCOM**	**GEO SATCOM**	**MEO SATCOM**	**GEO + HEO SATCOM**
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	4	3	3	2	2	2	5	4	5	4
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	4	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	4	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	4	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	4	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	4	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	4	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	1	2	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	4	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	4	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	3	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	1	2	1
	13	5	Ability to Support Broadcast Comms.	5	5	5	5	4	4	1	2	2	4	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	5	5	3	1	2	3	1	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	5	5	5	4	3	3	3	2	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	4	3	1	1	3	2	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	2	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	4	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	5	2	2	2	5	3	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	5	2	1	1	4	4	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	3	2	3
	22	3	Global Harmonization Risk	5	2	5	3	5	3	2	2	5	4	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	4	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	1	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	3	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*107*	*97*	*107*	*80*	*65*	*69*	*93*	*78*	*81*	*77*
		100	*Candidate Weighted Total Score*	*429*	*378*	*435*	*394*	*434*	*327*	*257*	*276*	*371*	*291*	*315*	*290*
			Candidate Priority in this Assessment	***3***	***5***	***1***	***4***	***2***	***7***	***12***	***11***	***6***	***9***	***8***	***10***

Figure 15 – Example A-A Candidate Evaluation in Surface (APT) Flight Domain



A-A Communication Candidate Rankings

Single Airspace Flight Domains

Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar	
1	L-Band	L-Band	L-Band	VHF	VHF	Top Tier
2	C-Band	VHF	VHF	L-Band	L-Band	
3	VHF	C-Band	C-Band	C-Band	C-Band	
4	S-Band	S-Band	S-Band	UHF	UHF	Middle Tier
5	UHF	UHF	UHF	LEO SATCOM	LEO SATCOM	
6	LEO SATCOM	LEO SATCOM	LEO SATCOM	S-Band	S-Band	
7	X-Band	X-Band	X-Band	X-Band	X-Band	
8	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	Lowest Tier
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO + HEO SATCOM	
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	Hybrid RF/ Optical	
11	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Optical	
12	Optical	Optical	Optical	Optical	#N/A	

A-A Communication Candidate Rankings

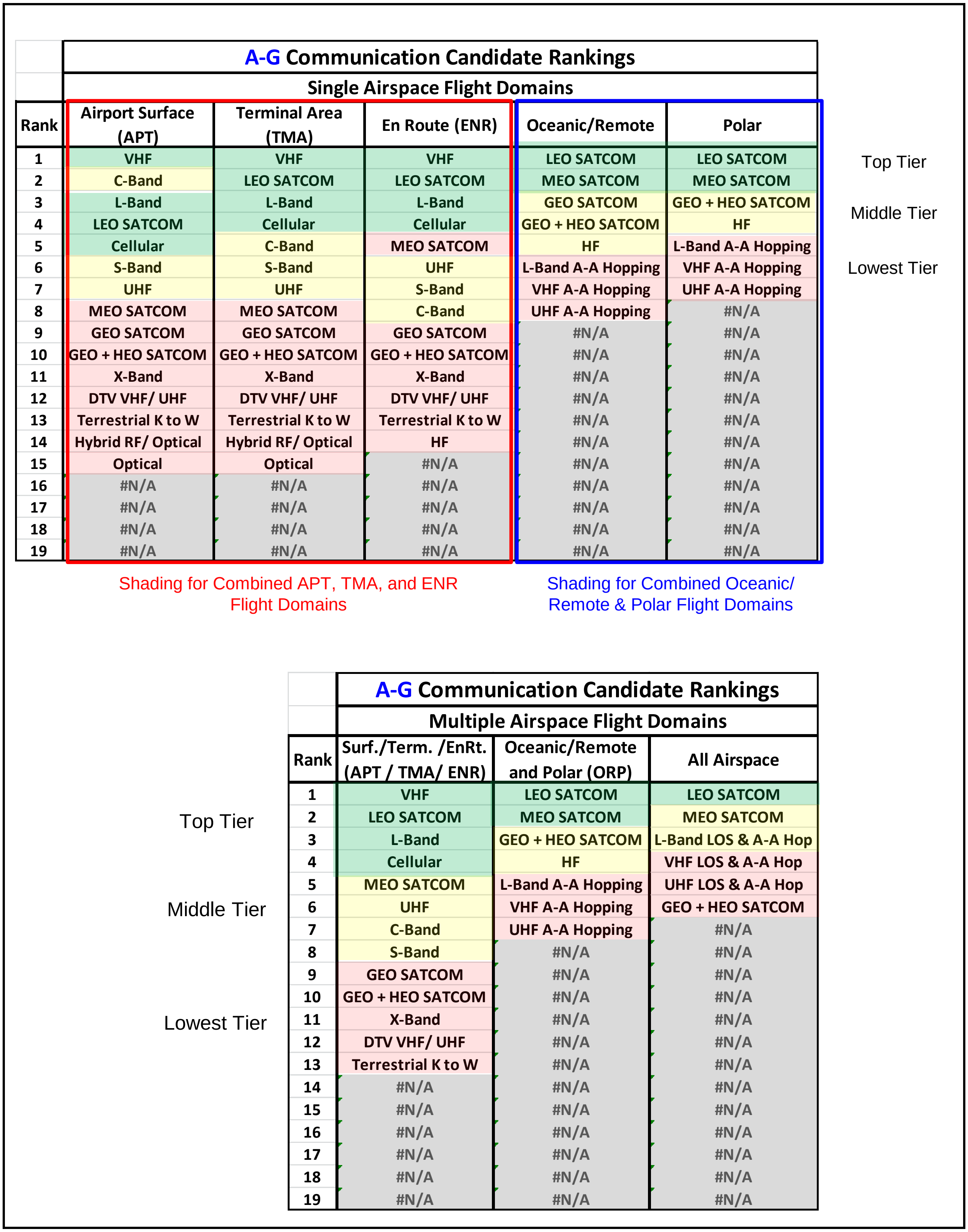
Multiple Airspace

Rank	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace	
1	L-Band	VHF	VHF	Top Tier
2	VHF	L-Band	L-Band	
3	C-Band	C-Band	C-Band	
4	S-Band	UHF	UHF	Middle Tier
5	UHF	LEO SATCOM	LEO SATCOM	
6	LEO SATCOM	S-Band	S-Band	
7	X-Band	X-Band	X-Band	
8	MEO SATCOM	MEO SATCOM	MEO SATCOM	Lowest Tier
9	GEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	
10	GEO + HEO SATCOM	Hybrid RF/ Optical	Hybrid RF/ Optical	
11	Hybrid RF/ Optical	Optical	Optical	
12	Optical	#N/A	#N/A	

Figure 16 – Summary of A-A Candidate Prioritization by Flight Domain

<u>Notes for Figure 16 and Figure 17</u>:

1. *"#N/A" stands for "Not Applicable." Each "#N/A" entry indicates that of the 12 A-A and 19 A-G communications candidates being evaluated, a candidate has been given a showstopper (SS) [i.e., unacceptable] rating for the flight domain(s) under investigation and thus is not included in the ranked list of candidates.*
2. *Green, yellow, and red shading indicate the top, middle, and lowest tier candidates for serving multiple airspace domains as indicated.*



A-G Communication Candidate Rankings

Single Airspace Flight Domains

Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar
1	VHF	VHF	VHF	LEO SATCOM	LEO SATCOM
2	C-Band	LEO SATCOM	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	L-Band	L-Band	GEO SATCOM	GEO + HEO SATCOM
4	LEO SATCOM	Cellular	Cellular	GEO + HEO SATCOM	HF
5	Cellular	C-Band	MEO SATCOM	HF	L-Band A-A Hopping
6	S-Band	S-Band	UHF	L-Band A-A Hopping	VHF A-A Hopping
7	UHF	UHF	S-Band	VHF A-A Hopping	UHF A-A Hopping
8	MEO SATCOM	MEO SATCOM	C-Band	UHF A-A Hopping	#N/A
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	X-Band	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	DTV VHF/ UHF	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	Terrestrial K to W	Terrestrial K to W	#N/A	#N/A
14	Hybrid RF/ Optical	Hybrid RF/ Optical	HF	#N/A	#N/A
15	Optical	Optical	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A

A-G Communication Candidate Rankings

Multiple Airspace Flight Domains

Rank	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace
1	VHF	LEO SATCOM	LEO SATCOM
2	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	GEO + HEO SATCOM	L-Band LOS & A-A Hop
4	Cellular	HF	VHF LOS & A-A Hop
5	MEO SATCOM	L-Band A-A Hopping	UHF LOS & A-A Hop
6	UHF	VHF A-A Hopping	GEO + HEO SATCOM
7	C-Band	UHF A-A Hopping	#N/A
8	S-Band	#N/A	#N/A
9	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	#N/A	#N/A
14	#N/A	#N/A	#N/A
15	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A

Figure 17 – Summary of A-G Candidate Prioritization by Flight Domain

2.3 Study Follow-on

An additional follow-on study is being planned to further identify and evaluate communications candidates for use in very low and low altitude UAS ATM applications. Beyond this follow-on investigation, additional R&D is recommended to more comprehensively evaluate the communication candidates for meeting the long-term needs of the NAS in a cost effective manner. Recommendations for additional study are included in Section 33.

2.4 Document Organization

- Section 1 provides an executive summary of this report.
- Section 2 provides introductory information relevant to the Com50 study and a more in-depth summary of the study results.
- Section 3 describes the future communications study, including an overview of the statement of work associated with this NRA study.
- Section 4 describes the technical approach used to complete this study.
- Sections 5 to 32 contain the main body of this report, which has been segregated into five parts. These five parts correspond with the five research phases as documented in the five interim reports that were developed during the execution of the study in compliance with NRA statement of work. The content of these five parts at a high level includes:
  - Part 1: Identifies and characterizes existing and emerging data communications technology candidates (Sections 5 to 15);
  - Part 2: Identifies and describes the infrastructure and architecture of existing and emerging communications candidates, and identifies and evaluates threats, vulnerabilities, risks, and mitigations for NAS air-to-air and air-to-ground communications (Sections 16 to 20);
  - Part 3: Contains a comparative cost analysis of the communications candidates (Sections 21 to 24);
  - Part 4: Identifies, describes, and prioritizes a set of long-term ATM applications; identifies which applications could be supported by the various communications candidates; and provides use case analyses for three of the highest priority applications including Delegated Interval / Interval Management, Delegated Separations, and Airborne Self-Separation (Sections 25 to 28); and
  - Part 5: Identifies criteria for prioritizing the communication technology candidates and describes the use of the criteria to prioritize the candidates from most promising to least promising (Sections 29 to 32).
- Section 33 provides a conclusion to the study and recommendations for further work.
- There are three appendices to this report, whereby:
  - Appendix A contains a list of acronyms and abbreviations;
  - Appendix B contains a copy of the public notice from the Federal Communications Commission dated March 6, 2012 advising of their zero tolerance policy regarding the enforcement of the law against cell jammers, GPS jammers, and other jamming devices; and
  - Appendix C overviews GPS vulnerabilities as identified and described in an FAA report released in January 2007.

3 DESCRIPTION OF THE FUTURE COMMUNICATIONS STUDY

This document describes the results of a study conducted by employees of Rockwell Collins under contract to NASA Ames Research Center in support of NASA's work in the Aeronautics Research Mission Directorate and the Concepts, Technology, and Development Project of the Airspace Systems Program. Representatives from the NASA Glenn Research Center provided technical monitoring and technical review for this study contract.

The specific research objectives of the study include:

1) identifying long-term technology candidates that allow air-to-air and air-to-ground data exchange for the future air transportation system,
2) characterizing the candidates, and
3) investigating how the candidates could serve the evolution of airspace applications over a National Airspace System (NAS) modernization time horizon of 50 years.

Note that within this report, the study is referred to as the Com50 Study and A-G communications are meant to also imply the reciprocal capability of Ground-to-Aircraft (G-A) communications.

The following subsections provide an introduction to the study and include relevant background information, a summary of the study program's objectives and tasking, and an identification of the study team.

3.1 Research Goals

The goals of the Com50 Study are to identify communications technology candidates that are expected to meet the data communications requirements of the future National Airspace System (NAS), quantify their attributes, map them to specific Air Traffic Management (ATM) functions, identify architectural and infrastructure needs & costs, and assess each candidate's ability to meet the requirements for current and anticipated future ATM applications.

3.2 Com50 Study Program Overview

On October 1, 2012, NASA awarded Rockwell Collins a contract to execute on this Com50 Study program per contract #NNA12AB82C. The NASA contract was awarded to Rockwell Collins as a one year base contract with a period of performance from October 1, 2012 to September 30, 2013, with an option for an additional year (option year 1). The option year was exercised in September 2013, with a period of performance from October 1, 2013 to September 30, 2014. The contract was subsequently extended ~1 month such that the final review meeting with NASA leadership would not be held at the end of the fiscal year (i.e., end of September).

A list of the significant milestones for this program is identified below. The milestone deliverables of the baseline 1 year study included #01 to #04, while the deliverables for the option year 1 included #05 to #09.

1. #01: Kickoff Meeting & Work Plan *[Completed: November 7, 2012]*
2. #02: Data Communications Technologies Candidates Report *[Submitted: June 26, 2013]*
3. #03: Infrastructure and Architecture Needs of Candidate Technologies Report *[Submitted: August 28, 2013]*
4. #04: Base Year Presentation and Report *[Completed: September 25, 2013]*

5. #05: Alternative Air-to-Air and Air-to-Ground Communications Systems Report *[Submitted: December 23, 2013]*
6. #06: Alternative Technologies Report *[Submitted: June 20, 2014]*
7. #07: Identification of Most Promising Technologies Report *[Submitted: August 28, 2014]*
8. #08: Optional Year 1 Presentation and Final Review *[Completed: November 4, 2014]*
9. #09: Final Comprehensive Report *[This report, submitted: October 24, 2014]*

3.3 NRA Statement of Work Summary

Summaries of the NASA NRA statement of work for the "Base Year" and "Option Year 1" study are provided in the subsections below.

3.3.1 Base Year – Summary of the Statement of Work (FY2013)

A summary of program tasking for the five task areas identified in the Statement of Work (SOW) for the base year program is provided in the subsections below.

3.3.1.1 Task 3.1: Kickoff Meeting & Work Plan

Task 3.1 required the development and presentation of a detail Work Plan (milestone deliverable #01) which outlined the work to be performed during the base year program and all associated metrics required to complete the work successfully. The kickoff meeting between NASA and Rockwell Collins representatives to discuss the work plan was held on November 7, 2012 at the NASA Glenn Research Center.

3.3.1.2 Task 3.2: Identification of Existing & Emerging Data Communications Technology Candidates

Task 3.2 required the development of a report entitled "Data Communications Technologies Candidates" (milestone deliverable #02) that described the technology candidates and their integrations that will allow air-to-air and air to-ground data exchange. This first interim report was developed and submitted to NASA on June 26, 2013. It described the findings from the following investigations:

- Identify existing technologies that are used for air-to-ground and air-to-air (both way communication, in each case) communications, including voice and data communications.
- Identify the additional technologies that are currently in research and development for future use. Include ADS-B information as a requirement in these discoveries, with the requirements on the current (1090 MHz and 978 MHz) as a baseline.
- Consider the trend of the R&D into these communication technologies and include other technologies may be possible beyond the 2012 – 2062 NextGen timeframe that may be applicable for aviation use.
- Identify how the technology candidates are integrated or can be integrated in the future.

- Quantify the functional attributes and characteristics of the technology candidates. Include a comprehensive list of attributes covering bandwidth, latency, communication range, vulnerabilities (with potential mitigations addressed), etc., essentially capturing what each technology candidate provides as an enabling capability to the user (i.e., quantified actual communication performance that can be provided.
- Review existing airspace applications and their requirements for communication performance required by the applications.
- Review future anticipated applications (NextGen and beyond) and identify initial requirements on communications performance and provide rationale.
- Map the technologies to applications based on the ability of the technology to support the application(s).
- Identify the strengths and weaknesses of each technology candidate, including how ADS-B could be made more cost effective.

The results of these investigations as documented in the first interim report and have been integrated into this final comprehensive report in Sections 5 to 15.

3.3.1.3 Task 3.3: Identify Infrastructure and Architecture Needs of Candidate Technologies

Task 3.3 required the development of a report entitled “Infrastructure and Architecture Needs of Candidate Technologies” (milestone deliverable #03) relevant to the air-to-air and air to-ground data exchange. The second interim report was submitted to NASA on August 28, 2013 and described the findings from the following investigations:

- Identify the architectural needs by the technology candidates and the initial list of systems and interfaces that need to change.
- Identify the airborne and ground infrastructure (and changes to existing infrastructure) required by the technology candidates.
- Identify vulnerabilities in the computing environment and communication technologies; comment on vulnerabilities in communications protocols.
- Outline methods to mitigate these vulnerabilities.
- Evaluate threats to new communication technologies. This includes consideration of the more highly networked ATM systems that include the corruption of information assets (either deliberate or accidental), the repudiation of safety-relevant actions, as well as the unavailability of services. It also includes consideration of the expansion of ATM functions and air-to-ground data exchange demands. While looking at these vulnerabilities, consider the security challenges to be addressed, including: integrity, authentication, non-repudiation, availability/continuity, data separation, and confidentiality.

The results of these investigations as documented in the second interim report have been integrated into this final comprehensive report in Sections 16 to 20.

3.3.1.4 Task 3.4: Conference Presentation

A presentation summarizing the findings of the research effort to date was developed and presented at the 2013 Integrated Communications, Navigation, and Surveillance (iCNS) conference. The presentation was entitled “Study of Long Term Candidates for Air-to-Air and

Air-to-Ground Communications in the National Airspace System." The iCNS conference took place on April 23-25, 2013 at the Westin Washington Dulles Airport Hotel in Herndon, Virginia. A copy of the presentation was provided to NASA for review and approval prior to the conference.

In addition to the one conference presentation identified in the statement of work, a joint presentation was developed by a team consisting of NASA, Rockwell Collins, and the two other NRA contractors (i.e., Honeywell and Xcelar/Agile Defense) working independently against the same statement of work for the 2013 IEEE Aerospace Conference held during the week of March 4, 2013 in Montana.

3.3.1.5 Task 3.5: Base Year Presentation

Task 3.5 required the development of a "Base Year Report" presentation (milestone deliverable #04) that described the findings and results of the research effort to date. The presentation for the base year report was held at NASA Ames on September 25, 2013 and included representatives from the NASA Ames, Glenn, and Langley Research Centers. An additional NASA executive briefing was conducted via Teleconference/WebEx on October 24, 2013, since some of the key NASA project leaders were not available to fully participate in the September 25 briefings at NASA Ames.

3.3.2 Option Year 1 – Summary of the Statement of Work (FY2014)

A summary of program tasking for the five task areas identified in the Statement of Work (SOW) for the option year 1 program is provided in the subsections below.

3.3.2.1 Task 3.6: Task Description – Option Year 1 (12 Months)

This WBS item defined the SOW scope of the Option Year 1 to include Tasks 3.7 to 3.12.

3.3.2.2 Task 3.7: Kickoff Meeting & Work Plan for Option Year 1

Task 3.7 required the development and presentation of a detailed Work Plan which outlined the work to be performed during the Option Year 1 and all associated metrics required to complete the work successfully. The Option Year 1 work plan was submitted on October 30, 2013 with the kickoff meeting held on November 22, 2013.

3.3.2.3 Task 3.8: Alternative Air-to-Air and Air-to-Ground Communications Systems

Task 3.8 required the development of a report entitled "Alternative Air-to-Air and Air-to-Ground Communications Systems" (milestone deliverable #05) describing the findings from an initial cost analysis of the candidates. This third interim report was submitted to NASA on December 23, 2013 and described the findings from the following investigations:

- Estimate costs for the implementation of the A-A and A-G candidate technologies, including airborne, satellite-based, and ground-based equipment and systems that are part of the infrastructure. Cost estimates should include facilities and equipment, and operation and maintenance.
- The cost estimates should make allowances for reuse of existing facilities and equipment. Include a range of performance characteristics (quality of service, bandwidth, etc., identified from Task 3.2) that have a cost impact on the cost estimates.

- The report should provide cost comparisons of multiple air-to-air and air-to ground communications alternatives (and their integration) based on costs, bandwidth, safety, reliability, and security.

The results of these investigations as documented in the third interim report have been integrated into this final comprehensive report in Sections 21 to 24.

3.3.2.4 Task 3.9: Alternative Technologies

Task 3.9 required the development of a report entitled “Alternative Technologies” (milestone deliverable #06) relevant to the air-to-air and air to-ground alternative ATM communication technologies. This fourth interim report was submitted to NASA on June 20, 2014 and described the findings from the following investigations:

- Prioritize and describe air traffic management applications (per Task 3.2), including ADS-B IN applications including Delegated Interval / Interval Management, Delegated Separation, and Airborne Separation (both one to one and one to many separations).
- For each ATM application, identify candidates that meet the needs of each application and describe the infrastructure required.
- Provide brief use case examples for Delegated Interval / Interval Management, Delegated Separation, and Airborne Self-Separation using ADS-B IN information.

The results of these investigations as documented in the fourth interim report have been integrated into this final comprehensive report in Sections 25 to 28.

3.3.2.5 Task 3.10: Identification of the Most Promising Technologies

Task 3.10 required the development of a report entitled “Most Promising Technologies” (milestone deliverable #07). This fifth interim report was submitted to NASA on August 28, 2014 and described the most promising technology alternatives and identifies expected future ATM applications for which they are suitable based upon the following investigations:

- Identify criteria for prioritizing the list of technology candidates from most promising to least promising.
- Use the criteria to identify the most promising technology alternatives.
- Identify which of the applications are feasible with the most promising candidates.

The results of these investigations as documented in the fifth interim report have been integrated into this final comprehensive report in Sections 29 to 32.

3.3.2.6 Task 3.11: Conference Presentation

A presentation summarizing the findings of the research effort was developed and presented at the 2014 Integrated Communications, Navigation, and Surveillance (iCNS) conference. The presentation was entitled “Study Findings from R&D of Long Term Future Communications Candidates for the National Airspace System (NAS).” The iCNS conference took place on April 8-10, 2014 at the Westin Washington Dulles Airport Hotel in Herndon, Virginia. A copy of the presentation was provided to NASA for review and approval prior to the conference.

Four additional conference papers and presentations, in addition to the presentation defined in the statement of work, have been completed as follows:

- The first is a paper and presentation, entitled "A Study of Future Communication Concepts and Technologies for the National Airspace System – Part I," that was developed for the 2013 Digital Avionics Systems Conference (DASC) held in Syracuse, New York during the week of October 6, 2013. The 2013 DASC paper and presentation were developed by a joint team of consisting of NASA, Rockwell Collins, and the two other NRA contractors (i.e., Honeywell and Xcelar/Agile Defense) working independently against the same statement of work. This work was completed on October 24, 2013 with the submission of the final paper to IEEE for publishing in the conference proceedings.
- The second paper and presentation, entitled "A Study of Future Communication Concepts and Technologies for the National Airspace System – Part II," was developed for the 2014 IEEE Aerospace Conference held in Montana during the week of March 3, 2014. This work was completed by joint team of consisting of NASA, Rockwell Collins, and the two other NRA contractors (i.e., Honeywell and Xcelar/Agile Defense). A summary of the paper was presented and the final paper was published as part of the 2014 IEEE Aerospace Conference proceedings.
- The third additional paper and presentation, entitled "A Study of Future Communication Concepts and Technologies for the National Airspace System – Part III," was developed for the 2014 DASC held in Colorado Springs, Colorado during the week of October 6, 2014. This 2014 DASC paper and presentation was also developed by the joint team of NASA, Rockwell Collins, and the two other NRA contractors (i.e., Honeywell and Xcelar/Agile Defense) and is published with the 2014 DASC conference proceedings.
- The fourth additional paper entitled "A Study of Future Communication Concepts and Technologies for the National Airspace System – Part IV" was developed for the 2015 IEEE Aerospace Conference to be held in Montana during the week of March 9, 2015. This paper was also developed by the joint team of NASA, Rockwell Collins, and the two other NRA contractors (i.e., Honeywell and Xcelar/Agile Defense).

3.3.2.7 Task 3.12: Option Year 1 Presentation and Final Comprehensive Report

Task 3.12 required the development of an "Option Year 1" presentation (milestone deliverable #08) that described the findings and results of the research effort to date. The presentation was held at NASA Ames on November 4, 2014 and included representatives from the NASA Ames, Glenn, and Langley Research Centers.

Task 3.12 also included the development of a "Final Comprehensive Report" (i.e., this report) which is milestone deliverable #09 that describes the findings and results of the Base Year and Option Year 1 efforts.

3.4 Program Team

The Rockwell Collins team completed the work for this NRA Com50 study under the technical, programmatic, and leadership oversight from NASA. The integrated Rockwell Collins and NASA program team members collectively have a great deal of experience in communication systems and technologies, as well as in current and NextGen airspace & applications. The core team consists of members from two NASA research centers (including NASA Ames and NASA Glenn) and from Rockwell Collins Advanced Technology Center and Commercial System groups. Figure 18 identifies the core team members and their role on this study program.

In addition to the core Rockwell Collins team executing on this contract, technical subject matter expertise and information was obtained from members of the Rockwell Collins International & Services Solutions (ISS) group familiar with the aircraft maintenance costs, Rockwell Collins Government Systems group familiar with the equipment and installation costs associated with HF ground systems, Information Management Services group familiar with VHF and HF networks (formerly ARINC), and other company experts knowledgeable in topics such as information security, UAVs, etc.

In addition to the core NASA team executing on this activity, there are a number of leaders at NASA providing overall project tasking, leadership, and review of the results, including for example, Parimal Kopardekar (PK) and Rudy Aquilina from NASA Ames, Mark Ballin from NASA Langley, and John Cavolowsky from NASA Headquarters.

Org.	Team Member	Com50 Program Role	E-mail Address and Phone
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	Rafael D. Apaza	Subject Matter Expert	Rafael.D.Apaza@nasa.gov (216) 433-2875

Figure 18 – Com50 Core Program Team Members

3.5 Rockwell Collins Pleased to Work with NASA on this Study Program

Rockwell Collins is pleased to have had this opportunity to perform this important NRA research under the direction and technical review of NASA in order to identify, characterize, and perform initial assessments of technology concepts intended to serve the communication needs of the air transportation system.

3.6 Rockwell Collins Overview

Rockwell Collins has a long heritage in providing trusted communication systems solutions that serve a broad range of government and commercial customers. A few examples of this heritage include:

- 1933: Provided voice communication for Admiral Byrd's first Antarctic expedition
- 1969: Relayed to the world Neal Armstrong's first words ever spoken on the moon
- Today:
    - Trusted communications and information management solutions supplier
    - Developer of the most advanced tactical data link and network in the world [i.e., the Tactical Targeting Network Technology (TTNT) and the Quint Networking Technology (QNT), which are capable of supporting hundreds of ad-hoc users in highly dynamic environments]

Rockwell Collins is a leading supplier of communication, navigation, and surveillance (CNS) systems products for the civil and military aircraft markets. In addition, we supply flight deck systems, flight management systems, displays, weather radars, flight control systems, cabin electronics, and flight information solutions. Figure 19 illustrates an example set of Rockwell Collins CNS air transport radios.

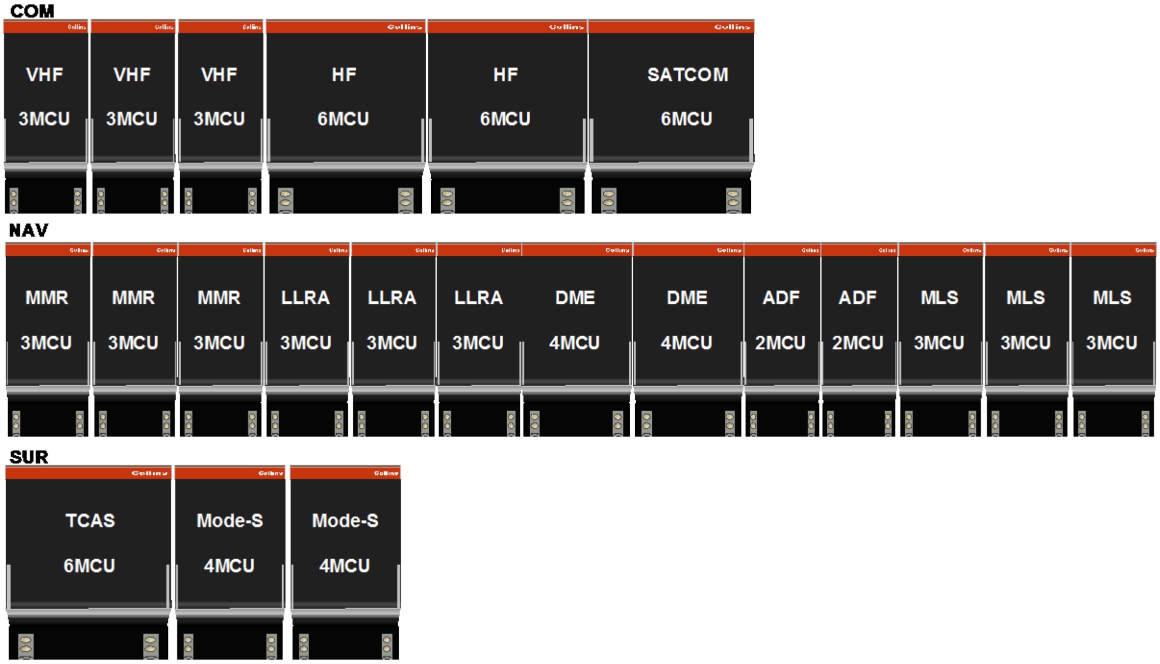


Figure 19 – Rockwell Collins Civil Aircraft CNS Radio Products

At least 90% of all commercial transport aircraft have some Rockwell Collins' products installed. Our civil communication products serve the air transport and business & regional aircraft systems marketplaces and include High Frequency (HF), Very High Frequency (VHF), and Satellite Communication (SATCOM) products.

Rockwell Collins also has civil aircraft surveillance and navigation functions that include radios that for the purposes of this study are considered also to be part of the air-to-ground (including ground-to-air) and air-to-air communications. Such functions include:

- ADS-B OUT transponders, which transmit (communicate) ADS-B surveillance information that is used both for air-to-air and air-to-ground applications;
- ADS-B IN Receivers, which receive surveillance information transmitted by other aircraft (air-to-air), as well as information transmitted from ground services (ground-to-air) for ADS-Rebroadcast (ADS-R) and Traffic Information Services – Broadcast (TIS-B);
- Air Traffic Control Radar Beacon System (ATCRBS) transponders, which transmit (communicate) position and altitude reports in response to Secondary Surveillance Radar (SSR) interrogations;
- VHF Data Broadcast Receivers, which receive transmissions from Local Area Augmentation System (LAAS) GPS ground stations; and
- Traffic Alert and Collision Avoidance Systems (TCAS).

Note that other "Navigation" receivers (e.g., GPS, GPS/SBAS, etc.) that receive and process data as part of the navigation signal, but such communications are not considered to be air-to-ground "communication" signals, but are rather information that is imbedded in the basic navigation signal-in-space to enable the navigation function.

Rockwell Collins also supplies a wide range of products to the military marketplace including communications and electronic systems, military data link systems, flight deck systems, displays, and navigation systems.

In addition to our Commercial Systems, Government Systems, and Information Management Services product groups, Rockwell Collins has an Advanced Technology Center team of researchers. The mission of the Advanced Technology Center is to leverage technical innovation to reduce the risk for technology insertion in our products. The Advanced Technology Center identifies and matures technologies that are potentially relevant to Rockwell Collins' products and services. The Advanced Technology Center works on internally funded research and development (R&D) programs, as well as seeks opportunities to engage with government entities, research institutions, universities, and other companies to identify and mature relevant technologies. The Advanced Technology Center works to identify, mature, and transition relevant technologies to bridge the "valley of death" gap between low technology readiness level (TRL) technologies, and the more mature TRL needed for transition into products, as is depicted in Figure 20 below.

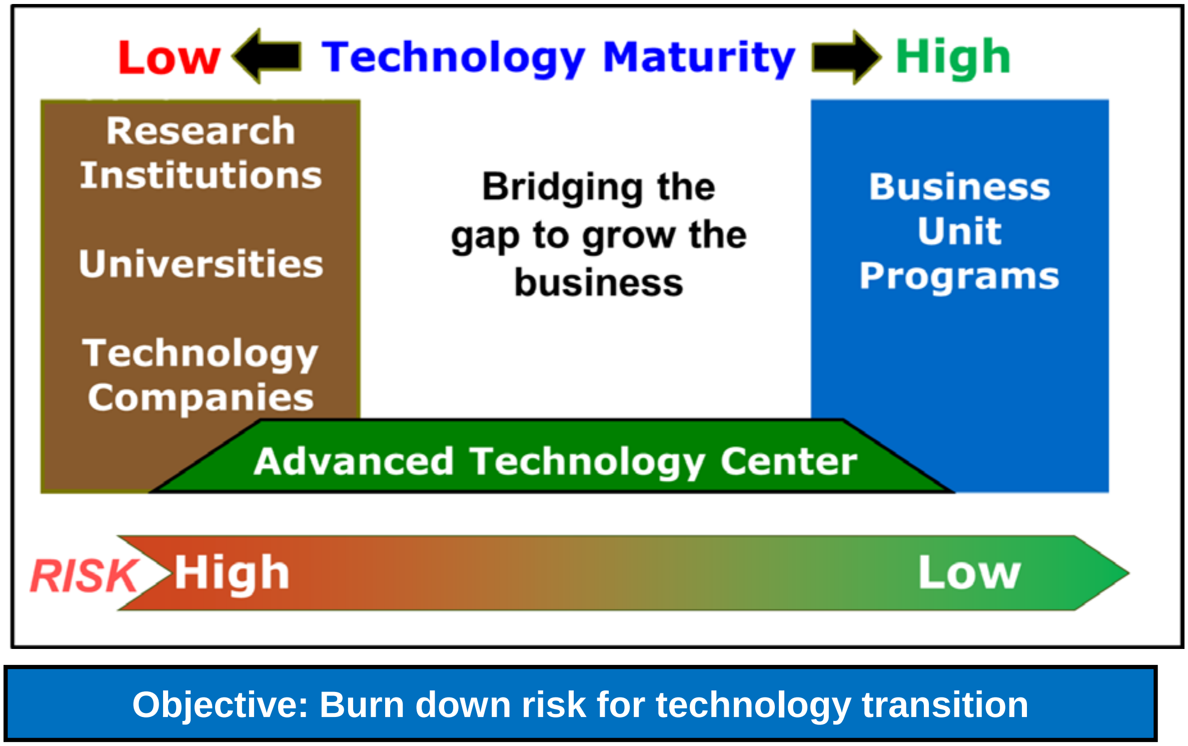


Figure 20 – Rockwell Collins Technology Transition Model

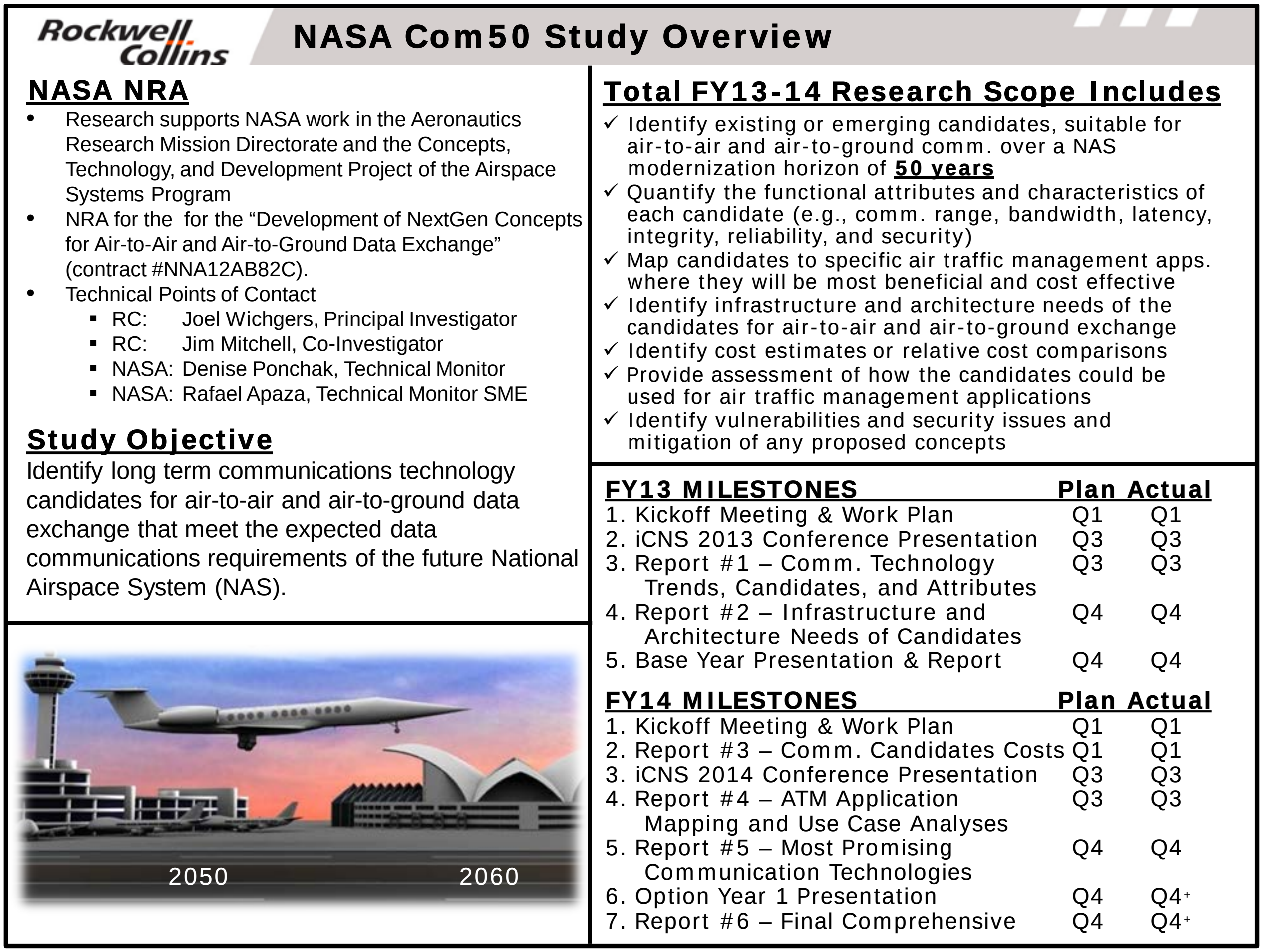
4 TECHNICAL APPROACH

This section describes the technical approach that was used to execute the Com50 study in order to satisfy the NASA NRA contracted research. An overview of the statement of work for this study was provided in Section 3.2.

Figure 21 captures a high-level summary of the Com50 study objective, research scope, and significant milestone deliverables completed as part of the study in FY2013 and FY2014. The study objective included identifying the long term communications technology candidates that could satisfy the air-to-air and air-to-ground data communication requirements for the future NAS. In order to accomplish this objective, NASA defined the research scope that included:

- Identifying existing or emerging candidates, suitable for air-to-air and air-to-ground communications over a NAS modernization horizon of 50 years;
- Quantifying the functional attributes and characteristics of each candidate (e.g., communications range, bandwidth, latency, integrity, reliability, and security);
- Mapping the candidates to specific air traffic management applications where they will be most beneficial and cost effective;
- Identifying infrastructure and architecture needs of the candidates for air-to-air and air-to-ground data exchange;
- Identifying cost estimates or relative cost comparisons of the communications candidates;
- Providing an assessment of how the candidates could be used for air traffic management applications; and
- Identifying vulnerabilities and security issues and mitigations of any proposed communications concepts.

Five interim reports were specified by the SOW to incrementally document the results of the study. A sixth report (this report) was also specified to comprehensively document the results of the entire two-year study.



NASA Com50 Study Overview

NASA NRA

- Research supports NASA work in the Aeronautics Research Mission Directorate and the Concepts, Technology, and Development Project of the Airspace Systems Program
- NRA for the for the "Development of NextGen Concepts for Air-to-Air and Air-to-Ground Data Exchange" (contract #NNA12AB82C).
- Technical Points of Contact
  - RC: Joel Wichgers, Principal Investigator
  - RC: Jim Mitchell, Co-Investigator
  - NASA: Denise Ponchak, Technical Monitor
  - NASA: Rafael Apaza, Technical Monitor SME

Study Objective

Identify long term communications technology candidates for air-to-air and air-to-ground data exchange that meet the expected data communications requirements of the future National Airspace System (NAS).

Total FY13-14 Research Scope Includes

- ✓ Identify existing or emerging candidates, suitable for air-to-air and air-to-ground comm. over a NAS modernization horizon of **50 years**
- ✓ Quantify the functional attributes and characteristics of each candidate (e.g., comm. range, bandwidth, latency, integrity, reliability, and security)
- ✓ Map candidates to specific air traffic management apps. where they will be most beneficial and cost effective
- ✓ Identify infrastructure and architecture needs of the candidates for air-to-air and air-to-ground exchange
- ✓ Identify cost estimates or relative cost comparisons
- ✓ Provide assessment of how the candidates could be used for air traffic management applications
- ✓ Identify vulnerabilities and security issues and mitigation of any proposed concepts

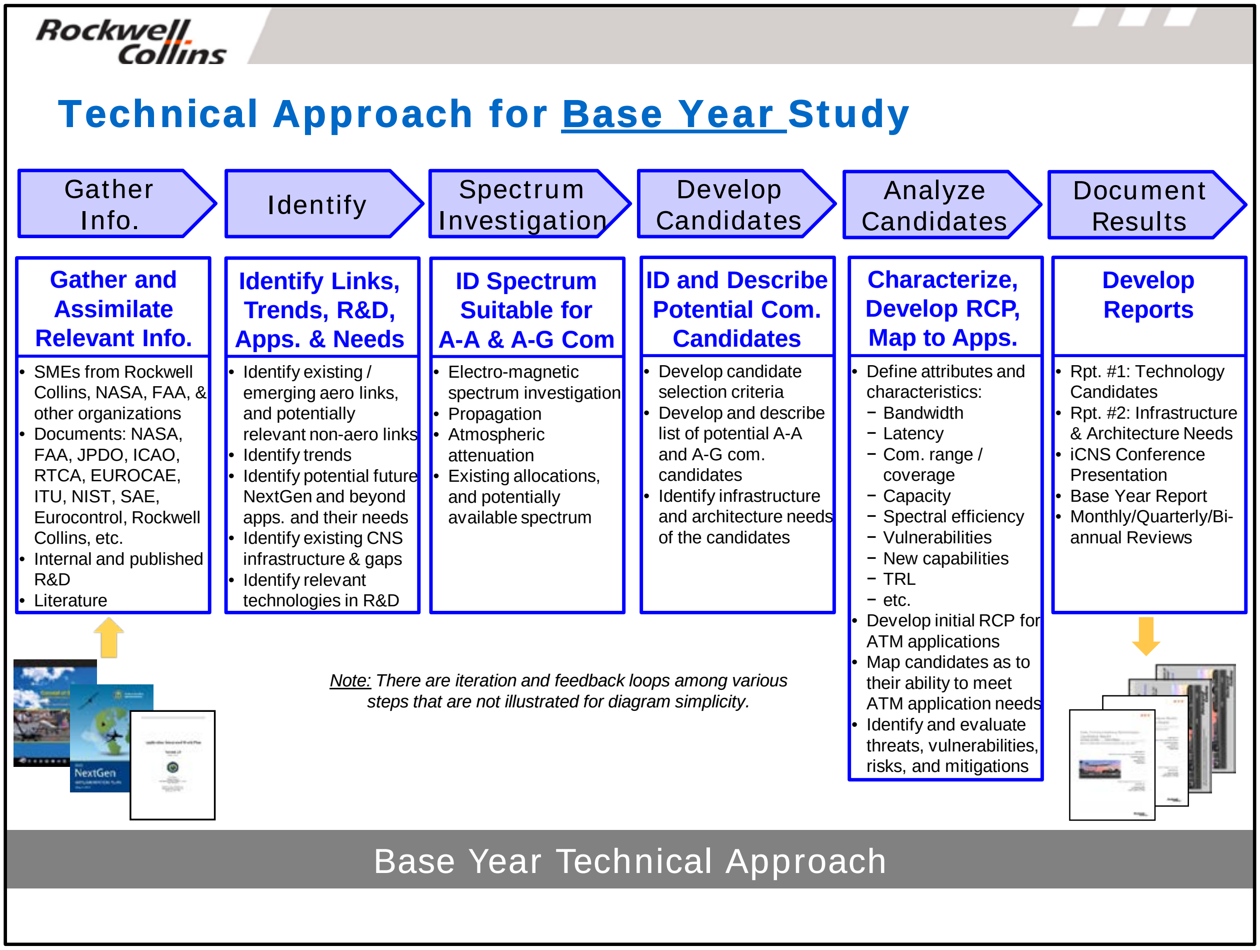
FY13 MILESTONES	Plan	Actual
1. Kickoff Meeting & Work Plan	Q1	Q1
2. iCNS 2013 Conference Presentation	Q3	Q3
3. Report #1 – Comm. Technology Trends, Candidates, and Attributes	Q3	Q3
4. Report #2 – Infrastructure and Architecture Needs of Candidates	Q4	Q4
5. Base Year Presentation & Report	Q4	Q4

FY14 MILESTONES	Plan	Actual
1. Kickoff Meeting & Work Plan	Q1	Q1
2. Report #3 – Comm. Candidates Costs	Q1	Q1
3. iCNS 2014 Conference Presentation	Q3	Q3
4. Report #4 – ATM Application Mapping and Use Case Analyses	Q3	Q3
5. Report #5 – Most Promising Communication Technologies	Q4	Q4
6. Option Year 1 Presentation	Q4	Q4$^+$
7. Report #6 – Final Comprehensive	Q4	Q4$^+$

Figure 21 – Program Overview of NASA Com50 Future Communications Study

In order to accomplish the work specified in the SOW, Rockwell Collins defined a work plan that included the technical approach to the research as is summarized in Figure 22 for the Base Year Study (FY2013) and Figure 23 for the Option Year 1 Study (FY2014). The technical approach was a classic approach that included gathering and assimilating relevant information leveraging the expertise of subject matter experts (SMEs) on the Rockwell Collins study team, as well as SMEs from other organizations including, for example, NASA, FAA, FAA contractors, MITRE, and other industry partners. Relevant information was also obtained from conducting a literature search that identified numerous documents and papers which addressed future communications studies, long range NAS visions, future communications technologies, communications security, etc. Such documents were reviewed and assimilated to establish a vision of the future air transportation system and the types of ATM applications that would be enabled with future communications. Predictions of potentially relevant environmental changes that may impact future aeronautical communications capabilities, needs, and requirements were also identified.

The next step in the study entailed identifying existing and emerging aeronautical communication links and potentially relevant non-aeronautical communication links that may become relevant to aeronautical communications in the future (e.g., cellular). Communication relevant trends and technologies were identified, as well as potential future NextGen and beyond NAS ATM-relevant applications, and the existing CNS infrastructure and architecture.



Rockwell Collins

Technical Approach for Base Year Study

Gather Info. → Identify → Spectrum Investigation → Develop Candidates → Analyze Candidates → Document Results

Gather and Assimilate Relevant Info.
- SMEs from Rockwell Collins, NASA, FAA, & other organizations
- Documents: NASA, FAA, JPDO, ICAO, RTCA, EUROCAE, ITU, NIST, SAE, Eurocontrol, Rockwell Collins, etc.
- Internal and published R&D
- Literature

Identify Links, Trends, R&D, Apps. & Needs
- Identify existing / emerging aero links, and potentially relevant non-aero links
- Identify trends
- Identify potential future NextGen and beyond apps. and their needs
- Identify existing CNS infrastructure & gaps
- Identify relevant technologies in R&D

ID Spectrum Suitable for A-A & A-G Com
- Electro-magnetic spectrum investigation
- Propagation
- Atmospheric attenuation
- Existing allocations, and potentially available spectrum

ID and Describe Potential Com. Candidates
- Develop candidate selection criteria
- Develop and describe list of potential A-A and A-G com. candidates
- Identify infrastructure and architecture needs of the candidates

Characterize, Develop RCP, Map to Apps.
- Define attributes and characteristics:
  - Bandwidth
  - Latency
  - Com. range / coverage
  - Capacity
  - Spectral efficiency
  - Vulnerabilities
  - New capabilities
  - TRL
  - etc.
- Develop initial RCP for ATM applications
- Map candidates as to their ability to meet ATM application needs
- Identify and evaluate threats, vulnerabilities, risks, and mitigations

Develop Reports
- Rpt. #1: Technology Candidates
- Rpt. #2: Infrastructure & Architecture Needs
- iCNS Conference Presentation
- Base Year Report
- Monthly/Quarterly/Bi-annual Reviews

Note: There are iteration and feedback loops among various steps that are not illustrated for diagram simplicity.

Base Year Technical Approach

Figure 22 – Technical Approach for Base Year Study in FY2013

A spectrum investigation was conducted to identify spectrum potentially suitable for A-A and A-G NAS communications considering the entire electromagnetic spectrum. This investigation looked at spectrum outside the traditional radio frequency spectrum and considered the expected maturation of communications technologies over the study's 50 year modernization time horizon. This investigation considered the electromagnetic propagation characteristics and attenuation characteristics of signals transmitted at the various frequencies across the spectrum, to identify atmospheric windows where communications are feasible and do not have ionizing radiation that could potentially harm living organisms. The investigation identified the existing allocations of spectrum among the various uses and spectrum that might potentially be available or become available during the study time horizon.

The next step included identifying and describing a set of potentially feasible A-A and A-G NAS communications candidates. Candidates were selected that:

a) were in compliance with the fundamental physics of electromagnetic propagation;

b) were expected to be able to meet the current and anticipated operational, performance, safety, and security requirements associated with NAS ATM relevant communications;

c) were expected to either be mature today, or mature during the modernization time horizon of the study;

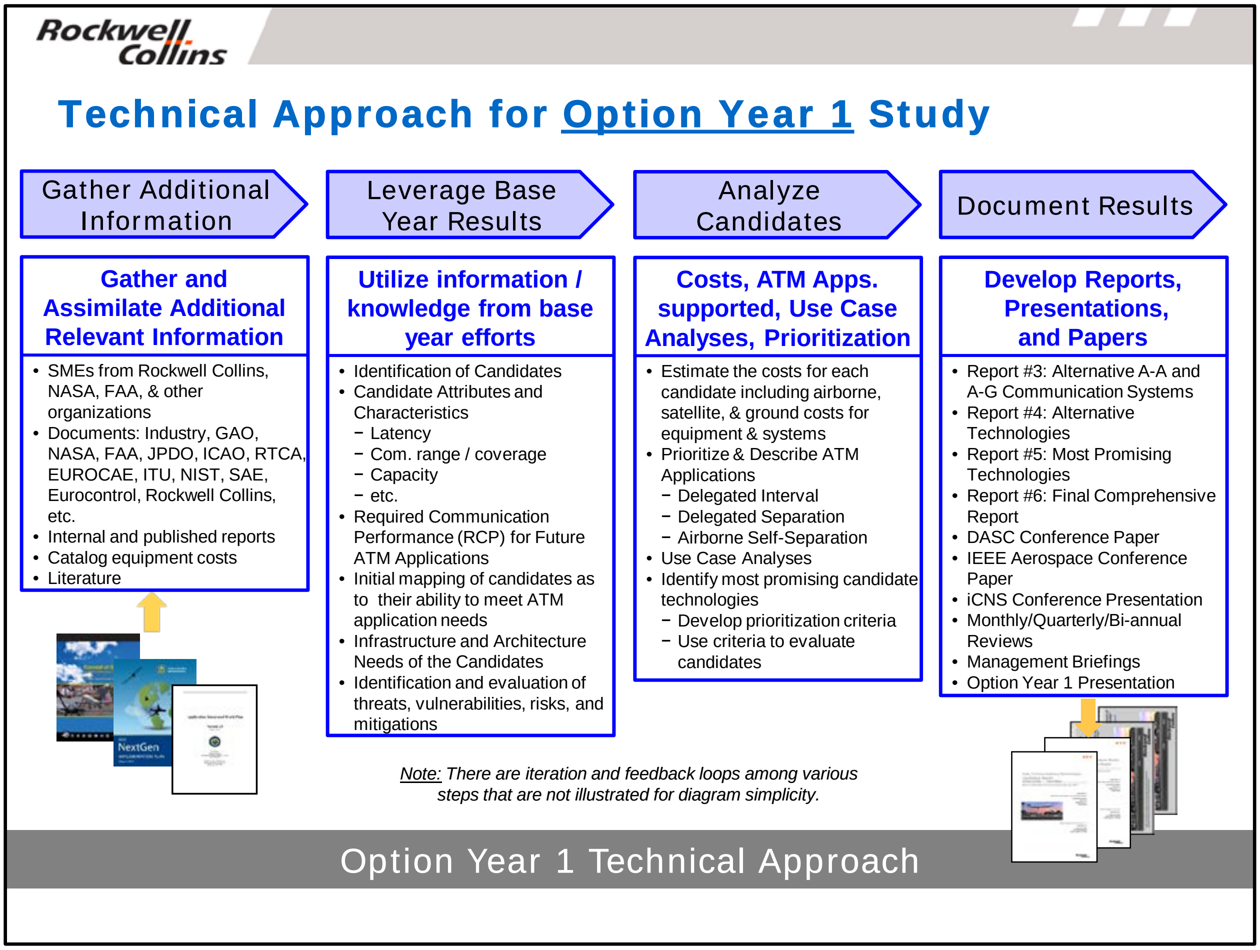
d) had an expectation that the spectrum was available or could potentially become available for aviation use during the modernization time horizon; and

e) had a plausible transition path from today's communications.

Then the attributes and characteristics of the candidates were defined, including for example, bandwidth, latency, communications range / coverage, capacity, spectral efficiency, technology readiness level (TRL), vulnerabilities, etc. as a means to define the Actual Communications Performance (ACP) provided by the various candidates.

Initial straw man Required Communications Performance (RCP) values were defined for a broad set of envisioned future ATM applications. Then, each candidate's ACP was compared against the RCP to determine the ability of the various candidates to meet the application needs.

An investigation to identify and evaluate threats, vulnerabilities, risks, and mitigations to the A-A and A-G communications in the context of ATM applications was then completed.



Rockwell Collins

Technical Approach for Option Year 1 Study

Gather Additional Information → Leverage Base Year Results → Analyze Candidates → Document Results

Gather and Assimilate Additional Relevant Information

- SMEs from Rockwell Collins, NASA, FAA, & other organizations
- Documents: Industry, GAO, NASA, FAA, JPDO, ICAO, RTCA, EUROCAE, ITU, NIST, SAE, Eurocontrol, Rockwell Collins, etc.
- Internal and published reports
- Catalog equipment costs
- Literature

Utilize information / knowledge from base year efforts

- Identification of Candidates
- Candidate Attributes and Characteristics
  - Latency
  - Com. range / coverage
  - Capacity
  - etc.
- Required Communication Performance (RCP) for Future ATM Applications
- Initial mapping of candidates as to their ability to meet ATM application needs
- Infrastructure and Architecture Needs of the Candidates
- Identification and evaluation of threats, vulnerabilities, risks, and mitigations

Costs, ATM Apps. supported, Use Case Analyses, Prioritization

- Estimate the costs for each candidate including airborne, satellite, & ground costs for equipment & systems
- Prioritize & Describe ATM Applications
  - Delegated Interval
  - Delegated Separation
  - Airborne Self-Separation
- Use Case Analyses
- Identify most promising candidate technologies
  - Develop prioritization criteria
  - Use criteria to evaluate candidates

Develop Reports, Presentations, and Papers

- Report #3: Alternative A-A and A-G Communication Systems
- Report #4: Alternative Technologies
- Report #5: Most Promising Technologies
- Report #6: Final Comprehensive Report
- DASC Conference Paper
- IEEE Aerospace Conference Paper
- iCNS Conference Presentation
- Monthly/Quarterly/Bi-annual Reviews
- Management Briefings
- Option Year 1 Presentation

Note: There are iteration and feedback loops among various steps that are not illustrated for diagram simplicity.

Option Year 1 Technical Approach

Figure 23 – Technical Approach for Option Year 1 Study in FY2014

The relative costs to implement the communication candidates were then estimated. These costs included the technology maturation and standards development for each candidate, as well as the airborne, ground, and satellite costs for the building the communications equipment, deploying it, and maintaining it over the assumed 25-year system life cycle.

Communications use case analyses were completed for three of the identified highest priority ATM applications including Delegated Interval / Interval Management, Delegated Separation, and Airborne Self-Separation.

Finally, the most promising A-A and A-G communications candidates were identified using an evaluation process that: a) identified a set of relevant criteria for prioritizing the candidates, b) defined the rating scales and weighting factors for each of the criteria, and c) evaluated and scored the candidates used the criteria rating scales and weighting factors to identify the most promising candidates. The study was iterative in nature and had feedback loops among the various investigations and analyses. The results of the entire 2-year study are provided in this report. Follow-on analyses are planned and recommended.

5 AIR TRAFFIC SYSTEM VISION

Today's National Airspace System (NAS) has served the community well in meeting past operational and safety needs. It has made effective and prudent use of air-routes, procedures, and traditional "stove-piped" Communication, Navigation, and Surveillance (CNS) systems to provide a level of capacity that was sufficient for the demand while maintaining a strong safety record. However, without change, the NAS will be unable to realize the capacity, efficiency, security, safety, and environmental improvements that are being demanded for the Next Generation Air Transportation System (NextGen) and beyond. To realize these improvements, the NextGen and beyond infrastructure is envisioned to be built on better, more capable, and optimally integrated communications, navigation, surveillance, information management, decision support, and automation systems. It will be performance-based and will support enhanced procedures and performance-based operations.

5.1 Vision of the Future Airspace

Today's airspace relies on a strong infrastructure that supports a well-defined daily operational plan with periodic updates. This plan is then passed to the aircraft and progress is monitored using radar and procedural methodologies. This system has served the community for many years providing a safe, highly robust operating environment.

This system, however, is based on a rigid set of rules and it operates quite well when all conditions are optimized, but lacks the flexibility to support operations in a more dynamic environment. The airspace of the future will require more flexibility to meet the growing capacity needs while providing the efficiencies necessary to ensure operations that support the evolving environmental challenges.

But the system of the future must be flexible. The performance-based airspace allows the system participants to manage how they will provide the level of performance necessary to meet the operational requirements. No longer will we have a requirement for specific technologies and hardware implementations. Performance will be described in terms of accuracy, integrity, continuity of function, and security. But this performance is a total system performance concept. The role of the aircraft and the ground systems must be described in a way that allows performance to be allocated between air and ground system elements as well as a sharing across the CNS domains. For example an aircraft with a highly capable navigation system capable of operating at an RNP 0.1 in all phases of flight, may not require the same levels of data communications or surveillance performance. Similarly, an aircraft with a moderate navigation capability may still be able access the high performance airspace because it has a more capable data communications and surveillance structure.

Key to enabling the future will be the availability of system wide information. The exchange of information and the use of that information brings with it responsibilities and burdens. It is likely that pilots and controllers will have access to too much raw data and information. To enable the future airspace, we will need to develop decision support systems that will merge and fuse information seamlessly to support optimized decision making based on the intelligence derived from that raw data. This means that pilots and controllers will take on new roles in optimizing the system. These new roles will be enabled by new automation technologies both on the ground and in the air.

The highly capable aircraft will be provided with operating constraints from ground systems that are constantly monitoring the progress of participating aircraft within the system. Those constraints will be used as decision elements by the computing systems on-board the aircraft to ensure that they can meet the agreements established to enable the flow managed system. This information will be exchanged seamlessly between the multiple automation platforms and optimized solutions will be presented to the managers of the system. While this places a greater reliance on airborne automation, it also helps to redefine the necessary decision capabilities of the ground systems.

Another aspect of information management will be to define a structure where all information can be seamlessly fused or merged. Decisions will be based on weather, terrain, obstacles, traffic, and available airspace all of which must be described in a common way to ensure that decisions can be made in an unambiguous way. Each of these “constraints” must be structured in a form that is usable by the system and consumable by decision support systems on the ground and in the aircraft.

We have seen a significant evolution of airspace operations over the past 50 years with the insertion of a variety of technologies. As we face the challenge of identifying communication candidates that will support operations over a NAS transformation of 50 years, we should recognize that communications technologies as well as NAS operations and requirements will evolve. Thus, the future air-to-air and air-to-ground communication systems should be architected to much more easily incorporate new technologies to meet the future NAS needs.

5.2 Range of Possible Futures

There are a range of opinions for the how the air transportation system will evolve over the next 50 or more years.

Some speculate that air transportation will not grow due to its high cost relative to alternative modes transportation (e.g., high speed trains) and virtual meeting technologies. Other visions of the future call for continued growth in the demand for air transportation such that the question is “when” various capacity demands will be needed (i.e., when will we need 2X, 3X, … 10X, etc. of today’s capacity?).

The Joint Program Development Office (JPDO) released their Concept of Operations (ConOps) report in 2004 predicting that by 2025 that the air transportation system passenger levels would need to be approximately 1.5 to 3X of the 2004 passenger levels (see Figure 24). While it is currently 2013 and we have not seen that type of growth rate in recent years that was predicted in part due to a worldwide economic downturn, current projections are returning to such growth trends.

Even with the economic downturn, demand for world air travel has increased an average of 5 percent annually over the past 20 years according to ICAO. While developing countries are seeing the most growth, Europe and North America continue to be among the regions with the highest volume of air travel. According to the FAA, the U.S. airlines are expected to reach the one billion passengers-per year mark by 2021.

If air traffic grows at an annual grow rate of ~4.7%, then in 50 years it could be ~10X of today’s traffic levels. If on the other hand traffic only grows at a rate of 2.2%, traffic will only be ~3X of today’s traffic levels. This is illustrated in Figure 25 which plots the predicted traffic level in 50 years as a function of yearly traffic growth rate.

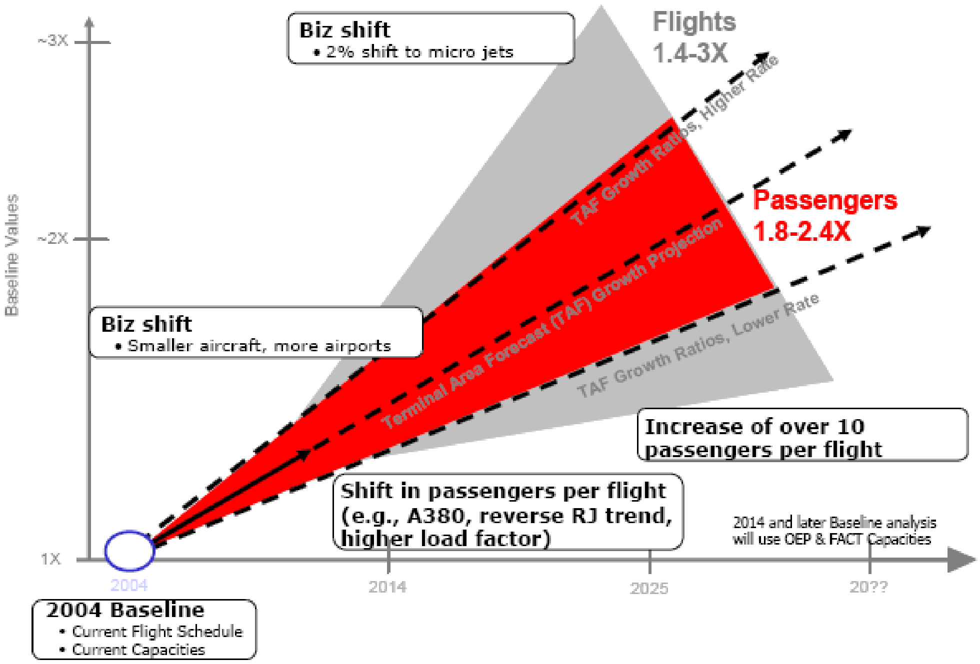


Figure 24 – Range of Future (Reference: JPDO ConOps, Version 3.2)

[Reference: JPDO ConOps, Version 3.2, page 1-1.]

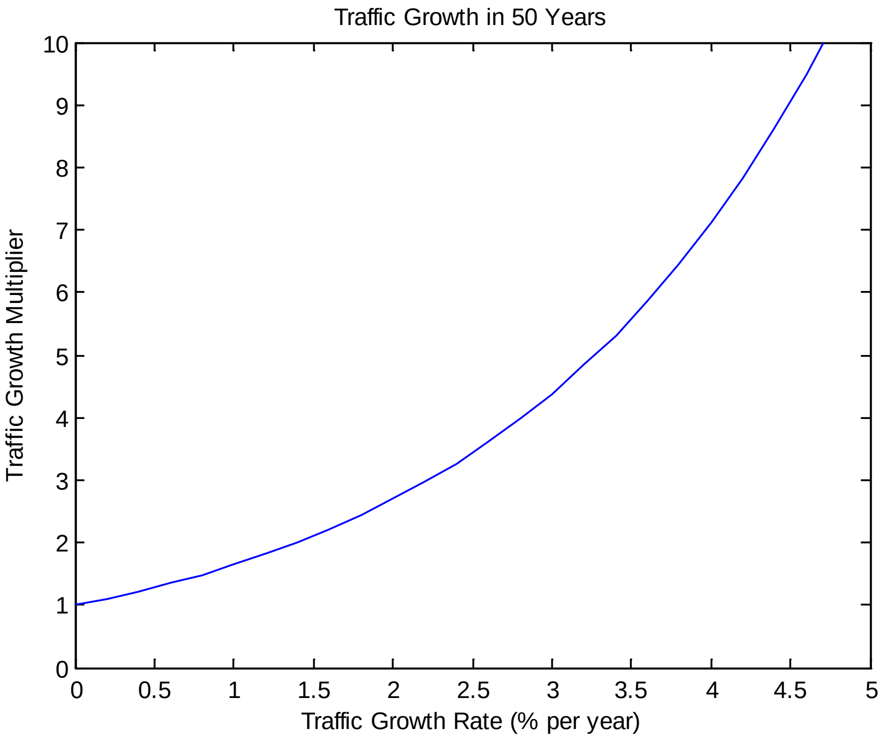


Figure 25 – Predicted Traffic Levels in 50 Years as a Function of Growth Rate

Equally important in the air transportation system vision is the operational philosophy for how aircraft are controlled and managed. For instance, will the aircraft in the future continue to be heavily controlled by Air Traffic Controllers (ATC) on the ground as they are today, or will ATC manage aircraft by exception with few communications as long as aircraft are conforming to their 4D flight plan, or will the role of ATC be significantly reduced by the introduction of self-separation capabilities on aircraft? Section 27.3 describes a possible future aircraft self-separation concept of operations that could significantly reduce the amount of air-to-ground communications between the aircraft and ATC.

As stated above, there are a range of possible future visions for the how the air transportation system will evolve over the next 50 or more years. The art work depicted in Figure 26 shows a futuristic vision of aircraft flying at very close spacings, almost like a flock of birds. While realizing the full futuristic vision depicted by this artwork may take many generations or never be fully realized, advanced aircraft operations (that are enabled with improvements to CNS systems) are expected to allow aircraft to more efficiently and safely utilize the available airspace.

Figure 26 – Flying Aircraft Like a Flock of Birds

[Reference: Picture Courtesy of Web site: http://www.flickr.com/photos/superlocal/273964362/

Picture Artist: Ho-Yeol Ryu, presented at the 4th Seoul International Media Art Biennale on October 10, 2006 at the Seoul Museum of Art.]

5.3 Data Communications, Key to How We Want to Fly in NextGen and Beyond

[Reference: FAA Data Communications "How We Want to Fly" Brochure, HQ-09818]

In today's National Airspace System (NAS) air traffic management largely depends on voice communications to relay a wide array of critical information between air crews and controllers. The use of voice communication is labor intensive, time consuming, and limits the ability of the

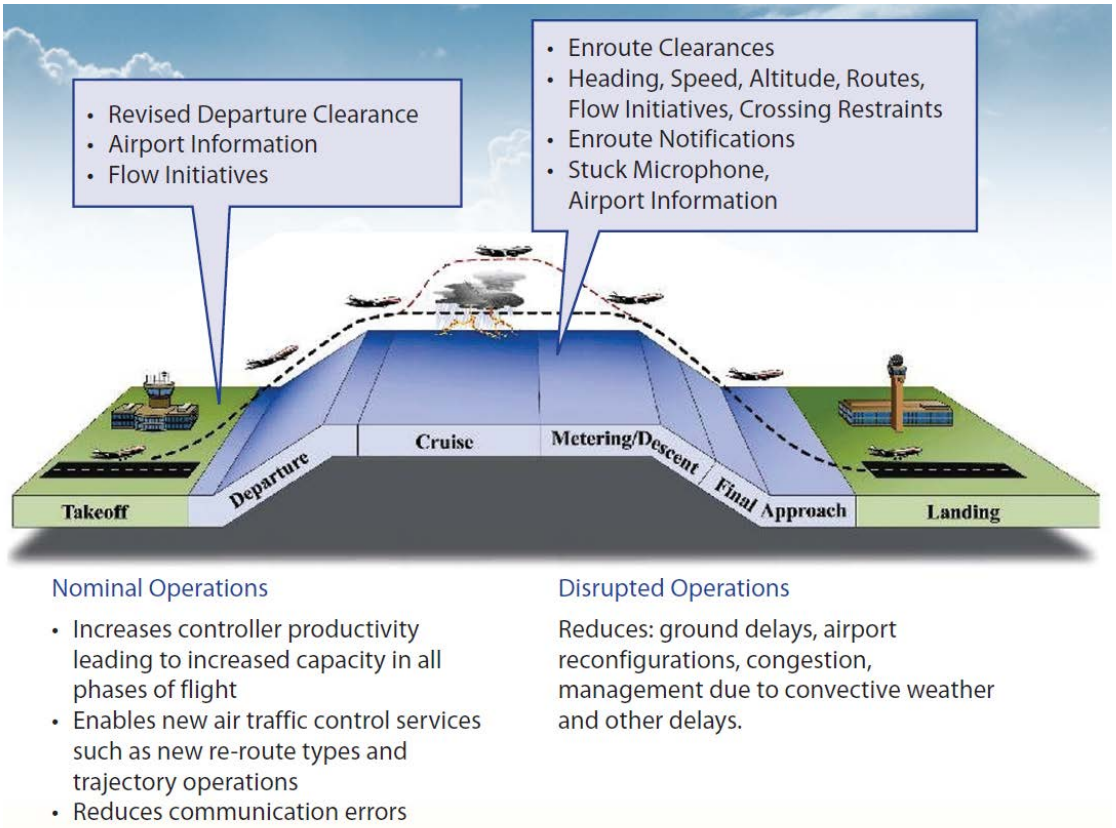
NAS to effectively meet future traffic demand. Data Communications will assume an ever-increasing role in air traffic control, ground management and flight crew communications. The introduction of Data Communications represents the first phase of the transition from the current decades old analog voice system to a predominantly digital mode of communication.

Data Communications will support the NextGen vision by providing data transmissions directly to pilots and their flight management systems, enabling more efficient operations, including trajectory based routing that evolves air traffic from short-term tactical control to managing flights strategically gate-to-gate. Data Communications will support safety-of-flight command, control and information services by providing comprehensive data connectivity, including ground automation message generation, transmission and routing. Data Communications will automate repetitive tasks, supplement voice communications with less workload-intensive data communications, and enable ground systems to use real-time aircraft data to improve traffic management.

Data Communications will supplement existing voice communications and provide two way data exchange between controllers and flight crews for clearances, instructions, advisories, flight crew requests and reports. Data Communications will provide comprehensive data connectivity for critical services and enhance air traffic safety with:

- More Timely and Effective Clearances
- More Time for Controllers and Pilots to Think and Select Appropriate Actions
- More Orderly Communications During Peak Traffic and
- More Reliable Messaging and Reduced Operational Errors Associated with Voice Communications

Data Communications will allow the National Airspace System to handle more traffic, reduce flight delays, enable more efficient routes to be flown, and enhance safety all while reducing operational costs for airspace users. As Data Communications becomes the norm, the majority of pilot-controller exchanges will be handled by Data Communications for appropriately equipped users. The operations enabled by Data Communications will have the added financial benefits of reducing ground delays and significantly increasing fuel savings through more efficient routes and optimized profile descents. Reduced fuel use will have the important environmental benefit of reducing aviation carbon dioxide and other greenhouse gas emissions. Figure 27 highlights the expected benefits of data communications for the airspace users.



- Revised Departure Clearance
- Airport Information
- Flow Initiatives

- Enroute Clearances
- Heading, Speed, Altitude, Routes, Flow Initiatives, Crossing Restraints
- Enroute Notifications
- Stuck Microphone, Airport Information

Nominal Operations

- Increases controller productivity leading to increased capacity in all phases of flight
- Enables new air traffic control services such as new re-route types and trajectory operations
- Reduces communication errors

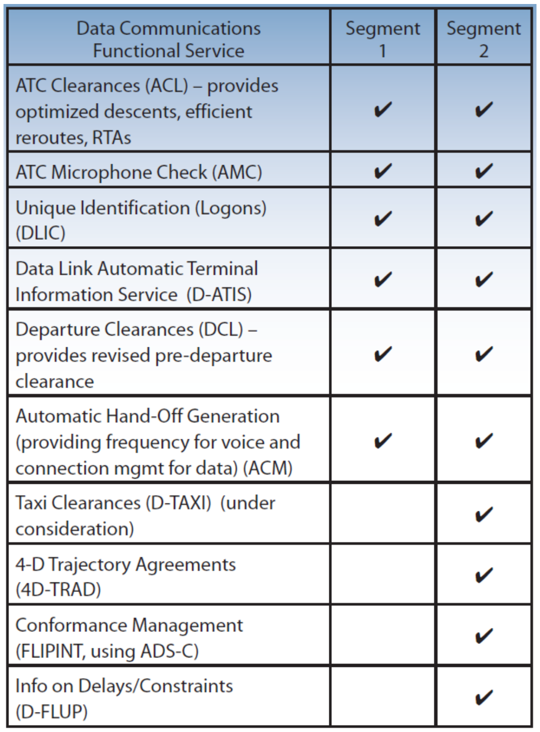
Disrupted Operations

Reduces: ground delays, airport reconfigurations, congestion, management due to convective weather and other delays.

Figure 27 – Data Communications Benefits for Airspace Users

[Reference: FAA NextGen Data Comm. Frequently Asked Questions Brochure, HQ-09818.]

The FAA has defined and is in the process of implementing a two segment Data Communications program. Segment 1 implementation is the initial transition step, which will utilize the VDL-M2 air-to-ground link. The initial capabilities defined for Segment 1 concentrate on implementing services in the tower and enroute environments while providing the initial building blocks for NAS-wide implementation and trajectory based operations. Throughout Segment 1, Data Communications provides a supplementary means of communications for non-time critical clearances and services. As depicted in Figure 28, Segment 2 builds upon communications services provided in Segment 1 and includes taxi clearances, 4-D trajectory agreements, conformance management, and information on delays/constraints. Authentication is planned to be implemented in the air-to-ground network during Segment 2.



Data Communications Functional Service	Segment 1	Segment 2
ATC Clearances (ACL) – provides optimized descents, efficient reroutes, RTAs	✔	✔
ATC Microphone Check (AMC)	✔	✔
Unique Identification (Logons) (DLIC)	✔	✔
Data Link Automatic Terminal Information Service (D-ATIS)	✔	✔
Departure Clearances (DCL) – provides revised pre-departure clearance	✔	✔
Automatic Hand-Off Generation (providing frequency for voice and connection mgmt for data) (ACM)	✔	✔
Taxi Clearances (D-TAXI) (under consideration)		✔
4-D Trajectory Agreements (4D-TRAD)		✔
Conformance Management (FLIPINT, using ADS-C)		✔
Info on Delays/Constraints (D-FLUP)		✔

Figure 28 – FAA Data Communication Functional Service By Segment

[Reference: FAA NextGen Data Communications Questions and Answers from the Aviation Community Brochure, HQ-09818.]

5.4 Harmonized "Near Term" Data Communications Roadmap Through 2030

The Com50 Study that is the subject of this report is intended to take a long range (50 year) look at the future of data communications. Previous studies evaluated communications technologies for nearer term data communications and developed nearer term proposed data communication roadmaps that have subsequently been harmonized at ICAO. For instance, the Figure 29 depicts a high level roadmap of the EUROCONTROL/FAA proposed approach for the implementation and evolution of the aeronautical mobile communications to support the emerging and anticipated needs of air traffic management in both Europe and the U.S.

According to this roadmap and conclusions from the joint EUROCONTROL/FAA Future Communications Study Final Conclusions and Recommendations Report (version 1.1, November 2007), in the near term, air traffic control operations will continue to use the VHF spectrum for voice communications throughout the U.S. and European regions. 8.33 kHz channel spacing has been implemented for the VHF band in Europe and will continue to expand into more airspace as needed to satisfy demand for voice channels. Initial data link using VDL-M2 in European airspace is being implemented to support various ATC data services. The FAA DATA COM program will develop and implement data applications in the U.S. domestic airspace using VDL-M2. 8.33 kHz voice channel spacing will be employed if necessary to increase the amount of spectrum available for data link services.

Surveillance applications in both the U.S. and Europe will continue to use L-band communications at 1030/1090 MHz for SSR/ATCRBS. In addition, both regions will support ADS-B using 1090 Extended Squitter (ES). The U.S. is also implementing UAT to support ADS-B services. In Europe, VDL-M4 is also being implemented on a regional basis.

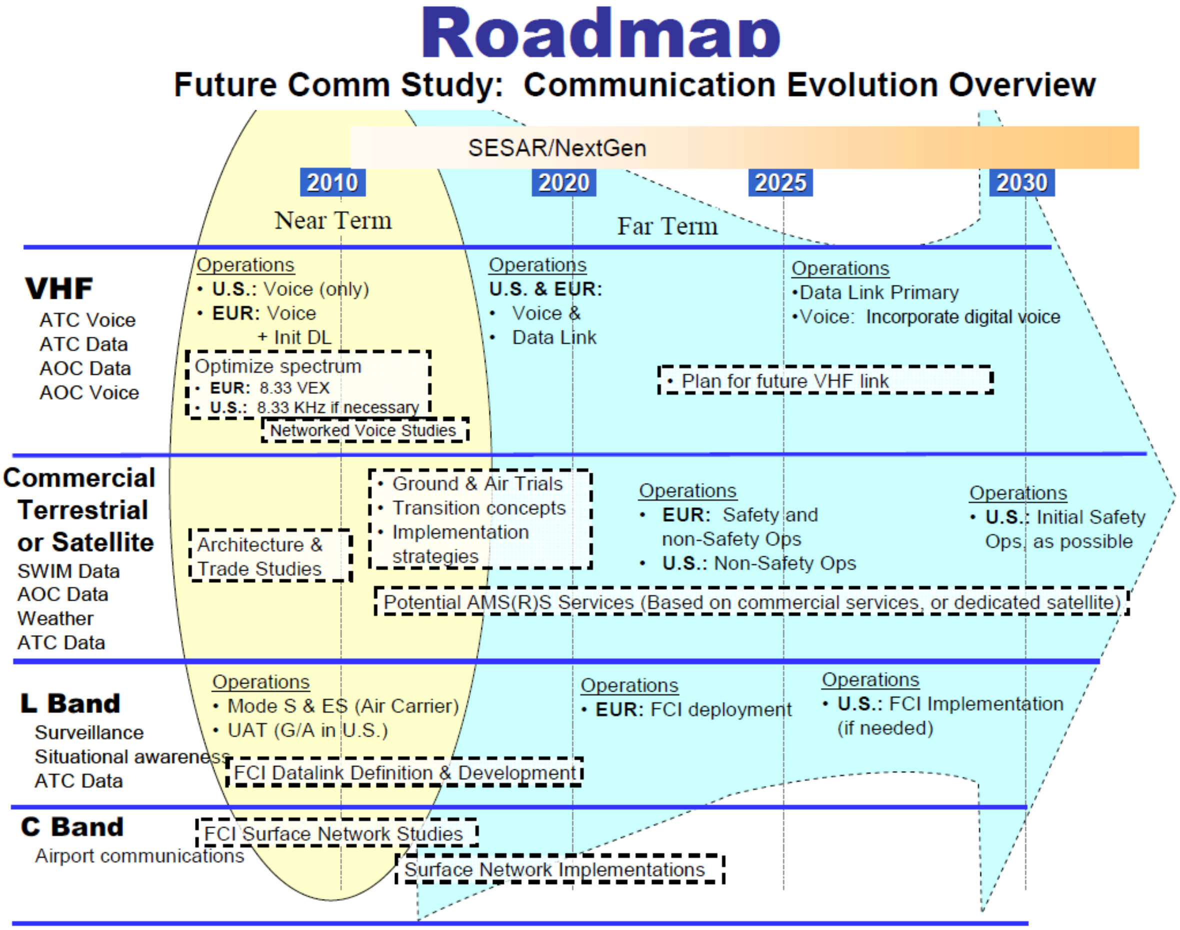


Figure 29 – Harmonized Near Term Aeronautical Mobile Communications Evolution Roadmap

[Reference: Action Plan 17, Future Communications Study Final Conclusions and Recommendations Report, Version 1.1, EUROCONTROL/FAA, November 2007, Page 12.]

5.5 ICAO Communications Roadmaps

ICAO Document 9750, entitled “2013-2028 Global Air Navigation Capacity & Efficiency Plan” describes a rolling 15-year strategic plan that is intended to leverage existing technologies and anticipate future developments. This document outlines a plan to achieve targeted groups of operational improvements in four aviation performance improvement areas along a timeline described in terms of block upgrades. The timeline for the block upgrades is such that the current capability (block 0) is followed by a timeline of 3 sets performance improvements, referred to as Block 1, Block 2, and Block 3 that are targeted for the 2018, 2023, and 2028 and onward timeframes, respectively as illustrated in Figure 30.

The plan provides a set of technology roadmaps in the CNS areas. The roadmaps applicable to communications using the block upgrade target dates are provided in Figure 31 and Figure 32. These figures provide a nearer term vision of the potential changes to the future communications than the long term 50-year time horizon that is the focus of this study. However, it is good to note the vision that ICAO has as it will influence the future NAS communications.

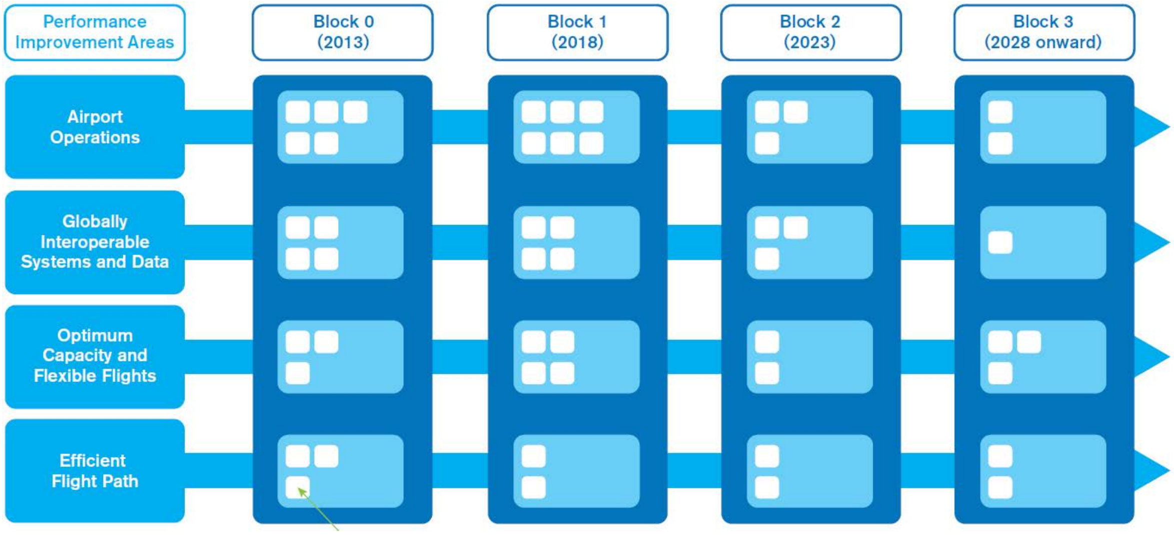


Figure 30 – ICAO Global Plan Aviation System Block Upgrade Target Dates

[Reference: 2013-2028 Global Air Navigation Capacity & Efficiency Plan, ICAO Doc 9750, Draft 2014-2016 Triennium Edition, page 11.]

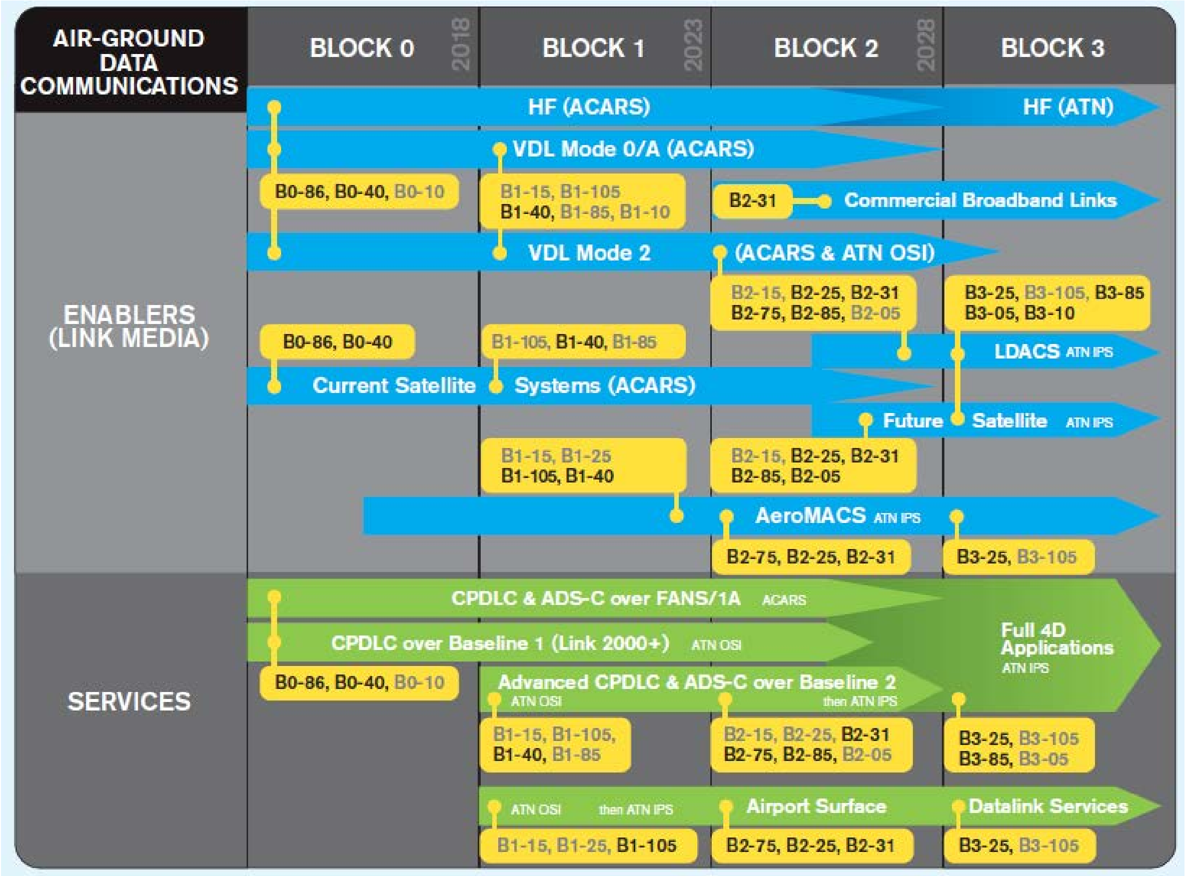


Figure 31 – ICAO Roadmap: Air-to-Ground Data Communications

[Reference: 2013-2028 Global Air Navigation Capacity & Efficiency Plan, ICAO Doc 9750, Draft 2014-2016 Triennium Edition, page 103.]

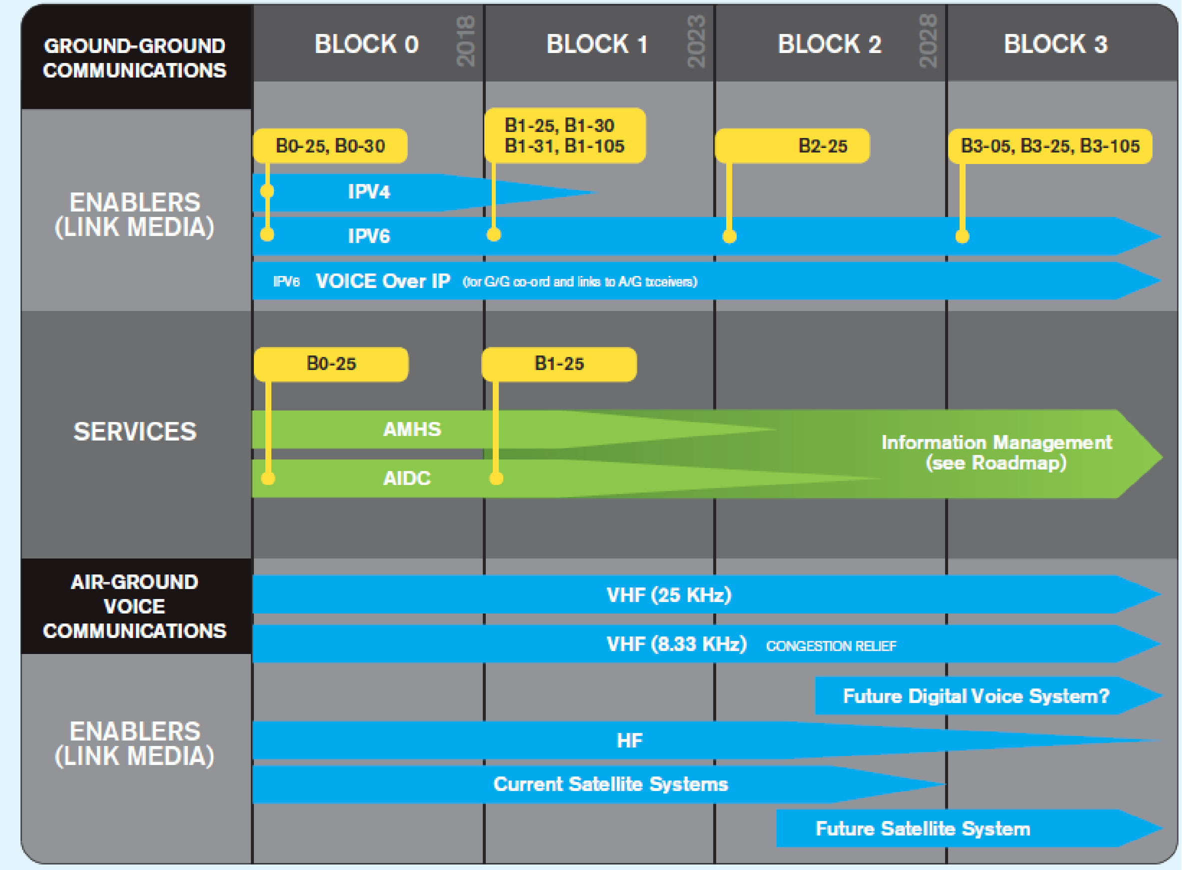


Figure 32 – ICAO Roadmap: Ground-to-Ground and Air-to-Ground Comm.

[Reference: 2013-2028 Global Air Navigation Capacity & Efficiency Plan, ICAO Doc 9750, Draft 2014-2016 Triennium Edition, page 105.]

5.6 JPDO Concept of Operations Vision

The NextGen Concept of Operations (ConOps) developed by the Joint Planning and Development Office (JPDO) envisions that the future airspace system will be based upon performance-based operations, similar to that illustrated in Figure 33.

The JPDO has identified a number of Operational Improvements (OI's) in its Integrated Work Plan (IWP) for changing the NAS for the purposes of realizing capacity, efficiency, safety, and security improvements in NextGen. One of the key foundational operational improvements identified is in the area of communications. Many of the OI's depend upon systems and services performing their functions at required levels of performance that are yet to be specified.

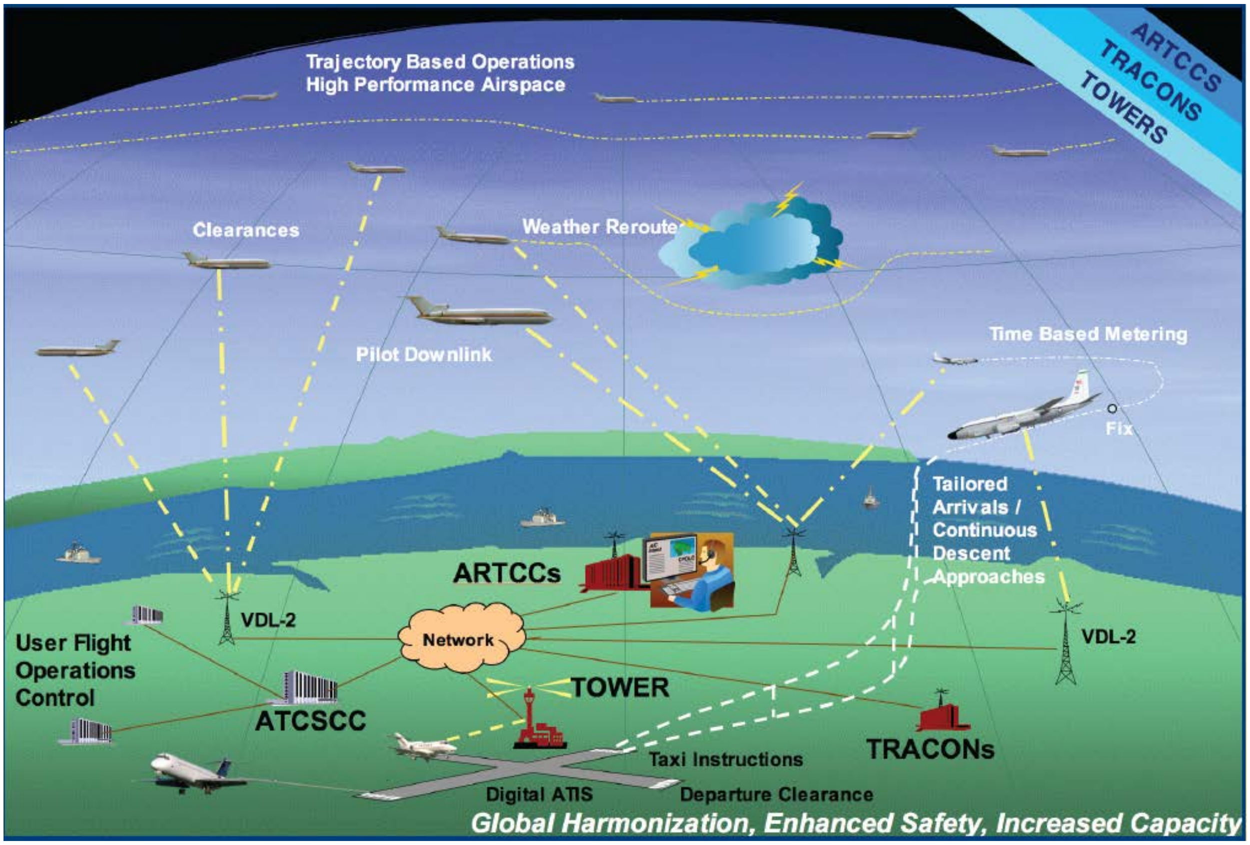


Figure 33 – Concept of Operations

[Reference: FAA NextGen Data Communications Frequently Asked Questions Brochure, HQ-09818.]

5.6.1 Net-centric Exchange of ATM Information

A foundational and transformational component of the JPDO ConOps for NextGen is the employment of a net-centric environment for exchanging air transportation-related information. Such information will provide authorized aviation stakeholders timely, accurate, and actionable information (e.g., weather, surveillance, aeronautical information, operational and planning information, as well as position, navigation, and timing information) to shorten decision cycles and improve situational awareness using a net-centric environment managed through enterprise services that meets the information exchange requirements to support the intended operations. The information exchanges will be more clearly targeted to the appropriate decision makers, reducing workload and unnecessary actions by those not affected. Machine-to-machine negotiation will replace labor-intensive, voice, or text-based processes.

Communications of relevant information is key to distributed decision making, the latter of which is also known as Collaborative Air Traffic Management (ATM). Information must be available, securable, and usable in real time among different communities of interest. Collaborative ATM hinges on a “common” awareness of overall constraints and understanding of the impacts of individual and system-wide decisions.

5.6.2 Performance Based Requirements

To realize the NextGen and beyond vision for performance-based operations requires the development of performance-based requirements. ICAO and other industry organizations have begun to conceptualize a hierarchy of performance-based requirements specifications beginning at the airspace level and flowing down to the individual components of the ATM system, to include Required Communications Performance (RCP), Required Navigation Performance (RNP), and Required Surveillance Performance (RSP). This is described in greater depth in Section 12 of this report.

Of particular interest to the Com50 study is the RCP, which is intended to be a characterization of the communication performance quality of service level, without reference to any specific technology. Various RCP quality-of-service levels are being established by ICAO to support current and future ATM applications.

Considering the performance-based specification framework including RCP, RNP, and RSP, the RNP is the most mature today. However today's RNP definition is only two dimensional (horizontal only), and it is currently being expanded to four-dimensions by adding the specifications of altitude and time of arrival control at designated (contracted) waypoints. ICAO currently has defined an initial baseline for Required Communications Performance (RCP) that will need to be expanded to support future operations and address data link communications. RSP has not yet been well defined by ICAO or any other authority, but such requirements concepts are expected to mature within this study's 50-year time horizon.

5.7 Key Characteristics of NextGen

Key characteristics of NextGen, many of which will drive requirements for the future air-to-air and air-to-ground communications include:

- User Focus – emphasis on providing flexibility and services to meet all user needs, with minimal constraints
- Distributed Decision-Making – decisions are made as close as possible to those affected, but with due consideration of the entire ATM environment
- Integrated Safety Management – identification and proactive mitigation of safety risks at all levels
- International Harmonization – collaborative development of standards and procedures to enable transparent operations worldwide
- Take Advantage of Human and Automation capabilities – appropriate allocation of functions between air and ground, and between human operators and supporting automation, to provide a more robust, safe and efficient ATM system
- Weather Operations – Consistent and enhanced weather information is used to develop optimized constraints that are integrated into planning and operations, so that the impact of weather is minimized
- Environmental Framework – Minimize adverse impacts on noise, pollution, climate effects, and energy usage
- Robustness and Resiliency – Degrade gracefully in the event of disruptions & failures
- Scalability – Accommodate a range of possible future system demands

5.8 Recommendations from ICAO Air Navigation Conference in November 2012

The ICAO Air Navigation Conference was held in Montreal in November of 2012. Recommendations from the meeting report for this conference that are relevant to this study include the following:

- (1/1) ICAO should take a total systems and performance-based approach (as opposed to a system or solution based approach)
- Chapter 1.3 (Technology) discusses the need for a "self-reserved data wireless network in the air" in context of increasing the levels of ATM automation
- (1/5) ICAO should define the accuracy requirements for the future use of a time reference and to prepare the necessary amendments to Standards and Recommended Practices (SARPs).
- (1/6) Data communication issues:
    - Review of air traffic control communication requirements and issues …
    - Review operation, management, and modernization of Regional digital network technical cooperation project …
    - Explore multi-modal solutions … to overcome transition issues
    - anticipate and accelerate the migration of ATM communication systems towards more efficient technologies to timely service the aviation system block upgrade modules
- (1/7) ADS-B and associated communication technologies to bridge gaps … to support future trajectory-based ATM …
- (1/8) Explore strategies to decommission some navigation aids and ground stations
- (1/9) Development and adoption of spaced-based ADS-B surveillance
- (1/10) Consider self-organizing wireless data networks like VDL-M4
- (1/12) Spectrum protection … develop and implement a comprehensive aviation frequency spectrum strategy … adequate spectrum to create a sustainable environment for growth & technology development to support … current & future … systems and allow for the transition between present and next generation technologies
- (1/13) Potential use of fixed satellite spectrum allocations to support safe operation of remotely piloted aircraft systems

5.9 Evolution of ATM A-G Communications Interactions of Voice and Data

The historical, current, and expected future evolution of ATM-relevant A-G voice and data communications between the Pilot in Command (PIC), air traffic controller, Flight Operational Control (FOC), Trajectory Management Unit (TMU), Trajectory Flow Management (TFM), the aircraft (A/C), and various automation functions are depicted in the following three figures. Figure 34 illustrates the historical interactions, where only voice communications were used between the PIC, ATC, FOC, and TMU. Figure 35 illustrates the current interactions which still remain mostly voice communications between most of these elements, with some data exchange to and between the automation functions, between the PIC and FOC, and between the PIC and the aircraft. Figure 36 illustrates the envisioned future interactions where virtually all communications among these elements are data, with some residual capability for voice communications between PIC and ATC, primarily for non-nominal operations.

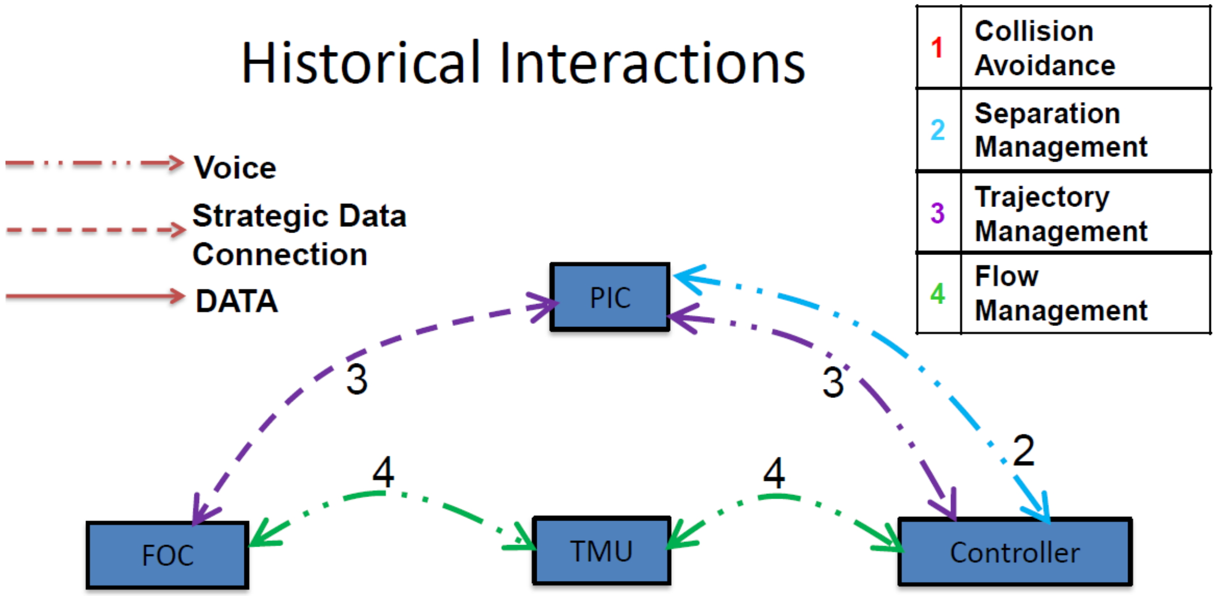


Figure 34 – Historical Interactions

[Reference: Steve Bradford (FAA NextGen Office) presentation, "SWIM in the Sky," June 2014.]

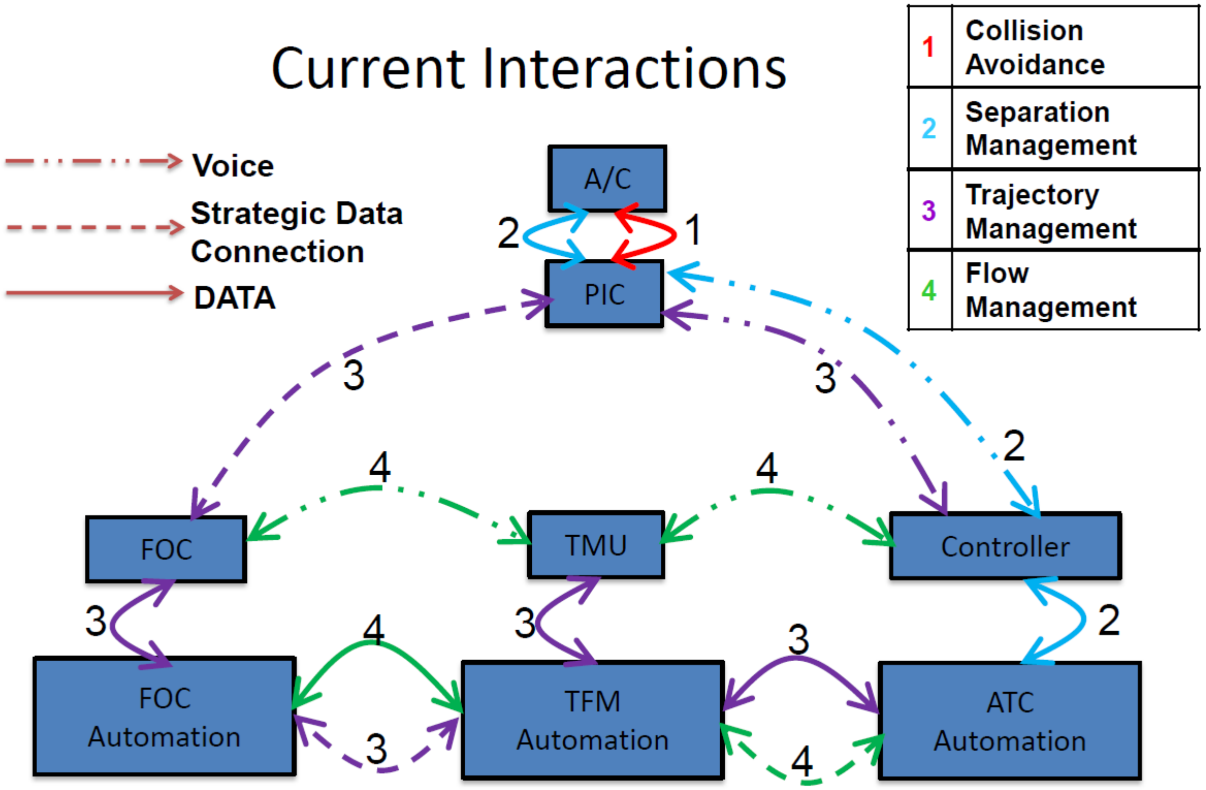


Figure 35 – Current Interactions

[Reference: Steve Bradford (FAA NextGen Office) presentation, "SWIM in the Sky," June 2014.]

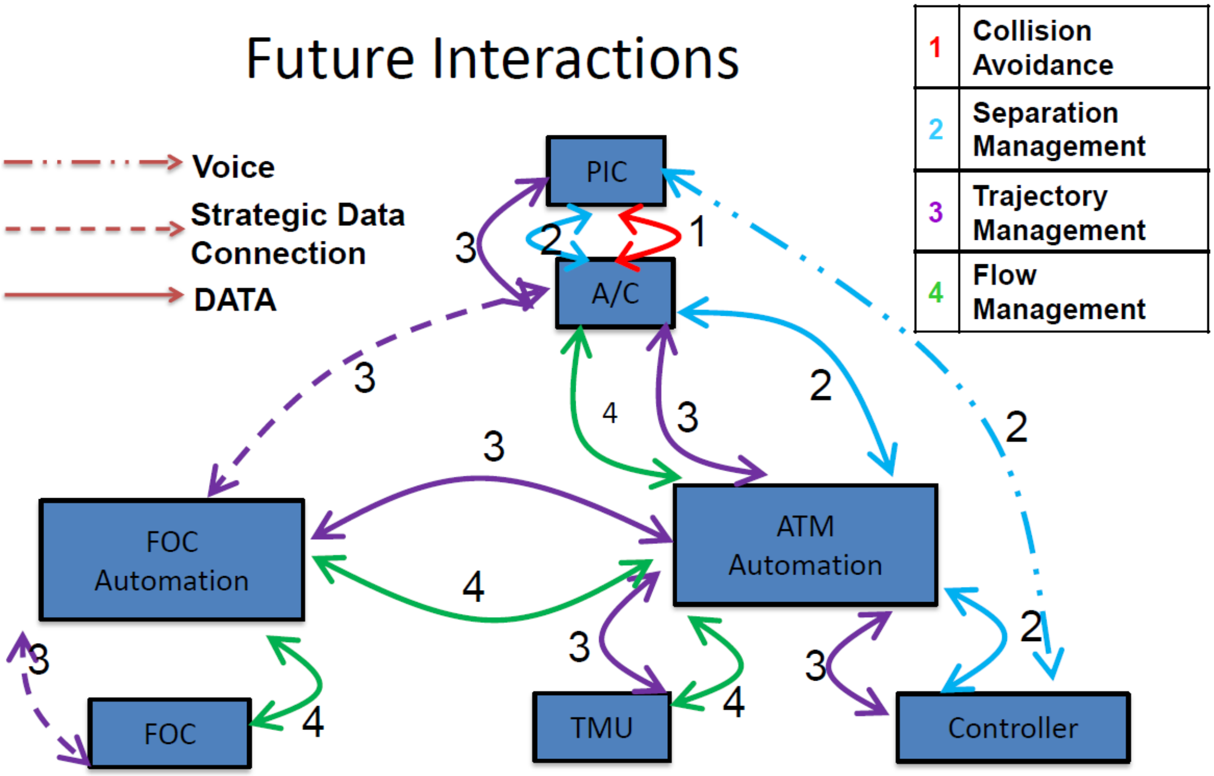


Figure 36 – Future Interactions

[Reference: Steve Bradford (FAA NextGen Office) presentation, "SWIM in the Sky," June 2014.]

6 COMMUNICATION TRENDS / STUDY ASSUMPTIONS / FUTURE PREDICTIONS

This section of the report identifies potential factors that will drive changes in the communication systems relevant to this study, captures the assumptions of this study, and based upon the identified factors and assumptions, predicts possible implications for future Air-to-Ground and Air-to-Air aircraft communication systems.

6.1 Communication Relevant Trends and Predictions about the Future

This section is meant to capture trends and predictions of the future to provide perspective and rationale for our expectations for the future of Air-to-Ground and Air-to-Air Communications in the future National Airspace System. The future is always difficult to predict. However, understanding the communication relevant trends, technologies, expected economic drivers, predicted regulatory changes, and the predicted environmental conditions is often helpful in making better long range predictions. As such, trends and predictions relevant to future communications in the NAS are articulated below in each of these areas.

6.1.1 Communication System Trends

Communication system trends include the following:

- Communications networks will be ubiquitous - wide-band, terrestrial, and space based
- Connectivity will become more robust with minimal drop-outs - enabled by multiple networks
- Airborne end systems will have Internet Protocol (IP) addresses for direct access
- System security will be a core requirement of communication systems
- Machine-to-Machine dialog/communications will become increasingly more prevalent for air-to-ground communications and will become the standard, with limited human-to-machine interaction, and human-to-human communications will become the exception.
- There will be an explosion in decision support systems which will drive the need for access to and communication of information.
- Scheduled information exchange will assist in network bandwidth management (off-prime scheduled communications)
- Cloud computing will be common
- Local networks will be the norm with inter-domain exchanges well understood (this allows improved frequency re-use)
- Personal electronic devices will be nodes on a network
- Preference sharing will become a "routing protocol" to improve network utilization
- Communication networks that provide advisory information to support aircraft operations will not be spectrum specific but will be "usable” for airspace applications if they provide the appropriate quality of service

6.1.2 Technology Trends

Communication system technologies will certainly mature over the next 50 years. Specifically, technology areas that are maturing that could potentially enabled improved air-to-air or air-to-ground NAS communications include:

- Increased processing capabilities
- Advances in signal processing
- Advances in software defined radios
- Advances in networking technology
- Low cost directional antennas
- Conformal antennas
- Other smart antenna technologies
- Chip-scale high quality / low cost clocks
- Multiple input and/or multiple output transmitters and receivers
- Data compression / data acceleration
- Broadband commercial connectivity to aircraft
- Free space optical and hybrid RF/optical communications
- Adaptive / cognitive radio technologies
- Electronic flight bags
- Artificial Intelligence and Autonomous Systems
- Information security

Each of these technology areas are discussed in Section 8.

6.1.3 Economic Conditions

Economic predictions about the future relevant to the future ATM communication needs include:

- Aviation will remain a viable means of transportation. While other modes of transportation may be improved (e.g., high speed trains), there will still be demand for air travel.
- Global growth will continue to drive need for increased air travel.
- Airlines and other aircraft owners will seek ways to further optimize their operations to significantly reduce operational costs. Communication systems technologies will be leveraged to reduce these costs (e.g., more efficient operations with decision aids, reduced or no piloted flights).
- Demand for oil will drive aircraft fuel prices at a rate higher than that of inflation
    - The implication for communication systems is that aircraft operators will become increasingly interested in leveraging information to improve the efficiency of their aircraft operations.

6.1.4 *Predicted Regulatory/Airspace Changes*

The expected regulatory/airspace changes that are envisioned to drive changes into future communications systems include:

- NextGen/SESAR and beyond transformations will introduce changes into aircraft operations, air traffic management, and airspace
  - Airspace moving to support 4D Trajectory-Based Operations (TBO)
  - Highly automated and integrated air traffic system based on real time information exchange
- Distributed decision making among ATC, Aeronautical Operational Control (AOC) [which includes, for example, Airline Operational Control], and flight crew
- Increasing focus on aviation security measures to address a wide range of terrorist threats
- Increasing focus on system robustness for common mode errors/failures
- Increased acceptance of handheld devices (e.g., Electronic Flight Bags - EFBs) on the flight deck
- Increased acceptance of “hybrid” avionics, which consist of a mix of certified “installed” avionics and “non-certified” devices
- Increased acceptance of leveraging commercial communications networks for information exchange
- It is expected that the ITU will continue to manage and allocate the frequency spectrum for all of the various applications, including aviation.

6.1.5 *Environment*

Environmental factors will drive the need for future ATM communications solutions including:

- Increased demand for air travel
  - Cluttered airspace in major metropolitan areas
  - Few new major airports or new runways
  - Drives the need for increased capacity of air-to-air and air-to-ground communication systems
- Higher fuel prices (also part of “Economics”)
  - Jet fuel is about $6 to $7 per gallon (2013), and by 2025 it is estimated to cost $15 to $20 per gallon. By 2060, jet fuel may cost $100/gallon.
  - Drives customers to be increasingly interested in ways to save fuel, including leveraging information available to conduct more efficient operations
- Continued concern about terrorists
  - Drives the need for authentication, encryption, etc. in CNS systems
- Increased environmental consciousness
  - Drives need for better efficiency, reduced aircraft emissions, noise abatement, and carbon tracking

- Growth in unoccupied air vehicles (UAVs) and UAVs in the NAS
- Possible emergence of single-piloted business, regional, and air transport aircraft operations
- Possible entry of commercial space launch vehicles in the NAS, that can launch from many locations including the ocean
- Possible emergence of “personal” air-vehicles that can get airborne virtually anywhere, and will want entry into the NAS
- Possible emergence of high speed civil transport aircraft
- More attractive alternative modes of transportation in some regions (e.g., high speed trains)

6.2 Study Assumptions

A number of assumptions have been made relevant to future NAS air-to-air and air-to-ground communications candidates including:

- Aviation will remain an economically viable means of transportation
- There will be increasing need for more air-to-air and air-to-ground communications to support future NAS air transportation system operations
- The propagation of electromagnetic radiated signals remains as we know it today, with the limited atmospheric windows that readily support propagation through the earth’s atmosphere (see Section 9) over distances needed to support air-to-air and air-to-ground aviation operations.
- Claude Shannon’s channel capacity theory holds true defining a theoretical maximum rate at which error free bits can be transmitted over a bandwidth limited channel in the presence of noise as:

  $$C = W \log_2 \left(1 + \frac{S}{N}\right)$$

  where: C = channel capacity in bits per second, W = is the channel bandwidth in Hertz, and S/N = signal-to-noise ratio of the communication signal.
- Aviation safety related communication networks will operate in spectrum solely allocated by ITU or other spectrum regulating body to provide protection from unintentional interference sources.

6.3 Significant NAS Challenges

There are a number of significant NAS modernization challenges that will be faced during this study’s 50 year modernization time horizon including:

- Upgrading the air-to-air and air-to-ground communication systems to extensively support the future demands (e.g., increased traffic, exploding information exchange, new operations, while addressing safety/security)
- Integration of advanced air-to-air and air-to-ground operational procedures into the NAS

- Integration of UAS into the NAS
- Integration of self-separating aircraft (e.g., NASA Autonomous Flight Rules concept) with IFR aircraft that need air traffic separation services
- Development, deployment, and integration of alternative PNT source(s) into the NAS (highly capable terrestrial backup to GNSS sources)
- Technology refresh of aging systems
- Incorporating of significantly more decision support systems and automation into Air Transportation System

6.4 Predictions for Future NAS Communications

Based upon the trends and study assumptions, the following is predicted for the Future NAS communications:

- Current communication system state of the art for well-defined waveforms can be implemented to achieve ~60% of Shannon's limit of channel capacity
    - In 50 years, technology may allow achieving higher than today's ~60% of Shannon's channel capacity limit (maybe 70 to 80%), and the state of the practice for communication systems may be 60 to 70%.
    - Today's communication waveforms used in civil aviation are not anywhere near the state of the art.
- ATM communications will consist mostly of machine-to-machine digital data. ATM voice services will exist but will be used only as backup or in special circumstances such as emergencies.
- VHF voice will continue; largely used by simple sport aircraft operating out of small airfields and not in controlled airspace.
- The aviation spectrum utilization to support Communication / Navigation / Surveillance (CNS) functions will evolve during the 50 year NAS study time horizon. This evolution may allow reallocation of "Aviation" spectrum resources.
- MLS C-Band spectrum will be used for airport, terminal area, and potentially for high bandwidth UAS command and control non-payload data link.
- Secondary Radars (those requiring transponders) will be decommissioned in favor of using ADS-B and ADS-C, backed up with wide area multi-lateration and primary radar. This frees up both 1030 and 1090 MHz which could be used for ADS-B improved integrity through redundancy.
- TCAS will evolve to ACAS-X and will primarily use ADS-B surveillance transmissions instead of the current transponder interrogation scheme.
- Airport Surveillance Primary Radars (2700-2900 MHz) and Air Route Surveillance Radars (1215-1350 MHz) would continue to be used as backup systems to ADS-B and ADS-C and to detect aircraft not required to have ADS.
- ADF will be decommissioned
- VOR will be decommissioned, potential to use 112 to 118 MHz band for Comm.

- DME may be modernized to become an alternative/authenticated/backup PNT source to GNSS, and provide the potential to reallocate most of the DME L-band spectrum for A-A and/or A-G communications
- ILS Glideslope and localizer will continue to exist as backup for GNSS landing aids, although; the number of ILS stations will be reduced. ILS Localizer frequencies (108 to 112 MHz) will also support GPS/LAAS VHF Ground-to-Air Data Broadcast. ILS Glideslope frequencies will be underutilized and may potentially support A-A or A-G communications.
- TIS-B and its corresponding ground-to-air broadcast will be retained to support A-A traffic applications.
- ADS-R will initially be fielded to support the crosslinking ADS-B information from 1090 MHz to UAT (978 MHz) and vise-versa. However, ADS-R will eventually be decommissioned as aircraft will be required to receive ADS-B on all approved ADS-B Out frequencies.

7 EXISTING AIR-TO-AIR AND AIR-TO-GROUND COMMUNICATIONS

This section of the report identifies the existing air-to-air and air-to-ground communications in the NAS. Aircraft-to-aircraft (A-A) and aircraft-to-ground (A-G) ATM relevant communications are conducted in the NAS today to support CNS functions as indicated in Figure 37 (on page 74), including:

a) Communications (C): between the ATC and pilot and between AOC and the pilot,

b) Navigation (N): broadcast of information to support GPS/LAAS-based precision approach, and

c) Surveillance (S): A-A communications between suitably equipped TCAS aircraft, A-G transponder communications to support SSR and ASDE-X, ADS-B A-A and A-G communications, and ground broadcast of DATIS/FIS/ADS-R/TIS-B information.

Figure 37 also characterizes the various NAS communications as to the frequency band, modulation, intended function, channel bandwidth, data rate, and typical communications range.

7.1 Existing Air-to-Air Communications

Existing NAS air-to-air (A-A) Communications are rather limited. Specific aircraft-to-aircraft communications are limited to: 1) Traffic Alert and Collision Avoidance System (TCAS) communications on 1030 and 1090 MHz frequencies, 2) VHF Communications on the Common Traffic Advisory Frequency (CTAF), and 3) the emerging ADS-B communications on both 1090 MHz and UAT which is on 978 MHz. *Note that in portions of Europe (including the Scandinavian countries in Northern Europe), ADS-B is communicated on VHF frequencies using VDL-M4.* Indirectly, pilots receive and listen to other aircraft-to-controller A-G party line communications that are received A-A, but are intended to be A-G communications.

7.2 TCAS Air-to-Air Communications

TCAS uses Mode S and Mode C transponders to communicate between suitably equipped aircraft. Interrogation squitters are sent on the 1030 MHz radio frequency, and replies to the squitters are sent on 1090 MHz frequency. Each Mode S transponder on a TCAS equipped aircraft pseudo randomly radiates (squitters) its unique Mode S address omni-directionally to let its presence be known to other like-equipped aircraft. Following receipt of a squitter, the TCAS system on the second aircraft then sends a Mode S reply to that specific Mode S address contained in squitter message. Directional antennas that receive the Mode S transponder signals are used to determine the bearing to the neighboring aircraft. Mode C altitude broadcasts are used to establish the altitude of the nearby aircraft, and the timing of the Mode S interrogation/response protocol is used to determine the distance between the TCAS equipped aircraft.

Once established, this bi-directional data link between each TCAS equipped aircraft is crucial to obtain traffic information to support traffic situational awareness and traffic, advisories for TCAS-I equipped aircraft, and additionally traffic resolutions for TCAS-II equipped aircraft.

For additional information on Mode S and Mode C transponders, see Section 7.3.5 (on page 84).

CNS Function	Freq. Band	Frequency Range	Voice /Data	Modula-tion	Function	Channel BW	Data Rate	Typical Com. Range
Communication	HF	~2 to 30 MHz	Voice	SSB	A-G: ATC & AOC Comm.	3.5 kHz	N/A	BLOS: 500 to 2500 km
	HF	~2 to 30 MHz	Data	M-PSK	A-G: ATC & AOC Comm., and ADS-C	3.5 kHz	Single channel: 300 to 1800 bps., higher with shared channels	BLOS: 500 to 2500 km
	VHF	118 to 137 MHz	Voice	DSB-AM	A-G: ATC & AOC Comm. A-A: CTAF (122-123 MHz)	25 kHz	N/A	LOS: 200 NM
	VHF	118 to 137 MHz	Data	DSB-AM - MSK, D8PSK	A-G: AOC Comm., DATIS, (Emerging ATC Comm.)	25 kHz	2400 bps to 31.5 kbps	LOS: 200 NM
	SATCOM	L-band (Ku & Ka Satellite Links)	Voice	Various	A-G: ATC & AOC Comm.	Various	N/A	Geo: ≤ 70 deg. N/S latitude, Global for Iridium
	SATCOM	L-band, (Ku & Ka Satellite Links), S-band	Data	Various	A-G: ATC & AOC Comm., ADS-C, and Sirius XM for WxR &Traffic, Aircell, MedAire, etc.	Various	For SOL Services: Single channel up to 10.5 kbps (Aero H, Aero H+), shared channel 64 kbps. For non-SOL Services: up to 432 kbps (Swift Broadband).	Geo: ≤ 70 deg. N/S latitude, Global for Iridium
Nav.	VHF	108 to 118 MHz	Data	D8PSK	A-G: (really G-A) VDB broadcast for GBAS/LAAS	25 kHz	31.5 kbps	LOS: Typically less than ~80 NM
Surveillance & Info. Services	L-Band	1030 and 1090 MHz	Data	PPM, DPSK	A-G: ATCRBS and Mode S	~2 MHz	1 Mbps signaling rate	LOS: ~200 NM
	L-Band	1030 and 1090 MHz	Data	PPM, DPSK	A-A: TCAS	~2 MHz	1 Mbps signaling rate	LOS: ~40 NM
	L-Band	1090 MHz	Data	PPM	A-A: ADS-B A-G: ADS-B, ADS-R, and TIS-B	~8 MHz	1 Mbps signaling rate	LOS: ~100 NM
	L-Band	978 MHz	Data	CPFSK	A-A: ADS-B A-G: ADS-B, ADS-R, TIS-B, and FIS-B	~2 MHz	1 Mbps signaling rate	LOS: ~100 NM

Figure 37 – Current A-A and A-G Communications

[Note: The shaded rows indicate emerging communications being conducted in the NAS today.]

7.2.1 *VHF Air-to-Air Communications*

VHF voice communications are used aircraft-to-aircraft on a Common Traffic Advisory Frequency (CTAF) to support aircraft operations at non-towered airports. The VHF voice communications are described in the A-G communications section on VHF (Section 7.3.2).

7.2.2 *ADS-B Air-to-Air Communications (Emerging)*

Automatic Dependent Surveillance – Broadcast (ADS-B) is an emerging A-A (and A-G) communications system that is being implemented on 1090 MHz frequency (as 1090 Extended Squitter – 1090ES) and on 978 MHz (Universal Access Transceiver).

This data broadcast of own-ship surveillance information enables suitably equipped aircraft and airport ground vehicles to be tracked by pilots of other aircraft that are equipped with ADS-B receive equipment (A-A), and air traffic controllers (A-G).

See Section 11.1 (starting on page 151) for a more detailed description of ADS-B.

7.3 Existing Air-to-Ground Communications

For the purposes of this report, Air-to-Ground communications include the ATM relevant communications between aircraft and Air Traffic Services (ATS) as well as between aircraft and Aeronautical Operational Control (AOC) services as depicted in Figure 38. It also includes Air-to-Ground communications in support of navigation, surveillance, and information services.

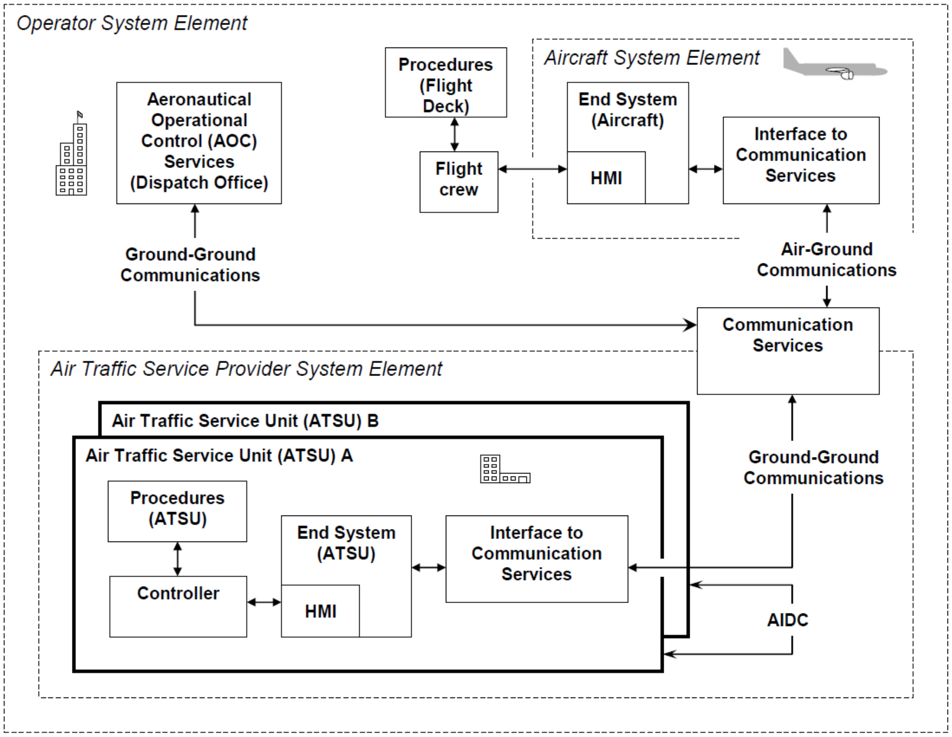


Figure 38 – Air-to-Ground Communications Context Diagram

[Reference: RTCA/DO-306, Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace, October 11, 2007, page 2.]

Existing NAS aircraft-to-ground (A-G) communications include:

a) HF, VHF, and SATCOM for supporting “communications” functions,

b) VHF Data Broadcast (VDB) for supporting “navigation” functions, and

c) L-band 978 MHz, 1030 MHz, and 1090 MHz for supporting “surveillance” and information services functions, and VHF for supporting information services (DATIS).

Direct pilot to ATC (voice) communications is required in all airspaces today. In domestic airspace (which includes surface, terminal area, and domestic enroute airspaces), the ATS communications requirement is VHF voice. In some countries, UHF voice to support military operations is also available. In oceanic or continental remote and polar airspace (outside of VHF voice communications coverage areas), the communications are supported by HF and SATCOM. In the event of communications failure, flight crews continue with their flight plans in accordance with the lost communication procedures. Each of the above A-G communications is described in subsequent subsections.

7.3.1 HF Air-to-Ground Communications

HF voice communications are required for all transoceanic flights and flights under air traffic control into remote areas that are not covered by VHF air-to-ground communications. HF radios provide aircraft with voice and data communications over long distance oceanic and trans-polar routes. HF communication is the safety network for beyond line of sight (BLOS) long distance data communication that augments existing VHF and SATCOM communications. Aircraft/Ground HF radio systems for aviation operate on a number of frequencies within the HF spectrum. Unlike aircraft VHF communications, the spectrum is not divided into a large number of contiguous channels, but rather allocations for aviation in the HF band are interspersed with many other services.

In the HF frequency range, radio waves propagate over long distances due to reflection from the ionized layers in the upper atmosphere. Due to variations in height and intensities of the ionized regions of the earth’s atmosphere, different frequencies must be used at different times of day and night and for different paths. There is also some seasonal variation (particularly between winter and summer). Propagation may also be disturbed and enhanced during periods of intense solar activity. HF propagation has considerable variations and is far less predictable than propagation at VHF.

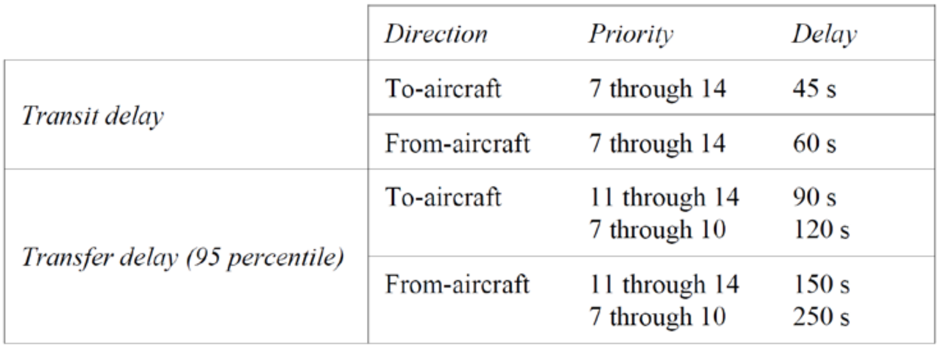
The frequencies selected for a particular radio path are usually set roughly mid-way between the lowest usable frequency (LUF) and the maximum usable frequency (MUF). The LUF is usually between 4 to 6 MHz during the day, dropping rapidly after sunset to around 2 MHz. The MUF is dependent on the season and sunspot cycle but is often between 8 MHz and 20 MHz. Hence a typical daytime frequency for aircraft communication might be 8 MHz, and it might be as low as 3 MHz during the night. Typical ranges for HF communications are on the order of 500 km to 2500 km and this effectively fills in the gap in VHF coverage.

The spectrum available for aircraft communications at HF is extremely limited. As a result, steps are taken to restrict the bandwidth of transmitted signals, for both voice and data to about 3.5 kHz. For voice, the modulation used is single sideband (SSB). HF data link (HFDL) uses M-ary phase shift keying (M-PSK) at data rates of 300 or 600 (for M=2), 1200 (for M=4), and 1800 (M=8) bps per channel. The rate used is dependent on the prevailing propagation conditions. HF data link is based on frequency division multiplexing (FDM) for access to ground station frequencies and time division multiplexing (TDM) within individual communication channels. Each TDMA frame is 32 seconds, and it is divided into 13 equal slot durations. The first slot of each TDMA frame is reserved for use by the HFDL ground station subsystem to broadcast link management data. The remaining slots are designated either as uplink slots, downlink slots reserved for specific HFDL aircraft, or as downlink random access slots for use by HFDL aircraft on a contention basis. These TDMA slots are assigned on a dynamic basis using a combination of reservation, polling, and random access assignments.

HF operates at single sideband (SSB) carrier frequencies available to the aeronautical mobile (R) service in the band of approximately 2 to 30 MHz. The following frequencies ranges in the HF band are allocated to aeronautical services:

- 2850 to 3155 kHz
- 3400 to 3500 kHz
- 4650 to 4750 kHz
- 5480 to 5730 kHz
- 6525 to 6765 kHz
- 8815 to 9040 kHz
- 10,005 to 10,100 kHz
- 11,175 to 11,400 kHz
- 13,200 to 13,360 kHz
- 15,010 to 15,100 kHz
- 17,900 to 18,030 kHz
- 21,870 to 22,000 kHz
- 23,200 to 23,350 kHz

For the HF data link, transit and transfer delays for network user packets (128 octets) with message priorities 7 through 14 are not to exceed the values in Figure 39 below.



	Direction	*Priority*	*Delay*
Transit delay	To-aircraft	7 through 14	45 s
	From-aircraft	7 through 14	60 s
Transfer delay (95 percentile)	To-aircraft	11 through 14 7 through 10	90 s 120 s
	From-aircraft	11 through 14 7 through 10	150 s 250 s

Figure 39 – HF Data Link Transfer Delay

[Reference: ICAO Annex 10, Volume III, Aeronautical Telecommunications, Second Edition including amendment 85 with applicability 11/2010, Table 11-1.]

7.3.2 VHF Air-to-Ground Communications

VHF communications provides the NAS air-to-ground communications between aircraft pilots and ATC as well as between the pilots and AOC for surface, terminal area, and enroute airspaces (not including remote, oceanic remote, and polar regions that are outside of coverage from a VHF ground station). Also, some information services like Digital Automated Terminal Information Service (DATIS) utilize the VHF ACARS frequencies for ground-to-air broadcast.

VHF air-to-ground communications include VHF voice and VHF Data Link (VDL). Today, ATC communicates with aircraft pilots using VHF voice using a listen before talk channel access. Emerging is the use of VDL for VHF communications between pilots and controllers, also known as controller-pilot data link communications (CPDLC). Both VHF voice and VDL are used for internal communications between aircraft and Aeronautical Operational Control centers.

VHF Communications in the NAS are in the 118 to 137 MHz portion of the VHF band. There are 760 channels with 25 kHz channel spacing in the NAS with the lowest assignable frequency at 118.000 MHz and the highest assignable frequency at 136.975 MHz.

In Europe, there are potentially up to 2280 channels with the 8.33 kHz voice channel spacings. Channels allocated to VDL utilize 25 kHz channels. Only those channels used for Double Side-Band Amplitude Modulation (DSB-AM) are allocated the 8.33 kHz channels. The DSB-AM analog modulation occupies about 7 kHz, with the excess bandwidth used as a guard-band to reduce the level of interference in adjacent channels.

ARINC is a service provider that operates the VHF Aircraft Communications Addressing and Reporting System (ACARS) that provides data link communications between aircraft and the aircraft operator’s control center. Other service providers provide similar services in other portions of the world. The original ACARS data link operates at 2.4 kbps, using DSB AM-MSK modulation. VHF Data Link (VDL) Mode 2 (VDL-M2) has been implemented to make more efficient use of the 25 kHz channel assignment by sending digital data at 31.5 kbps using the differential 8-state phase shift keying (D8PSK) modulation.

VDL Mode 2 is expected to soon emerge in the NAS to support CPDLC. It is being used for ACARS communications. VDL Mode 3 has been defined to provide both voice and data service capabilities, but has not been fielded in the NAS. VDL-M2 and VDL-M3 have been defined to use a common physical layer, the Differentially-encoded 8-state Phase Shift Keying (D8PSK), using a raised cosine filter, producing data transmission at a bit rate of 31.5 kbits/sec. VHF Data Link (VDL) Mode 4 has been developed and used in portions of Europe for air-to-air and air-to-ground communications. VDL-M4 is not currently used in the NAS. VDL-M4 uses a Gaussian filtered frequency shift keying (GFSK) modulation. GFSK is a continuous-phase, frequency shift keying technique using two tones and a Gaussian pulse shape filter, producing data at a transmission bit rate of 19.2 kbits/sec. VDL-M4 uses a self-organizing time division multiple access (STDMA) scheme based on time-shared use of a channel that employs (1) discrete contiguous time slots as the fundamental shared resource; and (2) a set of operating protocols that allows users to mediate access to these time slots without reliance on a master control station.

Figure 40 identifies the VHF frequency allocations in the NAS.

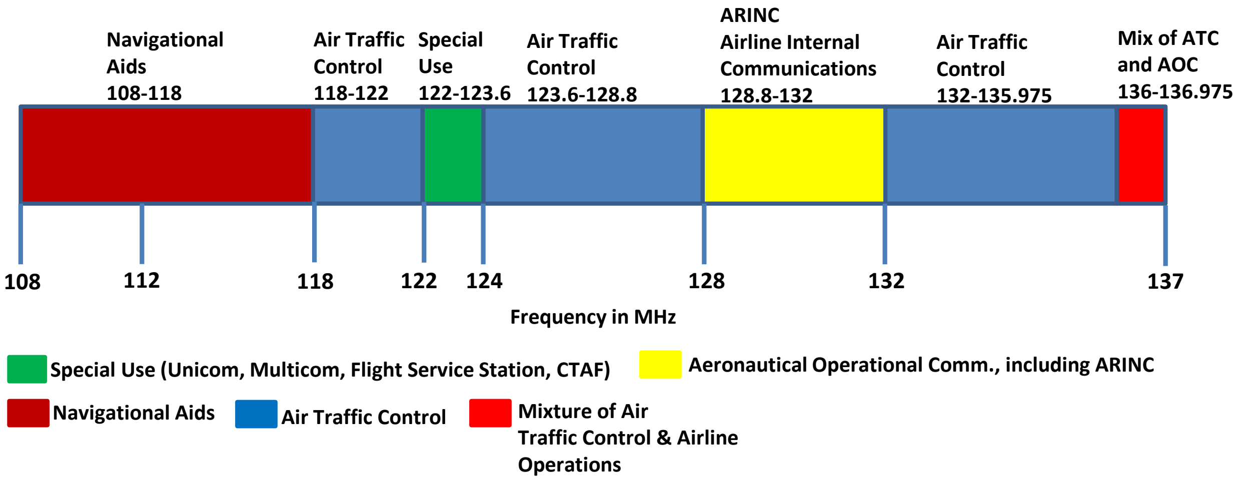


Figure 40 – VHF Communications Frequencies

7.3.3 SATCOM Air-to-Ground Communications

Satellite communication (SATCOM) systems use satellites to relay voice and data between aircraft and ground stations. The satellites used for SATCOM include both geo-stationary and those in low-earth polar orbits depending upon the service network.

SATCOM supports various safety services when aircraft are making trans-oceanic / trans-polar flights. SATCOM supports voice services between the pilot and air traffic control, aircraft position reporting for air traffic control [i.e., ADS-Contract (ADS-C)], and medical services communications (e.g., Aircell and MedAire) that allow the aircraft flight crew/ passengers to be able to communicate directly with emergency room physicians at the medical service provider's response center.

SATCOM A-G communications also support advisory services including the weather and traffic (i.e., Sirius XM Satellite Radio).

Aeronautical Mobile Satellite Services spectrum in the L-band is used to support ATS and AOC communications. The current spectrum allocated includes portions of the L-band, including parts of the spectrum between 1525 MHz and 1660.5 MHz.

There are many government and commercial SATCOM service providers. Two of the major providers include Iridium and Inmarsat, which are described in greater detail in the following subsections.

7.3.3.1 Iridium

[Reference: Iridium at www.iridium.com.]

Iridium provides complete worldwide satellite voice and data communications. The Iridium communications system consists of three major components including: 1) a space segment, 2) a ground segment, and 3) the subscriber terminals. The space segment consists of a satellite constellation of 66 low earth orbit satellites plus spares configured in a cross-linked and overlapping mesh to create its global coverage network. Each satellite supports three types of communication links – satellite-to-gateway, satellite-to-subscriber, and satellite-to-satellite.

The satellite-to-gateway link is supported by four Ka-band feeder link antennas at a rate of 3.125 Mbps full duplex. The uplink frequency is from 29.1 to 29.3 GHz, and the downlink frequency is from 19.4 to 19.6 GHz. The satellite-to-subscriber link uses three L-band antennas which project 48 spot beams (or cells) on the Earth, with each beam being approximately 600 km in diameter. The 66 satellite constellation has the potential to support 3,168 spot beams. The L-band antenna uplinks and downlinks operate from 1616 to 1626.5 MHz. The satellites are interconnected via four Ka-band inter-satellite cross-links operating from 23.18 to 23.38 GHz at 12.5 Mbps half duplex. Every satellite is cross-linked to four other satellites, two in the same orbital plane and two in an adjacent plane.

On the ground, Iridium has a network that includes gateways that provide the connectivity between the Iridium communication system and terrestrial communication networks in Arizona and Alaska, a satellite network operations center in Virginia, a technical support center in Arizona, and four tracking and control stations that are all interconnected by fiber-optic and broadband satellite links.

Subscriber terminals include those installed on a variety of aircraft platforms from a broad segment of the market including air transport, business aviation, general aviation, as well as defense and government aircraft.

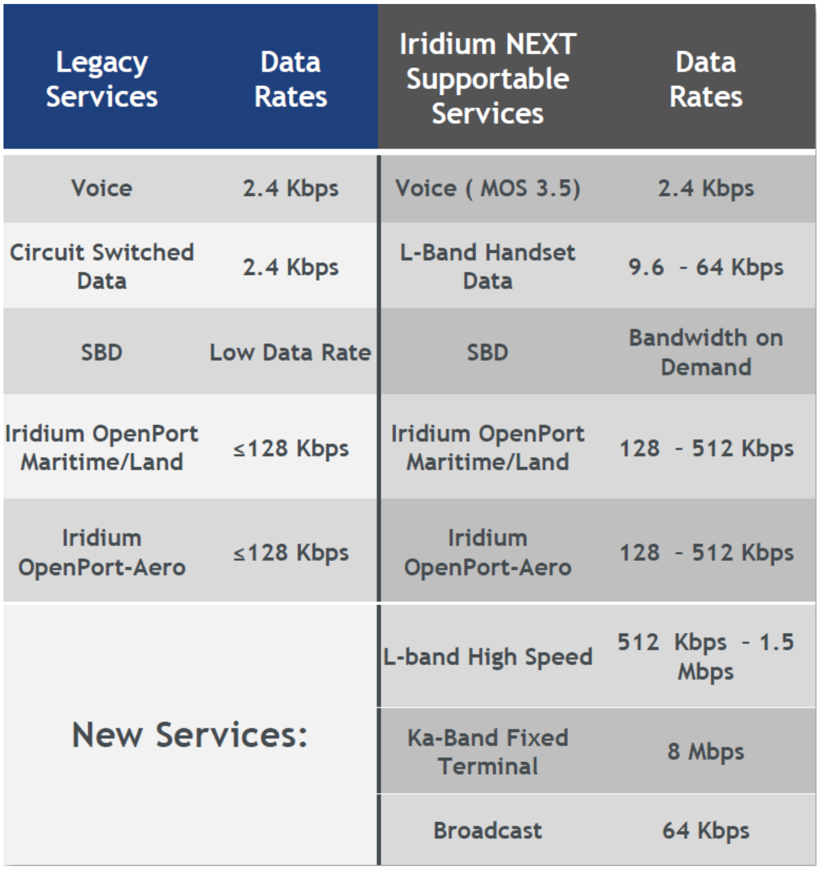
Iridium provides worldwide voice communications as well as data communications that are currently providing 2.4 kbps.

Because the communication has to go up to the orbiting satellite and come back, a communication delay does occur. The delay is approximately 0.25 seconds. The Iridium network is global with no holes in coverage. Iridium systems are less invasive for aircraft installation/retrofit; although, they are more susceptible to interference by other onboard systems.

Iridium has been approved by the FAA to support aviation safety services, including FANS Authorization (June 2011) and is expected to soon be approved to support Air Traffic Services (ATS) Voice communications, as aligned with RTCA DO-262A and DO-270 (MASPS and MOPS).

Iridium has developed a next-generation satellite constellation named “Iridium NEXT.” NEXT is being developed with an architecture offering the same voice services and a higher-powered data transfer system with backward compatibility for existing users. The Iridium NEXT satellite constellation is expected to be fully deployed by 2017.

A comparison of the current Iridium services and the anticipated Iridium NEXT services is given in Figure 41. Iridium NEXT is expected to include legacy voice service with improved voice quality and a variety of L-band data services with rates ranging from 2.4 kbps to 1.5 Mbps, using bandwidth-on-demand. Data services offered range from Short Burst Data (SBD), OpenPort-Aero data (128 kbps – 512 Kbps), high speed data (512 Kbps – 1.5 Mbps), and broadcast data service at rates up to 64 Kbps. Fixed and transportable Ka band services in data rates up to 8 Mbps will be offered. Aeronautical services are planned for altitudes up to 30 km above mean sea level and at speeds up to 2800 km/hr.



Legacy Services	Data Rates	Iridium NEXT Supportable Services	Data Rates
Voice	2.4 Kbps	Voice (MOS 3.5)	2.4 Kbps
Circuit Switched Data	2.4 Kbps	L-Band Handset Data	9.6 - 64 Kbps
SBD	Low Data Rate	SBD	Bandwidth on Demand
Iridium OpenPort Maritime/Land	≤128 Kbps	Iridium OpenPort Maritime/Land	128 - 512 Kbps
Iridium OpenPort-Aero	≤128 Kbps	Iridium OpenPort-Aero	128 - 512 Kbps
New Services:		L-band High Speed	512 Kbps - 1.5 Mbps
		Ka-Band Fixed Terminal	8 Mbps
		Broadcast	64 Kbps

Figure 41 – Iridium Services, Current on Left, Iridium NEXT on Right

[Reference: Iridium NOW & NEXT, IDB Aero SATCOM Seminar – Stockholm, Sweden, March 9, 2012, by Jeffery White, page 22.]

7.3.3.2 Inmarsat

[Reference: Inmarsat at http://www.inmarsat.com/sectors/aviation]

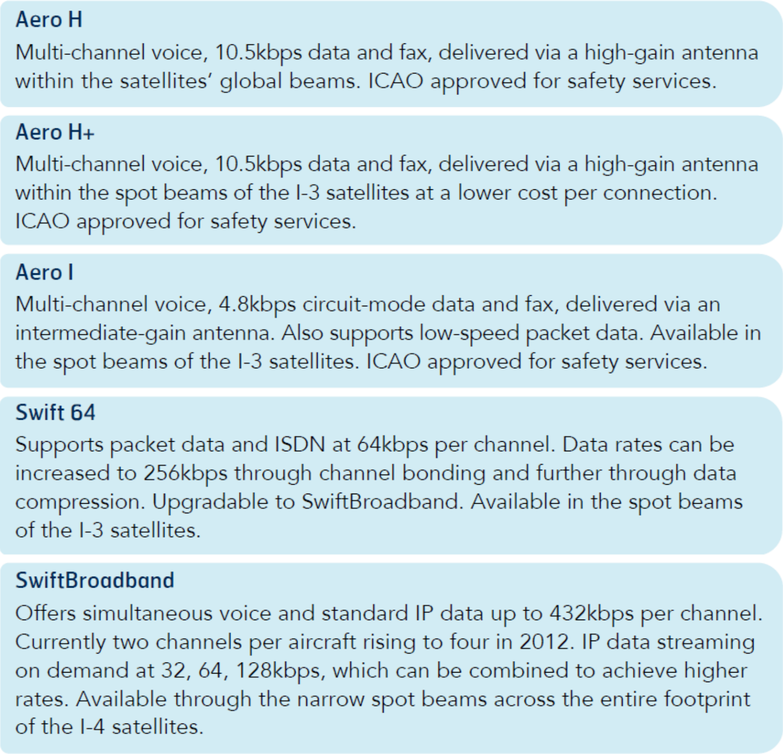
Inmarsat is an international satellite service provider. Inmarsat offers both voice and data services including Aero H, H+, I, M, Swift 64 and their popular SwiftBroadband high-speed data service. Swift 64 and SwiftBroadband systems are commonly used in air transport and larger business aircraft due to the current size of the high-gain antenna system normally installed on the tail of the aircraft. SwiftBroadband is an IP-based packet-switched service offering "always-on" data at up to 432 kbps per channel that is available globally except for polar regions above ~70 degrees North/South latitude. It can also provide IP streaming at various rates up to a full channel.

Inmarsat’s satellite-to-subscriber frequencies are from 1525 to 1559 MHz and from 1626.5 to 1660.5 MHz.

Equipping an aircraft with Inmarsat SATCOM enables a wide range of uses in the cockpit and the cabin. These include aviation safety communications services, weather and flight-plan updates, as well as passenger connectivity for email, internet access, voice over IP (VoIP) telephones, and GSM and SMS messaging. Up to four channels per aircraft can be used.

Inmarsat's Aviation Safety Services include the following, as summarized in Figure 42:

- Classic Aero services and SwiftBroadband:
  - Classic Aero services are accessible over both the Inmarsat-3 (I-3) and Inmarsat-4 (I-4) satellite systems.
  - SwiftBroadband services are provided with the I-4 satellites.
  - Global coverage ≤ 70 degrees North/South latitude.
- Classic services – Aero H: Aero H provides packet data rates of up to 10.5 kbps for ACARS, FANS, and ATN communications and up to 9.6 kbps per channel for multi-channel voice, fax, and data links through a high gain-antenna - anywhere in the global beams of the I-3 satellites. In addition to safety applications, other applications include passenger, operational, and administrative communications.
- Classic services – Aero H+: Offers all the features of Aero H, but uses the I-3 regional spot beams and 4.8 kbps voice codecs to deliver voice services at lower cost. Outside of regional spot beams, Aero H+ terminals operate in the global beams in the same way as standard Aero H systems. Aero H+ is also available in the full I-4 satellite footprint.
- Classic services – Aero I: Use intermediate-gain antennas and the I-3 regional beams, providing multi-channel voice and 4.8 kbps circuit-switched data services. Aero I packet data is also available in the full I-4 footprint.



Aero H

Multi-channel voice, 10.5kbps data and fax, delivered via a high-gain antenna within the satellites' global beams. ICAO approved for safety services.

Aero H+

Multi-channel voice, 10.5kbps data and fax, delivered via a high-gain antenna within the spot beams of the I-3 satellites at a lower cost per connection. ICAO approved for safety services.

Aero I

Multi-channel voice, 4.8kbps circuit-mode data and fax, delivered via an intermediate-gain antenna. Also supports low-speed packet data. Available in the spot beams of the I-3 satellites. ICAO approved for safety services.

Swift 64

Supports packet data and ISDN at 64kbps per channel. Data rates can be increased to 256kbps through channel bonding and further through data compression. Upgradable to SwiftBroadband. Available in the spot beams of the I-3 satellites.

SwiftBroadband

Offers simultaneous voice and standard IP data up to 432kbps per channel. Currently two channels per aircraft rising to four in 2012. IP data streaming on demand at 32, 64, 128kbps, which can be combined to achieve higher rates. Available through the narrow spot beams across the entire footprint of the I-4 satellites.

Figure 42 – INMARSAT Aviation Services

[Reference: "Services for Air Transport," September 2008, INMARSAT Global Limited, www.inmarsat.com.]

Inmarsat is deploying a worldwide wireless broadband network called Inmarsat Global Xpress. Three Inmarsat-5 (I-5) satellites will be deployed with full global coverage expected by the end of 2014. The satellites will operate at Ka-band in the range of 20–30 GHz. Each Inmarsat-5 will carry a payload of 89 small Ka-band beams which combined will offer global Ka-band spot coverage. Inmarsat is planning to offer high-speed inflight broadband on airliners.

7.3.3.3 Comparison of Iridium and Inmarsat Services

A comparison of Iridium versus is Inmarsat today is given in Figure 43.

Iridium	***Inmarsat***
Number of Users: 500,000+	**Number of Users:** 400,000+
Satellite Quantity: 66 satellites plus multiple in-orbit 7 backup satellites	**Satellite Quantity:** I3: 5 satellites I 4: 3 satellites
Low-Earth Orbiting (LEO)	**Geo-Stationary (GEO)**
Orbital Height: 485 miles	**Orbital Height:** 22,000 miles
Orbital Period: 1 hour, 40 minutes	**Orbital Period:** Stationary
Satellite Weight and Size: 1,500 pounds 14 feet long/3.5 feet high	**Satellite Weight and Size:** I4: 13,200 pounds 23 feet long/10 feet high
Spot Beams: 48 per satellite (30 miles in diameter per beam)	**Spot Beams:** I3: 1 global, 7 spot beams I4: 1 global, 19 regional, 228 narrow
Frequencies: Downlinks: 1616-1626.5 MHz Uplinks: 1616-1626.5 MHz	**Frequencies:** 1525.0-1559.0 MHz 1626.5-1660.5 MHz
Data Transmission Rate: 2.4-10 Kbps	**Data Transmission Rate:** 432 Kbps
Satellite Lifetime: 2015 – 2017 Current Generation 2015 – 2025 Iridium NEXT	**Satellite Lifetime:** 10+ years

Figure 43 – Comparison of Iridium and Inmarsat Today

[Reference: Duncan Aviation, http://www.duncanaviation.aero/straighttalk/satcom/what_is_satcom.php.]

7.3.4 VHF Data Broadcast (VDB) Ground-to-Air Communications (Emerging)

The VHF Data Broadcast (VDB) is the information transmitted from the Ground Based Augmentation System (GBAS) [also known as the Local Area Augmentation System (LAAS)] to support high integrity / high accuracy GNSS applications such as Category I / II / III precision approach operations (see Figure 44). The VDB broadcast application information includes GNSS differential correction information, satellite integrity data, final approach segment definition data, and ground station location data.

The broadcast is a TDMA, VHF data broadcast that complies with the physical layer of the ISO stack protocol described in ICAO Document AMCP/3-R/8A (VHF Digital Link Manual). The VDB link layer is similar, but different than VDL-M2. Currently, operation of the VDB in the 112 to 118 MHz frequency range has been approved, and in the future this is expected to be expanded to also include the 108 to 112 MHz frequencies.

Like VDL-M2, the VDB uses the D8PSK modulation to achieve a 31.5 kbps nominal signaling rate. VDB is an emerging data communication in the NAS. As of this writing, in addition to a number of prototype and test systems, there are two operationally commissioned GBAS systems with their VDB ground to aircraft data broadcast systems operating in the NAS to support GPS-based Category I precision approach operations. One GBAS station is at Newark Airport in New Jersey and a second station is at Houston Airport in Texas. These GBAS systems were commissioned by the FAA, with the first one approved at Newark for operational service on September 28, 2012.

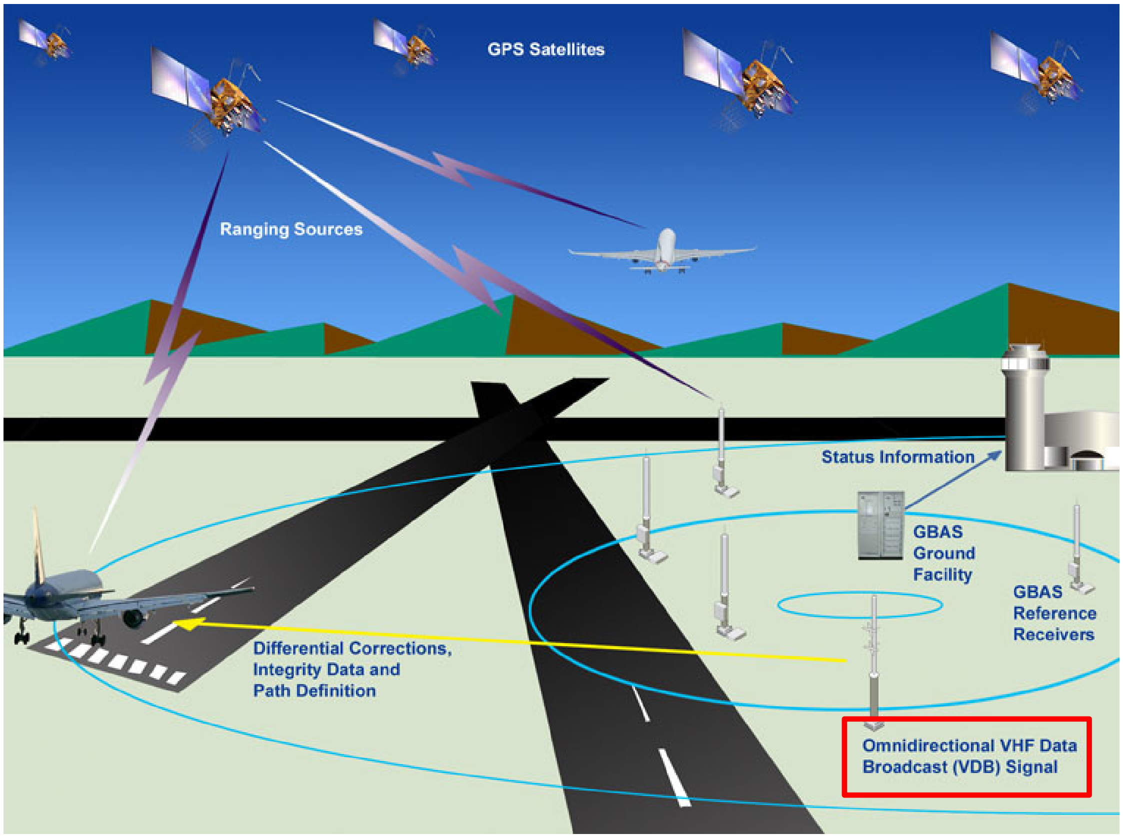


Figure 44 – GBAS / LAAS Includes VHF Data Broadcast (VDB)

[Reference: Source FAA.]

7.3.5 ATCRBS and Mode S Air-to-Ground Communications

The Air Traffic Control Radar Beacon System (ATCRBS) consists of transponders that are installed on aircraft and secondary surveillance radars (SSRs) installed on the ground. The SSR repetitively transmits interrogations from a rotating SSR radar antenna. The interrogations specify what type of information a replying transponder should send by using a system of modes.

There are four modes in common use today including:

1) Mode 1, which is used to sort military targets,
2) Mode 2, which is used to identify military aircraft missions,
3) Mode 3/A, which is used to identify each aircraft in the radar's coverage area, and
4) Mode C, which is used to request/report aircraft altitude.

Two other modes, Mode 4 and Mode S are not considered part of the ATCRBS system, but use the same transponder hardware. Mode 4 is used by military aircraft for the Identification Friend or Foe (IFF) system, and Mode S is a discrete selective interrogation, rather than a general broadcast, that facilitates TCAS for civilian aircraft. Mode S transponders ignore interrogations not addressed with their unique identity code.

The interrogation is done on the 1030 MHz frequency and it consists of three pulses, 0.8 μs in duration. Mode 3/A uses a spacing of 8.0 μs between the first and the third interrogation pulses (P1 and P3) and is used to request the beacon code assigned to the aircraft. Mode C uses a P1 to P3 spacing of 21 μs and requests the aircraft's pressure altitude. Mode 2 uses a P1 to P3 spacing of 5 μs and requests that military aircraft transmit its Military identification code. Pulse P2 is used for side-lobe suppression, whereby comparing the relative strengths of the received pulses, airborne transponders can determine whether or not the SSR antenna is pointing at the aircraft when the interrogation is received.

Replies to interrogations are done on 1090 MHz and consist of 15 time slots, each 1.45 μs in width. The reply is encoded by the presence or absence of a 0.45 μs pulse in each slot. The aircraft transponder will send a reply to the interrogation after a 3.0 μs delay providing the requested information. The interrogator system will then decode the reply and identify the aircraft. It will also determine the range (based upon the elapsed time between the interrogation and the reply) and the azimuth to the aircraft (based upon the direction of its antenna when the interrogation is received).

Mode S (or Mode Select) was developed as an evolutionary addition to ATCRBS to provide enhanced surveillance and communication capabilities to support not only SSR, but also air-to-ground and air-to-air data link communications. RTCA DO-181 (latest revision is E) defines the Minimum Operational Performance Standards for ATCRBS / Mode S Airborne Equipment.

A primary feature of Mode S that differs from ATCRBS is that each aircraft is assigned a unique address code such that interrogations can be directed to a particular aircraft and replies unambiguously identified. Mode S interrogations are done on 1030 MHz using binary differential phase shift keying (DPSK) and consist of a 24-bit discrete address. The Mode S interrogator provides surveillance of all beacon-equipped aircraft (both ATCRBS and Mode S) within its line of sight. The nominal maximum range is 200 NM. Mode S can provide for air-to-ground (which includes ground-to-air) and air-to-air data links.

The primary function of Mode S is surveillance. The Mode S transponder communicates using “short” (56 bit) squitters or “long” (112 bit) extended squitters. The extended squitter is used by ADS-B /ADS-R /TIS-B (air-to-ground and air-to-air), TCAS (air-to-air) and other ATC uses for air and surface surveillance. Mode S can be used to transmit longer messages by using the extended length message (ELM) capability. Using this capability, a sequence of up to 16, 80-bit message segments (each within the 112-bit transmission) can be transmitted.

7.3.6 ADS-B / ADS-R / TIS-B Air-to-Ground Communications (Emerging)

Automatic Dependent Surveillance – Broadcast (ADS-B) is an emerging A-G (and A-A) communications system that is being implemented on 1090 MHz frequency (as 1090 Extended Squitter – 1090ES) and on 978 MHz (Universal Access Transceiver). This data broadcast of own aircraft and airport surface vehicle surveillance information (referred to as ADS-B OUT) enables: a) ground receivers to receive the surveillance information and provide it to air traffic controllers (A-G), and b) other aircraft receivers to receive the broadcast and use the information for a variety of on-aircraft traffic applications (A-A).

Automatic Dependent Surveillance – Rebroadcast (ADS-R) is an emerging ground-based traffic information service (A-G) that relays ADS-B information transmitted by an aircraft or vehicle using one ADS-B link technology (e.g., UAT) and received by the ground station for subsequent rebroadcast for use by aircraft or vehicles using another ADS-B link technology (e.g., 1090ES).

Traffic Information Service – Broadcast (TIS-B) is an emerging ground-based traffic information service (A-G) that broadcasts traffic surveillance information for those aircraft/vehicles that are not broadcasting ADS-B surveillance information and for which ground surveillance information is available from another source, such that ADS-B IN equipped aircraft have a complete set of traffic surveillance information for aircraft in their vicinity.

See Section 11.1 (including subsections starting on page 151) for a more detailed description of ADS-B, ADS-R, and TIS-B.

ADS-B, ADS-R, and TIS-B on 1090ES and UAT use a Pulse Position Modulation (PPM) encoding of the message data, whereby a pulse transmitted in the first half of the interval represents a ONE and a pulse transmitted in the second half represents a ZERO. For more information regarding the transmission, see RTCA/DO-260 (latest revision is B) for 1090ES and in RTCA/DO-282 (latest revision is B) for UAT.

7.3.7 FIS-B Air-to-Ground Communications

Flight Information Service – Broadcast (FIS-B) is a ground-based service that provides meteorological and aeronautical data to suitably equipped aircraft. The FIS-B service is being provided today using the UAT data link (978 MHz), which is also the link typically being used by General Aviation aircraft for implementing ADS-B OUT in the United States. FIS-B ground stations receive weather and aeronautical data from a variety of information sources and generate sets of products specific to their location and region of interest for broadcast to aircraft users. These products are broadcast over the UAT link so that pilots of aircraft that receive the FIS broadcast have timely information of regional weather and National Airspace System status and changes that might impact their flight.

Current FIS-B products include: Airmen’s Meteorological Information (AIRMET), Significant Meteorological Information (SIGMET), Convective SIGMET, Meteorological Aviation Routine Weather Report (METAR), Continental United States Next-Generation Radar (CONUS NEXRAD), Regional NEXRAD, Notice to Airmen (NOTAM), Pilot Report (PIREP), Special Use Airspace (SUA) Status, Terminal Aerodrome Forecast (TAF), Winds & Temperatures Aloft, and TIS-B Service Status. Additional FIS-B products may be offered in the future, including, for example: Echo Tops, Cloud Tops, Icing NowCast, One-Minute Observations (OMO), Lightning, and Digital Automated Terminal Information System (DATIS).

Graphical weather is also another product often discussed for the future, although, as of this writing the bandwidth requirements for delivery of such information to aviation users has not been defined and standardized.

8 TECHNOLOGIES IN R&D POTENTIALLY RELEVANT TO FUTURE A-A OR A-G AERONAUTICAL COMMUNICATIONS

This section of the report identifies a number of technologies in research and development (R&D) that if appropriately matured could potentially be leveraged to improve future air-to-air and/or air-to-ground NAS communications, including:

- Increased processing capabilities
- Advances in signal processing
- Advances in software defined radios
- Advances in networking technology
- Low cost directional antennas
- Conformal antennas
- Other smart antenna technologies
- Chip-scale high quality / low cost clocks
- Direct sampling radio technologies
- Multiple input and/or multiple output transmitters and receivers
- Data compression / data acceleration
- Broadband commercial connectivity to aircraft
- Free space optical and hybrid RF/optical communications
- Adaptive / cognitive radio technologies
- Electronic flight bags
- Artificial intelligence and autonomous systems
- Information security
- High transmit power
- Split proxy and IP forwarding
- High speed optical transistor
- Onboard SATCOM technologies (IP switch and processing)
- Band aggregation
- Multi-hop aircraft-to-aircraft network technology
- Decrease in satellite launch costs
- Plasmonics
- New physics

The subsections below overview each of the technology areas and describe their potential to enhance NAS communications.

8.1 Increased Processing Capabilities

While Moore's Law is "collapsing" (as is described in the next paragraph), other technologies will continue to provide increased processing capabilities well into the future. This is important, so that implementations of potential future communication system waveforms requiring significantly more processing than today's waveforms can be cost effectively realized.

Collapse of Moore's Law: Historically, processing performance has increased dramatically with advances in microprocessors. Known as Moore's Law, the growth rate for the density of transistors on microchips has doubled every ~18 months to two years since the invention of the transistor. In addition to increased transistor density, the clock frequency has also closely tracked the growth rate of transistor density. This has led to ever smaller, higher performance device geometries. However, soon (some predict within the next decade) the limits of device geometry size reduction will be reached. The masks used to fabricate high-density/high-speed devices are already extremely difficult to make due to the fineness of today's lithography. Additionally, as the geometry size is reduced, breakdown voltage is also reduced limiting the signal excursion voltage of today's devices to less than that required to fully turn on or off a gate. This means that the gates must be biased partially on which results in a significant "leakage current". As geometry sizes are reduced, the ratio of leakage to signal current is increased as is the relative power dissipation of the device.

The Figure 45 illustrates the historical increases in microprocessor clock frequency over the last several decades and Figure 46 illustrates the increases in transistor density, clock speed, and power. While many factors impact processor computing performance, clock frequency has been a dominant factor for determining processor performance. The dashed line illustrates what would have happened to microprocessor clocking frequency if increases had continued on their historical trend. The vertical scale is logarithmic. Note the break in the growth rate around 2004. Prior to 2004, processor performance / clock frequency was increasing by a factor of about 100 per decade. In recent years, it has become harder to exploit higher clock speeds to gain significant processing speed, due to several physical issues, including too much heat that is hard to dissipate, too high of power consumption, and high current leakage.

While Moore's law is collapsing with today's transistor technologies, progress in computing will continue in the dimensions of more sophisticated computing architectures (e.g., multi-core processors, embedded application specific micro-coded processing, cache), algorithms (e.g., hyper threading), and other device technologies.

Today, there are two classes of programmable computing engines that are widely used: 1) the Microprocessor (including Digital Signal Processors), and 2) the Field Programmable Gate Array (FPGA). We also have the custom Application Specific Integrated Circuits (ASICs), which is a special purpose computing engine that is not programmable in the general sense. FPGAs tend to be used where the need for reprogramming is important or where economics does not justify developing an ASIC. Properly designed ASICs almost always outperform their FPGA equivalents in terms of speed, power efficiency, and cost, but they often require a very expensive development cycle that is not required for implementations that use off-the-shelf FPGAs.

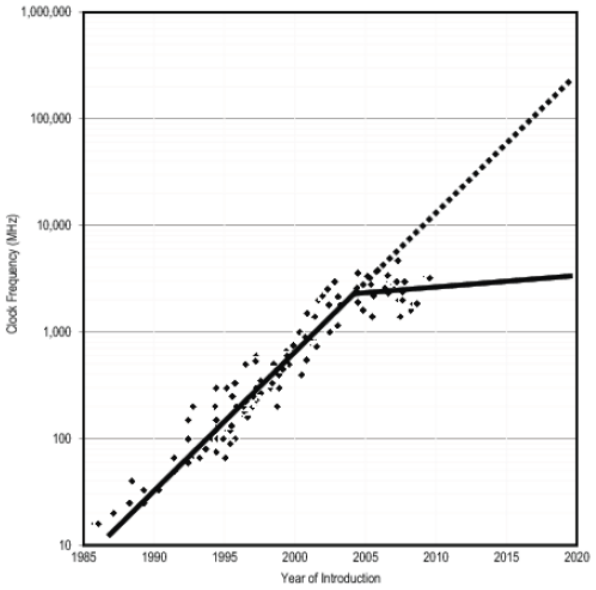


Figure 45 – Microprocessor Clock Frequency Increases Over Time

[Reference: "The Future of Computing Performance: Game Over or Next Level?" The National Academies Press, 2011, Figure S.1, page 9.]

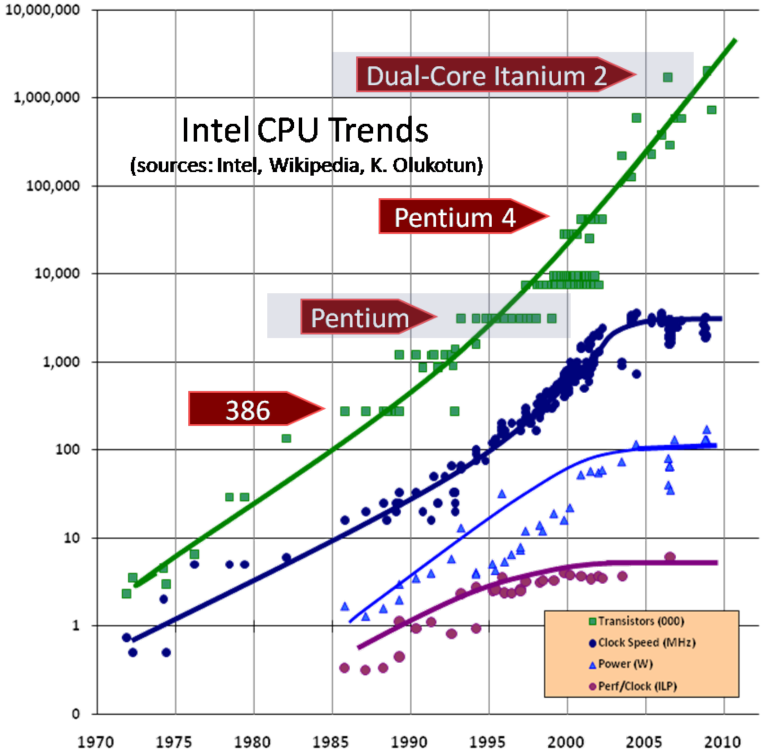


Figure 46 – Historical Increases in Transistor Density, Clock Speed, and Power

[Reference: "The Free Lunch is Over: A Fundamental Turn Toward Concurrency in Software," August 2009, http://www.gotw.ca/publications/concurrency-ddj.htm, by Herb Sutter.]

MathStar was a start-up company (2003 to 2008) that came up with the concept of the Field Programmable Object Array (FPOA). This device retained the programmability of the FPGA but, using an array of parallel processing blocks, achieved nearly the speed, power efficiency, and cost effectiveness of an ASIC. The company developed the FPOA concept to the point of producing prototype devices but succumbed to the general economic downturn of the 2007 recession. The failure of this company does not take away from the brilliance of the FPOA idea and it is inevitable that a similar computing device class will be created and available in the next 50 years. This development is most likely to come from the FPGA Industry as a natural architectural evolution in the same way that the microprocessor industry spawned a wide array of special device classes.

The FPOA concept is ideally suited to the communications digital signal processing role as well as network routing and switching. After this technology is sufficiently matured, it is expected to provide major benefits in signal-in-space spectrum efficiency and network speed for the future air-to-ground and air-to-air NAS communications.

8.2 Advances in Signal Processing

Advances in signal processing, including analog-to-digital (A/D) and digital-to-analog (D/A) converters, higher performance filters, higher performance signal processing, optical receiver front ends, and optical processing will lead to more sophisticated modulation/demodulation, error correction and data compression will continue to push wireless communication capabilities closer to Shannon's Bits/Hz Limit. Harnessing this trend will provide more efficient use of the limited spectrum available for ATS/ATM functions. It will also enable simultaneous reception of entire bands of the spectrum. Rather than tuning a single channel, it will be possible to cost effectively receive all channels in one low cost radio.

Example functions that could benefit from signal processing improvements include:

- ADS-B: ADS-B could be made much more spectrally efficient by developing a waveform specifically for this purpose, rather than today's 1090 MHz extended squitter, which could utilize state-of-the-art signal processing concepts. If combined with the redundancy gained by operating on two (or more) frequencies (e.g., 1030 and 1090 MHz), ADS-B could be designed to have the performance required to provide the sole surveillance information source for Separation Assurance (without Secondary Surveillance Radar backups). ADS-B could be the cornerstone of a revised passive TCAS function to provide the Aircraft Collision Avoidance function that no longer requires on interrogation/reply transmissions further saving spectrum congestion.
- ATM Communication: This is envisioned as wireless communication network using VHF or L-band spectrum (e.g., for the latter, future NAS communications may get an L-band allocation should DME be fully or partially decommissioned or other L-band spectrum become available). This network would be used for enroute ATM communication and is supported by an FAA networked ground infrastructure. The waveform is specifically developed for the compromise of range vs. throughput required for this task. This state-of-the-art IP-based network supports point-to-point machine-to-machine ATM data exchanges as well as point-to-point ADS-C message flow.
- HF Data Radio: HF plays a valuable role in providing backup for availability purposes to satellite based communications in transoceanic and transpolar ATM operations. Advanced Signal Processing concepts applied to HF will improve throughput and HF network performance as the predominant form of ATM communication shifts from voice to data.

- C-Band Ground and Terminal Area Communications Network: The MLS band is repurposed to provide Ground and Terminal Area Communications for which this band is ideally suited. A custom network waveform (e.g., perhaps similar to 802.16) could be developed to optimize its functionality. Other uses of the C-Band to support UAS Control Non-Payload Control (CNPC) would also benefit from signal processing advances to increase the communications bandwidth.
- VHF-DL and Voice: Today's VHF communication frequencies (118 to 137 MHz) are expected to continue to be used for NAS communications, primarily via data link or digital voice, with some limited VHF voice channels. The VHF communications spectrum may at some point in the future be extended to including today's VOR frequencies (112 to 118 MHz) upon de-commissioning of VOR, or in regions where the VOR spectrum is not being used for navigation functions. The VHF Data Link waveform (currently D8PSK) will be updated to enhance its performance (e.g., improve spectral efficiency, reduce re-use distance, and reduce FM interference issues). VHF voice is still expected to be used for simple sport aircraft operating in uncontrolled airspace. Additionally, the capability to provide a modest data service allows local area NOTAMS, Weather Alerts, etc. to be provided to a broad class of aircraft.

8.3 Advances in Software Defined Radios

The current and past generations of aircraft radio products have typically been developed to perform specific very narrow subsets of a single Communication, Navigation, or Surveillance function. Some emerging radios can be dynamically reconfigured to the environment via an onboard processor. The radio may have selectable modulations, standards, protocols, RF bands, IF bandwidths, pre-selector filters, and antennas, that are capable of adaptive smarter spectrum use.

Note: Rockwell Collins has a history of developing digital radio system elements starting in the 1970s and 1980s. One product developed in 1998 for U.S. Customs had a tunable bandwidth from 2 Hz to nearly 2 GHz with options for higher bands. This product was called "Spectrum 2000" and this radio had a complement of modulations, bandwidths filters, and Automatic Link Establishment (ALE) all digitally controlled. Since then there have been many radios developed with digital signal processing providing unique agility to each system including commercial and DoD waveforms.

Over the study time horizon, the technology will mature such that multi-mode / multi-function software defined radios are expected to be the configuration of choice. In the future, it is unlikely that a radio will have such a customized function that it is only used for minutes of a flight (e.g., ILS Localizer, ILS glideslope, marker beacon). Instead, radio resources are expected to be capable of performing a multitude of CNS functions and be readily upgradable (e.g., with a minor software update) to support multiple standards simultaneously. Not only will software defined radios become an economical way to implement a wireless device for the avionics market, but they also allow for relatively inexpensive timely upgrades.

8.4 Advances in Network Technology

In the next 50 years, it will be desirable for ATM/ATS communication to standardize on commercial IP-based networking and thereby retiring the ATN stack. Not only would this make it easier to stay up with vigorously evolving Network Technology but it would also simplify using both private ATM and public commercial networks for ATM/ATS service communications.

Qualcomm is currently pursuing permission to use the Ku commercial SATCOM uplink band for broadband air-to-ground communications for commercial aircraft similar to the services offered by Aircell and GoGo. Such a service could offer a redundant path for ATS/ATM communications thereby improving communications availability in the same way that SATCOM and HF do today for communications in oceanic, remote, and polar regions.

8.5 Low Cost Directional Antennas

Low cost directional antennas enable directional networking that potentially offers a number of advantages over traditional omni-directional antennas. Directional antennas can be realized using a number of technologies, including for example phased array antennas. The benefits of directional antennas include:

- Range extension: By shaping the antenna gain pattern into the desired direction (e.g., toward a ground transmitter or receiver), the effective range of the link can be significantly increased. A 6 dB increase in the antenna gain may double the range.
- Data rate increase: Increased antenna gain can be used to enhance the signal-to-noise ratio, allowing information to be exchanged at higher data rates.
- Power reduction: Increased antenna gain can allow reduced transmit power for a given data rate/range requirement.
- Frequency re-use: By directing the signal power into desired regions and reducing signal power in other regions, this may allow re-use of the frequency at shorter distances.
- Co-site interference reduction: With multiple antennas installed on an aircraft or ground system, directional antennas can be used to reduce undesired interference received at co-site antennas.
- Safety/Security: Directional antenna technology can be used to reduce the influence of undesired signal interference and jammers when such signals are arriving at the antenna at different angles than the desired signal. By maximizing the gain in the direction of the desired signal and/or reducing the gain in the direction of the undesired signal, the region where service is unavailable can be reduced.

8.6 Conformal Antennas

Lower cost, highly capable conformal antenna technology is anticipated to become a mature technology and widely used on aircraft to reduce aerodynamic drag while providing the benefits of the “low cost directional antennas” described in the previous section.

Conformal antennas are one form of phased array antenna that is built from many small antenna elements. A conformal antenna can be designed with its multiple antenna elements to conform to a prescribed shape (e.g., the skin of an aircraft). Each antenna element is driven by a phase shifter to control the phase of the individual antenna elements which allows controlling / forming the resulting beam or beams from the composite of all antenna elements in the desired direction(s). In a receiving antenna, the weak individual signals received by each antenna element are combined in the correct phase to enhance signals coming from a particular direction and reject interfering signals coming from other directions. In a transmit antenna, the radiated signal can be directed toward the receive antenna to increase the receive signal power.

In a conventional phased array, the individual antenna elements are mounted on a flat surface. In a conformal antenna, they are mounted on a curving surface where the phase shifters also need to compensate for the different phase shifts caused by the varying path lengths of the radio waves due to the location of the individual antennas on the curved surface. Because the individual antenna elements must be small, conformal arrays are at frequencies in the UHF to microwave range are more feasible, where the wavelength of the waves is small enough that small antennas can be used.

8.7 Other “Smart” Antenna Technologies

Smart antenna technologies are begin developed that will enable cost effectively moving the entire radio (or at least the radio front end) as close to the antenna as possible to greatly reduce installation losses from RF cables, connectors, splitters, etc. between the antenna and the radio. Some of these losses can be quite significant on very large aircraft (e.g., greater than 15 dB). Eliminating or significantly reducing the installation losses can greatly improve the link budget enabling some combination of increased data rate, longer range, and/or reduced transmit power.

8.8 Chip-Scale High Quality / Low Cost Clocks

Small size, weight, power, and cost (SWaP + C) chip scale clocks that provide the accuracy and stability of today’s atomic clocks are a technology that is rapidly maturing. Today, electronics that need high quality clocks typically use quartz-based clocks, such as Oven-Controlled Crystal Oscillators (OCXOs) and Temperature Compensated Crystal Oscillators (TCXOs). Newer clock technologies will provide many orders of magnitude better time performance (i.e., at or near atomic clock quality) in an acceptably small SWaP + C that will enable solutions that can precisely maintain highly accurate / high integrity time in the presence of GNSS outages / interference. For size, such clocks will be 100 to 10000 times smaller than today’s atomic clocks, weight almost nothing, and consume at most a few thousandths of a watt of power, all for an acceptably low cost.

This technology is expected to become important for future air-to-ground and air-to-air communications [e.g., be able to know the precise time for maintaining communications in the appropriate time slot(s)], navigation [e.g., maintaining precise time for supporting GNSS and alternative PNT systems], and surveillance [e.g., being able to maintain precise time for accurate time of arrival measurements in the presence of GNSS time being unavailable].

8.9 Direct Sampling Radio Technology

Direct sampling radio (DSR) is a maturing technology area that will enable increased radio communications capacity and improved radio functionality. Current analog to digital converter (ADC) technology limitations in the areas of sample rate and effective number of bits (ENOB) are the primary impediments to realizing highly advanced DSRs. DSR can provide significant value by reducing the time required for in-field system reconfiguration and reduce the cost and time for incorporating new functionality. Moving analog frequency down-conversion to the digital domain (DSP, FPGA, or ASIC) allows digital control of both frequency and bandwidth and maximizes system flexibility and re-configurability. It is envisioned that this technology will in the future enable simultaneous sampling and demodulation in their entirety of a plurality and/or mix of satellite transponders (e.g., L, Ku, Ka, V) enabling simultaneous reception of services such as AIS or AIM type information and services such as IFE broadcast and 2-way cabin data.

Note: Rockwell Collins is developing direct sampling radio (DSR) technology based on high resolution, high frequency digitizers as part of a DARPA R&D project called DISARMER (Direct Sampling Digital Radio)]. While this program is military in origin, the technology is extensible to *commercial aeronautical applications. In this project, photonic and electronic component technologies are being leveraged to exploit the best capabilities of both technologies to achieve digitizer performance capabilities that exceed current and projected device improvements. A notion of how it might be integrated in future is indicated in Figure 47.*

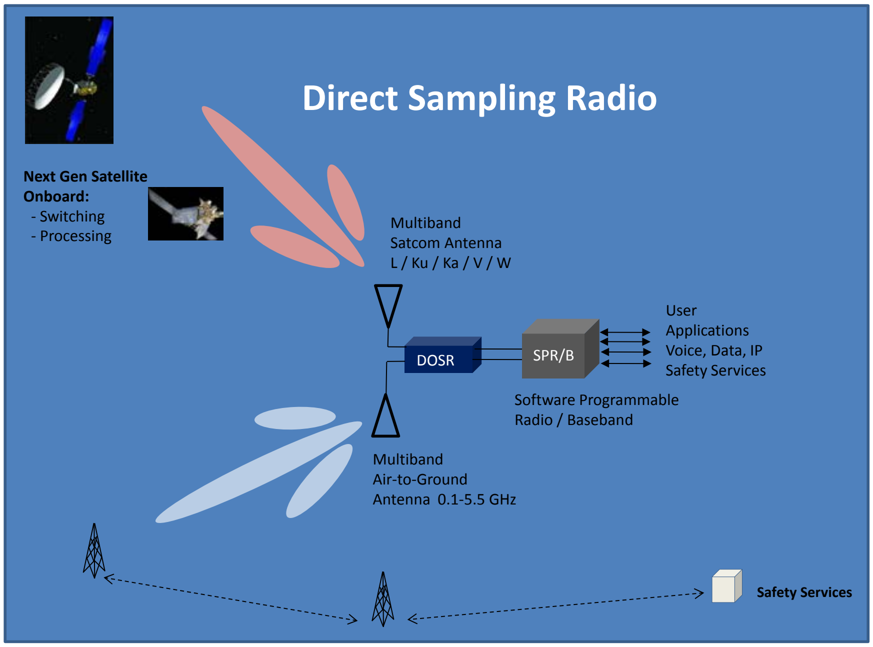


Figure 47 – Direct Sampling Radio

8.10 Multiple Input and/or Multiple Output Transmitters and Receivers

Multiple-input and/or multiple-output transmitters and receivers is a maturing technology that is based upon the use of multiple antennas at either the transmitter or receiver (or both) to improve communications performance of the link. When both the transmitters and receivers have multiple antennas, this is known as multiple-input multiple-output (MIMO). When only either the transmitter or receiver has multiple antennas, it is known as multiple-input / single-output (MISO) and single-input / multiple-output (SIMO), respectively.

Multiple input and/or multiple output wireless communications enables significant increases in data throughput (primarily in the presence of multipath) and link range without additional bandwidth or increased transmit power. This is achieved by spreading the transmit power over the antennas to achieve an array gain that improves the spectral efficiency (more bits per second per hertz of bandwidth) or to achieve a diversity gain that improves the link reliability (reduced fading). Because of these properties, MIMO is an important part of modern wireless communication standards such as IEEE 802.11n (Wi-Fi), 4G, 3GPP Long Term Evolution, WiMAX, and HSPA+.

Such technology could be used to improve the communications performance of future air-to-air and air-to-ground communications systems. For example, it could be used to improve reception of aircraft-to-aircraft communications (like ADS-B) by utilizing two antennas at the receiver (e.g., top and bottom mounted aircraft antennas). Today’s ADS-B Out 1090 MHz broadcast has reception problems on the airport surface. Using multiple receive antennas could improve ADS-B reception, especially on the airport surface, but also airborne.

8.11 Data Compression / Data Acceleration

Data compression involves encoding information using fewer bits than the original representation. Compression can be either lossy or lossless. Lossless compression reduces bits by identifying and eliminating redundancy. No information is lost in lossless compression. Lossy compression reduces bits by identifying and removing marginally important information.

Data acceleration is a lossless process of accepting strings of information (primarily done today with text, but could be applied to data) and replacing them with unique shorter codes. It requires substantial processor resources and is used today for accelerating Internet traffic. It is also used by some SATCOM systems to improve bandwidth. As processors get faster with time and "code books" get deeper, acceleration benefits will improve. Acceleration generally may be followed by compression for additional gain. By 2050 code books will be large enough to cover most internet traffic and the entire world's language pushing non-compression benefit beyond 5X and perhaps peaking and eventually averaging more than 10 to 20X.

Data compression and acceleration are useful for communications systems because they reduce the number of information bits that need to be transmitted to communicate information. However, because data that is compressed / accelerated typically needs to be decompressed / decoded prior to being used, it often requires additional processing.

There are many new techniques being developed that are anticipated to further improve on data compression and acceleration, and thus reduce the overall bandwidth required to communicate information. Such techniques in research and development that may greatly aid in data compression include for example, pattern matching, fuzzy data compression, predictive coding, grammar-based coding, improved probabilistic coding techniques, transform encoding, genetics compression, and multispectral data compression.

It is expected that over the study period, that improvements in data compression and data acceleration may enable significant reductions in the information bits needed to communicate today’s air-to-air and air-to-ground information content.

8.12 Broadband Commercial Connectivity to Aircraft

Commercial broadband communication capabilities for aircraft are being vigorously developed today. In the next 50 years, air-to-ground connectivity is predicted to be greatly enhanced over the initial offerings available today and will provide global service for domestic, transoceanic, and transpolar operations. This capability will be provided by a combination of terrestrial wireless networks and satellites that are descendants of the following current example systems.

- Inmarsat Global Xpress: 1 meter Ka band: 50 Mbps down 5 Mbps up: Transoceanic; Geostationary orbit; system is designed for large air transport aircraft and larger business jets
- Iridium Next: Small dish: L band (subscriber), various up/down rates, Transpolar; Low Polar Earth Orbit; could be used for ATS/ATM communications
- Viasat SkyLink: Ku Band (12 inch dish); Various Mbps down/up; Transoceanic; Geostationary orbit; designed for business aircraft; could potentially be used for ATS/ATM communications

- Broadcast Satellite TV: Small dish, Ku or Ka band; could be used to distribute weather radar data, NOTAMS, and other broadcast ATS services.
- Qualcomm Ground Network: Small antenna; Ku Band; high communications bandwidth down/up; domestic; could potentially be used for ATS/ATM communications

As an example of the increased commercial connectivity to aircraft provided by services, Figure 48 shows the growth in aircraft equipped with Iridium.

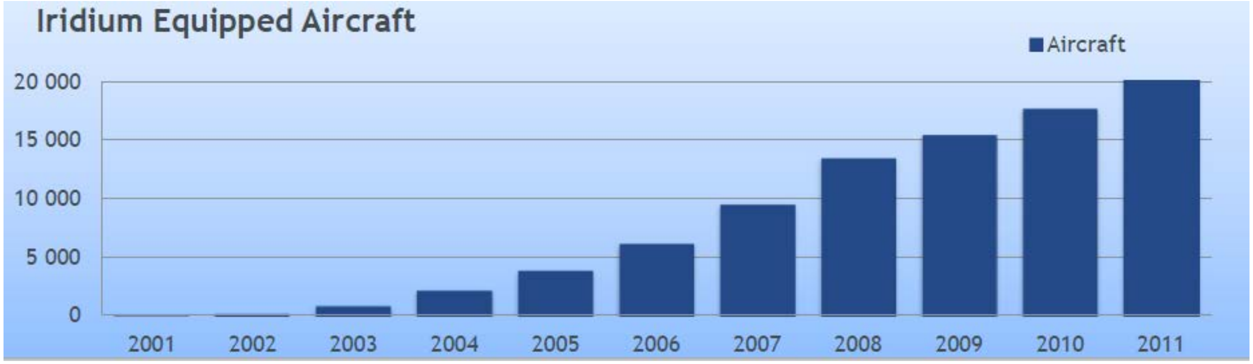


Figure 48 – Iridium Equipped Aircraft Growing

[Reference: "Iridium Now & Next, IDG Aero SATCOM Seminar – Stockholm, Sweden, March 9, 2012, by Jeffrey White, page 11.]

As an example of how broadband connectivity is expected to grow, currently in-flight Internet service is provided with 4 MHz bandwidth in the UHF band (~800 MHz). There is current a proposal by Qualcomm before the Federal Communications Commissions (FCC) to operate air-to-ground Internet service in 14.0 – 14.5 GHz (Ku band) on a non-interference basis with Fixed-Satellite Services (FSS) earth-to-space communications. If this proposal is approved, the spectrum available for in-flight broadband connectivity would grow from 4 MHz (in 2013) to 504 MHz within a few years and could within the next few years provide broadband capacity of up to ~300 gigabits per second. Over the study modernization time horizon of 50 years, broadband connectivity is expected to be enhanced much further than this proposed next step.

8.13 Free Space Optical and Hybrid RF/Optical Communications

Sending data wirelessly with lasers has great potential. Such a technology is referred to as free space optical communications. Free space optical communications transmit their data stream through narrow light beams through the atmosphere between the transmitter and receiver.

A huge potential benefit (under the right conditions) of free space optical communications is very high data rates, on the order of 100 to 1000 times as great than what is achievable with RF data links. Ten gigabytes per second at 100 kilometers is the current benchmark data rate [reference: AOptix] and this will likely go up by 100 to 1000 times or more during the study period. Perhaps the greatest benefit is the ability to reuse the same optical band over and over again – with no or low interference with others because it is a near perfectly bounded beam (directive). Laser outputs propagate like a particle whereas RF propagates as a wave. The directional spectrum reuse benefit of optical communications may especially benefit the surface and terminal area A-G communications. In addition, there are significantly more available frequencies in the light range (~300 GHz) than the radio waves portion of the electromagnetic spectrum (~10 GHz), which provides significantly more total bandwidth to potentially support free space optical communications. Additionally, free space optical technology potentially offers security advantages. The military is interested in maturing free space optical communications to mitigate signal detection and jamming by advisories.

A disadvantage of free space optical communications is that there must be a line of sight between the transmitter and receiver. Atmospheric obscurants (e.g., fog, clouds, haze, dust, snow, rain, etc.) depending upon the intensity and conditions can cause free space optical communication links not to close. Free space optical communications tend to have very narrow beam widths, which results in a challenge to acquire and maintain pointing between transmit and receive antennas, especially on moving platforms. In addition there are concerns with eye safety with optical communications.

Given the high promise of this technology, there are areas that need additional maturation. The sizes of electro-mechanical-optical systems are currently much larger than those for SATCOM antennas. For example, a system several feet in diameter has been designed for pointing optical pointing over a 100 mile range. The system must maintain pointing on the order of micro radians with tracking on the order of microseconds, while the aircraft is being buffeted and rolling. Wider beams require higher power lasers. A return path must also be established for 2-way communications. Some of these challenges have been solved, but a smaller lower cost realization of the system is required. Similar issues are present with pointing SATCOM antennas and are a challenge because the aircraft fuselage and tail flexing are not a currently part of the INS sensor outputs (uncontrolled random decoupling of the airframe with the sensor). In the future, miniaturized, highly accurate, low cost inertial sensors integrated with the antenna are expected to help antenna pointing.

Absorption of the optical bands is well known (see Section 9). Issues such as absorption and scatter rob transmit power reducing link margin for closing a link. Furthermore Rayleigh scattering introduces time variant channels which critically complicate the receive process and limits channel information rate. Research selecting optimal bands or band combinations that use extremely high-speed adaptive digital equalizers will likely lead to future breakthroughs during the study period of 50 years.

Hybrid RF/optical free space communications is a technology area in R&D that is attempting to preserve the advantages of optical communications while overcoming some of the disadvantages. See Figure 51. The RF channel in a hybrid RF/optical link can be used to improve the QoS by providing a backup channel in the presence of atmospheric obscurants and to provide a command channel to acquire and maintain pointing of the optical link antennas. An RF / optical integrated system can be developed to be a future robust bandwidth on demand communications system.

Free space optical communications could be very useful for: 1) uplinking/downlinking information from the Network Operations Center (NOC) to the satellite (if the NOCs are located in regions with relatively few atmospheric obscurants), 2) communications between aircraft and satellites, and 3) cross linking information between satellites.

NASA has a R&D project to demonstrate how free space optical communications technology can be used to link Earth-based ground stations to spacecraft traveling millions of miles away in the solar system. For example, the Mars Reconnaissance Orbiter takes approximately 90 minutes to transmit a single high-resolution image back to Earth at 6 megabytes per second. NASA's proposed optical communications data link could potentially have the capacity to transmit data at 100 megabytes per second or more, and to reduce the single image transmission time to about 5 minutes. The distance between Mars and Earth averages about 225 million kilometers.

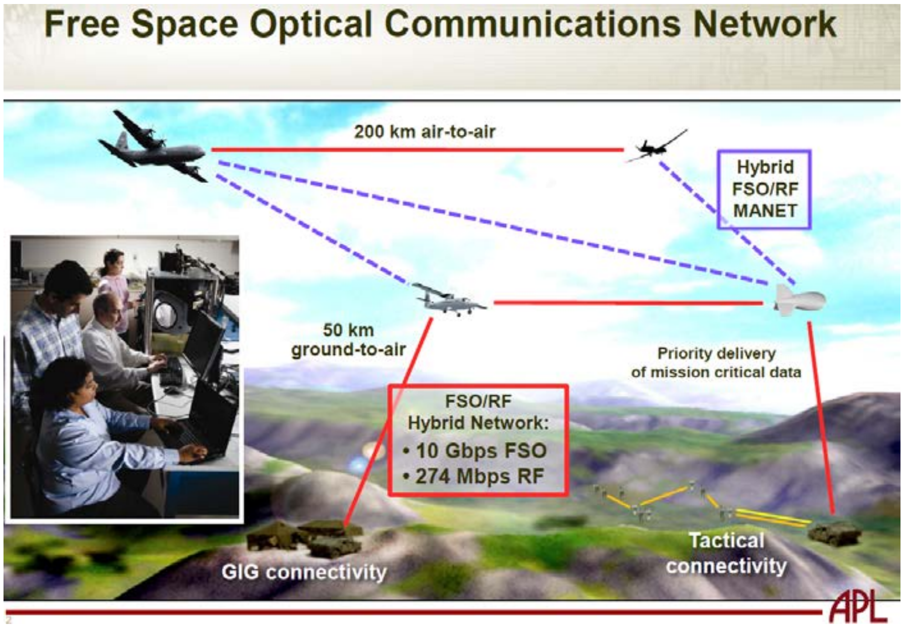


Figure 49 – Free Space Optical Communications

[Reference: Presentation entitled “Hybrid RF Network & Free Space Optical Communications,” by J. Krill and V. McCrary, The Johns Hopkins University Applied Physics Laboratory, circa 2010, page 2.]

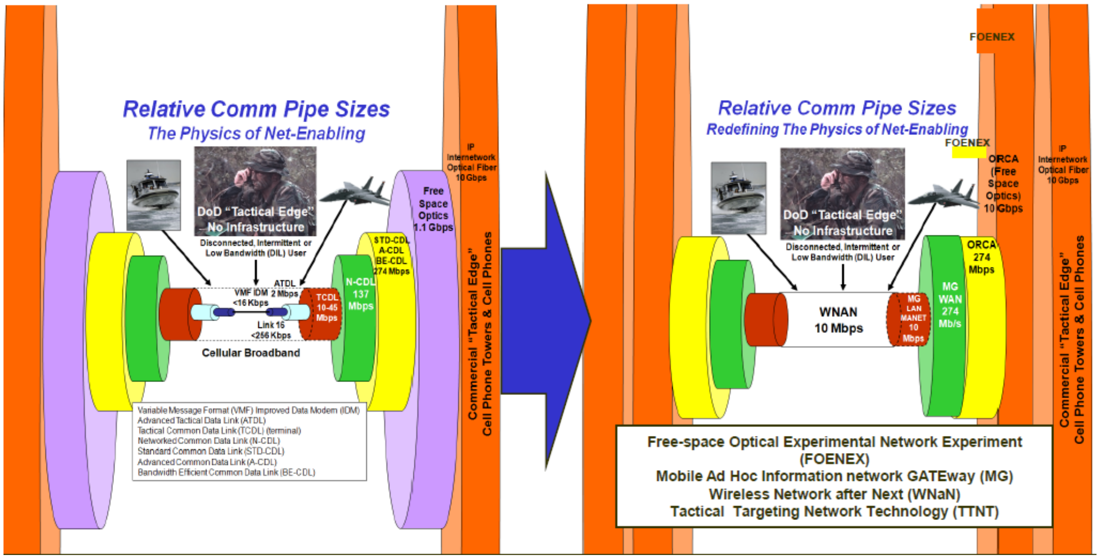
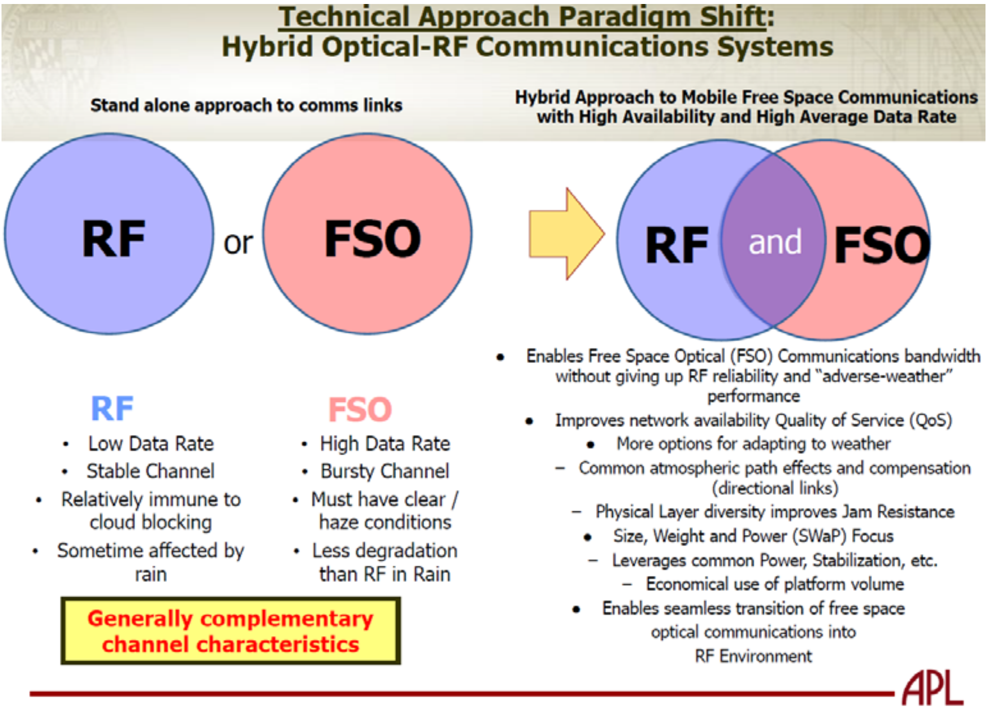


Figure 50 – Free Space Optical Communications Capable of Very High Bandwidths

[Reference: Presentation entitled “Hybrid RF Network & Free Space Optical Communications,” by J. Krill and V. McCrary, The Johns Hopkins University Applied Physics Laboratory, circa 2010, page 3.]



Technical Approach Paradigm Shift:
Hybrid Optical-RF Communications Systems

Stand alone approach to comms links

Hybrid Approach to Mobile Free Space Communications with High Availability and High Average Data Rate

RF

- Low Data Rate
- Stable Channel
- Relatively immune to cloud blocking
- Sometime affected by rain

FSO

- High Data Rate
- Bursty Channel
- Must have clear / haze conditions
- Less degradation than RF in Rain

Generally complementary channel characteristics

- Enables Free Space Optical (FSO) Communications bandwidth without giving up RF reliability and "adverse-weather" performance
- Improves network availability Quality of Service (QoS)
  - More options for adapting to weather
  - Common atmospheric path effects and compensation (directional links)
    - Physical Layer diversity improves Jam Resistance
  - Size, Weight and Power (SWaP) Focus
    - Leverages common Power, Stabilization, etc.
      - Economical use of platform volume
  - Enables seamless transition of free space optical communications into RF Environment

Figure 51 – Hybrid Optical-RF Communications Systems

[Reference: Presentation entitled "Hybrid RF Network & Free Space Optical Communications," by J. Krill and V. McCrary, The Johns Hopkins University Applied Physics Laboratory, circa 2010, page 6.]

8.14 Adaptive / Cognitive Radio Technology

Adaptive or cognitive radios is a technology that potentially enables further spectrum sharing in space and time whereby devices that would like to communicate seek a currently used portion of spectrum. The Defense Advanced Research Projects Agency (DARPA) claimed in 2005 that only 2 percent of the spectrum is in use in the United States at any given moment, even though virtually all the spectrum is allocated *[Reference: Avionics Magazine, Policy-Controlled Radio – Making Room in the Spectrum, by Charlotte Adams, page 34]*.

Adaptive / cognitive radio technology is expected to mature and could potentially be used for NAS communications enabling multiple systems share the same spectrum. By sharing information in near real time for how each system is actually using or intending to use the spectrum, the systems sharing the same spectrum can adapt and not interfere with each other. Thus, the spectrum can be more fully utilized based upon actual use and not based upon how the systems might use the spectrum. Such adaptive spectrum utilization and control techniques could be used to manage system and information priorities. Thus, for example, if spectrum sharing was deployed between radar and air-to-ground communication systems, the radar system may typically have limited spectrum utilization when ADS-B is working well and thus enable A-G communications to utilize most of the shared spectrum. However, when ADS-B aircraft position information is not available (e.g., due to loss of the ADS-B GNSS position source), then radar may need more of the shared spectrum and less would be available for A-G communications.

In the near term, it is not envisioned that cognitive radio spectrum sharing would be certifiable for critical ATM communications, but perhaps it could potentially be acceptable for some A-G or A-A advisory information (e.g., aircraft to AOC communications). In the future as this technology becomes mature and robust, adaptive spectrum sharing may become capable of supporting higher quality of service levels and communicate more than just advisory information.

8.15 Electronic Flight Bags

The wide scale emergence of electronic flight bags into the cockpits of aircraft is a trend that is expected to continue well through the study period. Electronic flight bags are a technology that enables more rapid introduction of new capabilities (e.g., data, information, communications, display, human-machine interface, operations, etc.) on the flight deck and in the future may be used on the ground by AOC or even ATC.

8.16 Artificial Intelligence and Autonomous Systems

Advances in artificial intelligence and autonomous systems technologies will drive changes into the communications connectivity. Machine to machine communications will be commonplace to gather and distribute information necessary for decision support and automation systems that will be applied to the Air Transportation System.

8.17 Information Security

Information security is a technology that will mature during the next 50 years and drive changes in the air-to-air and air-to-ground communication systems. Today's Internet protocols use a communications model that only supports secure point-to-point communications between devices with network addresses. Information security is being expanded to better address building security around the data that is being requested and delivered.

8.18 Higher Transmit Power

The ability to transmit higher power signals is a technology area that will enable transmitting more information in a smaller bandwidth. Higher power will allow higher signal-to-noise ratios that will enable higher order modulations.

8.19 Split Proxy Communication Technology

Split proxy communications technology advancements will better enable communications through two (or more) separate networks (e.g., IP forwarding from one system to another). This technology will allow two (or more) separate networks to be used for seamlessly sending and receiving data. For example, air-to-ground LOS networks could send information and Ku SATCOM could receive. This technology may be used to accommodate latency issues and position location.

8.20 High Speed Optical Transistor

A recent discovery (by the Planck Institute and University of Georgia in December 2012) suggests that electron field manipulation within a SiO_2 crystal by femto-second high-energy pulse lasers will provide a more ideal transistor switch. If this technology matures, it could result in faster electronics and computer systems as well as polymorphic antenna structures, the latter of which supports smaller and more directive antennas in reduced foot prints.

In perhaps 20 years (or less), this “femto-second” light switch could provide for more than 3 to 5 orders magnitude faster “transistor” replacements. Finding ways to integrate the newly discovered physics and its potential spin-offs will be the main effort for a number of years until made practical. Once matured, the impact to DSP and direct sampled radio architectures may result in orders of magnitude faster A/D converters and DSPs which would enable digitizing larger swaths of SATCOM bandwidth with greater dynamic range.

8.21 SATCOM Technologies

A new class of SATCOM systems (generation 4) will include peer-to-peer communications using IP switches. What this means is that client subscribers may directly forward communications through the satellite without the need for tagging or touching base with the Network Operating Center (NOC). This will enable direct aircraft-to-aircraft communications via SATCOM with low latency and high bandwidth. Applications for this may include AIS, AIM, sharing Weather Radar images, etc.

Since many next “generation 4” and beyond satellites will include IP switches, it is predicted that onboard processing will also emerge providing flexible bandwidth resource management. Once this capability matures for mobile applications, new capability coupled with an aircraft software radio will enable powerful aircraft bandwidth on-demand capabilities and more choices with lower cost.

Other SATCOM technologies being matured include use of multiple bands, many tighter “hotter” spot beams, onboard switching / routing, on-board processing, dynamic reallocation of unused BW, BW based on traffic statistics, and statistical multiplexing. Capability will soon reach 100 to 1000 Gbps, with terminal rates from 2-30 Mbps and up to 3 million subscribers. Performance will continue to climb over the modernization period.

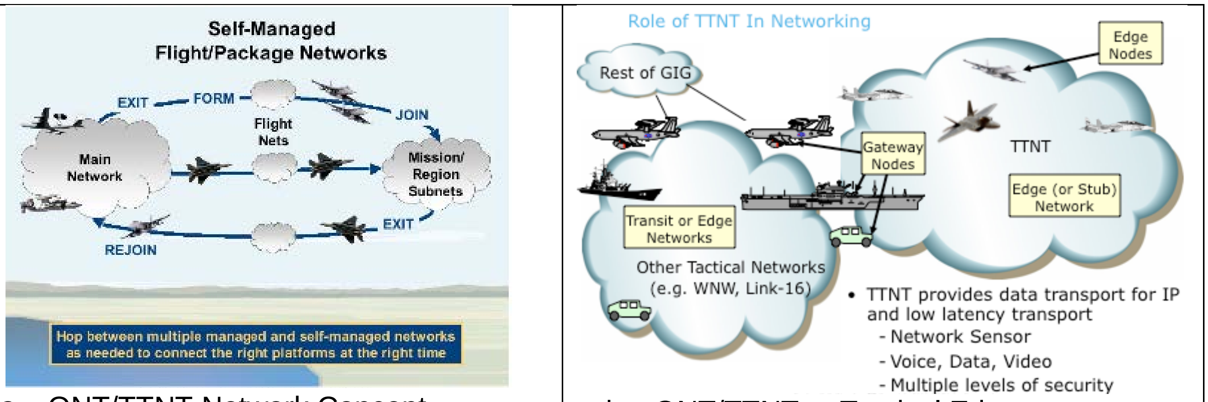
8.22 Band Aggregation

This very important technology trend is being used in HF to cellular bands. It enables smaller disparate channels to be brought together as one virtual data channel. For example, two 10 MHz bands may be aggregated together as one 20 MHz channel.

8.23 Multi-Hop Wireless Aircraft-to-Aircraft Networking Technology

Aircraft-to-aircraft wireless networking is a technology area that is rapidly maturing. For example, the United States Department of Defense (DoD) is developing a sophisticated communications networks known Quint Networking Technology (QNT) that leverages the high bandwidth/low latency Tactical Targeting Network Technology (TTNT) waveform. These systems are in the early stages of fielding. Such technologies may be suitable to support the future needs of NAS data communications, including extending the range of air-to-ground communications from the main networks (e.g., terrestrial air-to-ground VHF) to aircraft in remote regions (e.g., oceanic, remote, or polar) that are connected to the main network via multiple hops between other aircraft platforms in the NAS. This multi-hop networking technology could also be used for air-to-air communications between aircraft that are outside of direct traditional LOS communications.

Figure 52(a) illustrates the QNT/TTNT communications architecture technology currently being developed and matured. Figure 52(b) illustrates how QNT/TTNT supports flight networks away from the main network and mission sub-networks. This provides the ability to connect users at the tactical edge with the main communications networks. The QNT system being developed by the military connects many platforms including manned aircraft, unmanned aircraft, air control, ground users, ships, and other weapon systems. TTNT's role in networking includes transit or edge networks, gateway nodes, and stub networks serving to transport for data, voice, video, and sensor information at multiple levels of security.



a. QNT/TTNT Network Concept

b. QNT/TTNT at Tactical Edge

Figure 52 – QNT/TTNT Multi-Hop Networking Technology

8.24 Huge Decrease in Satellite Launch Costs Predicted

Over the study period, it is envisioned that a number of new technologies will significantly reduce the satellite launch costs. Satellites will become lighter from a wide range of new technologies in electronics, lighter/stronger materials, and reduced need for high weight liquid satellite fuel with enhances in alternative power sources including, for example, solar energy technology. Other technologies being developed and factors that may further reduce satellite launch costs include simultaneously launching a large number of satellites, launching satellites from aircraft platforms, the maturing of low-cost non-rocket space lunch technologies (e.g., such as the proposed circular magnetic satellite launch system concept shown in Figure 53), and increasing competition from commercial entities (e.g., SpaceX and others) that will be capable of successfully launching satellites.

Figure 53 – Magnetic Circular Satellite Launch System

[Reference: LaunchPoint Technologies, http://www.launchpnt.com/portfolio/aerospace/satellite-launch-ring/]

8.25 Plasmonics

Plasmonics is a technology watch area for applicability to future A-A and A-G communications. This technology includes control / generation of a pseudo-wave front of photons and light polarization. It is not fully clear yet how this technology may benefit future NAS communications; however, application to nano-antennas and sensors may become part of an overall efficient integrated antenna concept.

8.26 New Physics (50+ years)

Future discoveries may change our understanding of wave propagation and could enable other communication mechanisms orders of magnitude greater in benefit during the 50 year modernization timeframe for this study. For example, one physics area to watch is the Higgs Field (H-Field) that has recently been discovered. Research may identify possible H-field modulation capability (much as the electron field) leading to coding and decoding of atomic sized / coded messages of enormous capacity. Future H-Field modulation discoveries may help reduce atomic mass / features to "infinitesimal" size, enabling transmission of these atomic codes at the speed of light. Perhaps "wired" implementations will come first followed by wireless. This concept could possibly go beyond the communications limitations expressed by Shannon's information theory associated with today’s understanding of physics. Application may include ultra-high-capacity ground networks (e.g., replacement of multi-Gbit optical fiber to Higgs Field "conduit" with several orders of magnitude greater in capacity) as well as potential application to wireless communications. Moore’s Law may be replaced by a completely new reduction standard. Future application to aviation might find impact first in larger terrestrial networking facilities and eventually into integrated devices and wireless applications.

9 SPECTRUM AND CHARACTERISTICS OF GOOD CANDIDATES FOR AERONAUTICAL COMMUNICATIONS

This section describes the electromagnetic spectrum and identifies those portions of the spectrum potentially suitable to support air-to-air and/or air-to-ground NAS communications. One of the primary technical considerations when identifying suitable candidates in the Electromagnetic Spectrum (EM) is to identify those portions of the spectrum that have appropriate propagation characteristics through the earth's atmosphere and bandwidth to support NAS communications, without emissions that cause harm to occupants or the environment.

9.1 Electromagnetic Spectrum Overview

The electromagnetic spectrum is the set of all frequencies of electromagnetic radiation from essentially DC to Gamma rays as depicted in Figure 54 and Figure 55. This study has considered the suitability of the entire electromagnetic spectrum to potentially be used to support air-to-air and air-to-ground communications.

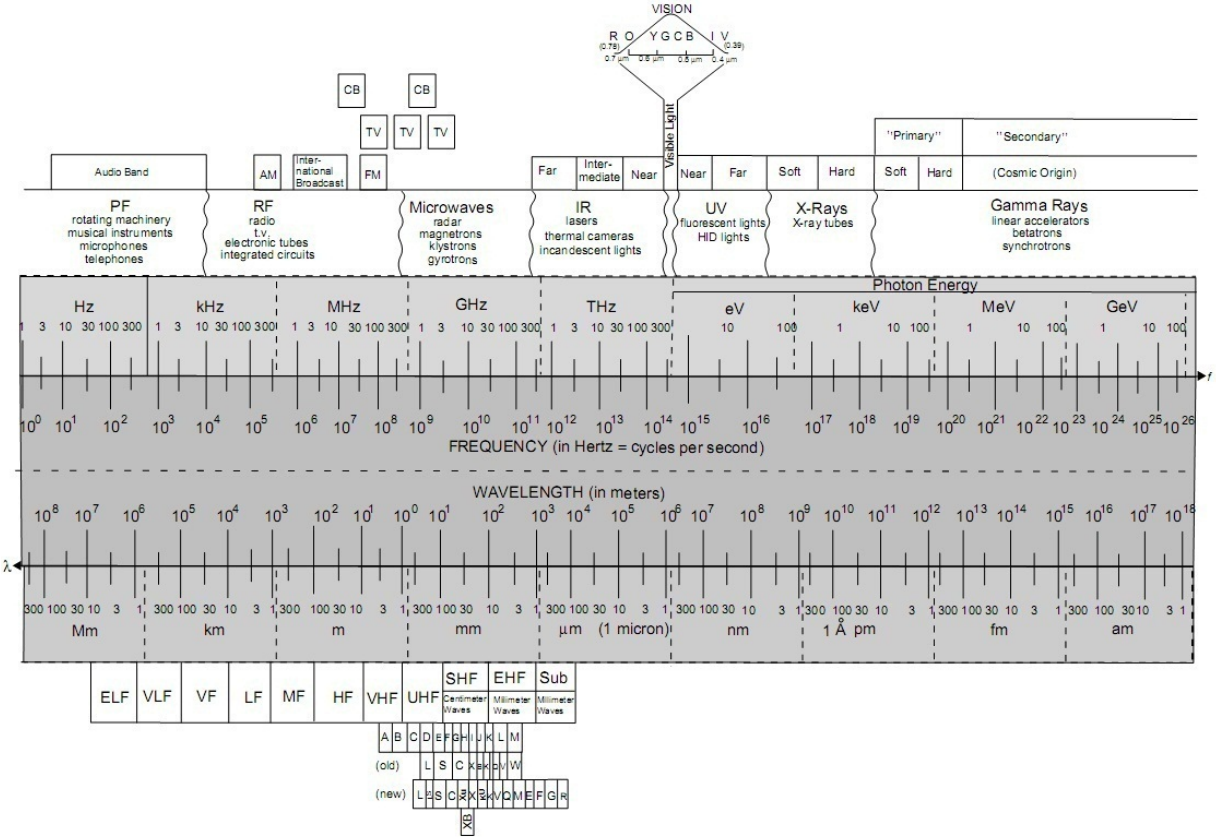


Figure 54 – Electromagnetic Spectrum

[Reference: The Electromagnetic Spectrum, Aleph9 Waveform Research Journal, http://www.aleph9.com/Research/?p=117]

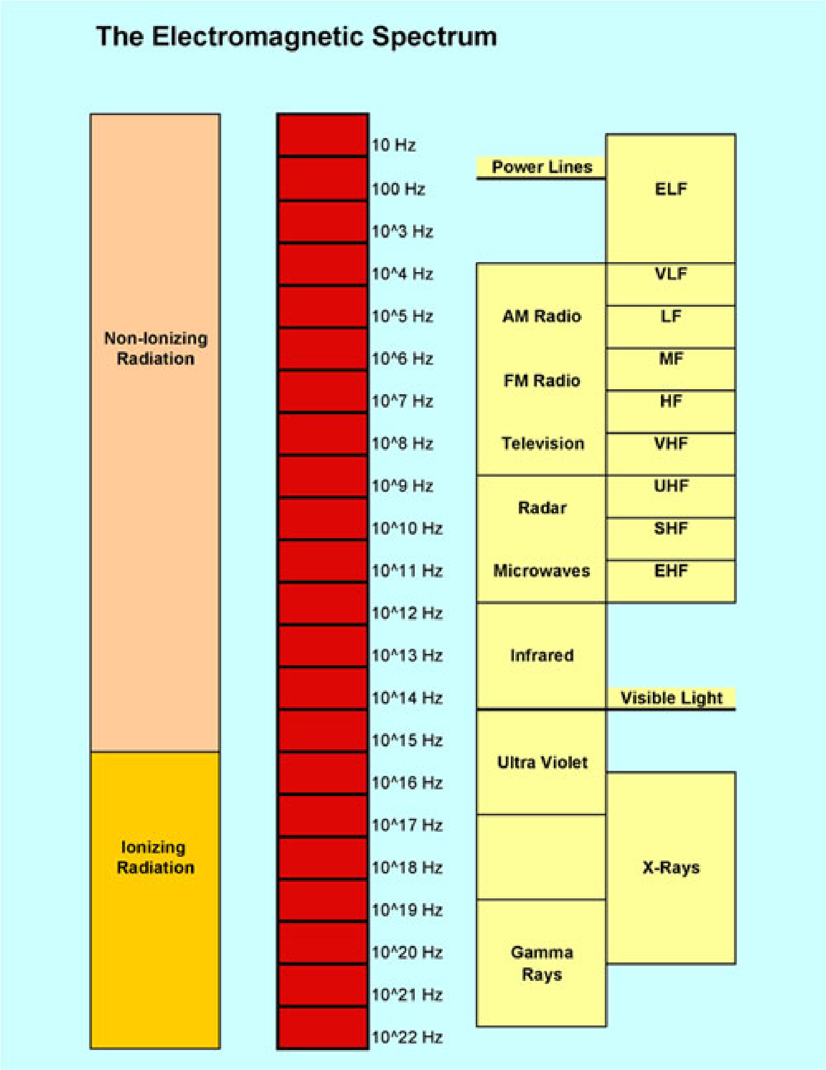


Figure 55 – Electromagnetic Spectrum – Typical Functions

[Reference: UCE Information Systems Corporation, 2008, EMF Safe Home, http://www.emfsafehome.com/electromagnetic_radiation_vancouver.htm]

9.2 Spectrum – a Limited Resource

Spectrum is a limited resource. The radio frequency (RF) spectrum is a portion of all frequencies electromagnetic spectrum and is defined as ranging from 3 Hz to 300 GHz. To prevent interference and allow for efficient use of the radio spectrum, services have been allocated to only use specific frequencies.

Since the evolution of the wireless radio communications, the RF portion of the EM spectrum has become increasingly scarce. There are many potential users of the RF spectrum, who want to be allocated sole use of a portion of it to support a wide range of services including not only aeronautical communication services, but also, for example, TV, radio, wireless broadband, mobile phone/data services, GNSS, emergency services, aeronautical navigation services, surveillance services, weather radars, and a variety of Department of Defense and Department of Homeland Security services.

Allocation of the spectrum among all those who desire to use it is becoming increasingly more difficult as systems have been fielded that have been allocated much of this limited resource and new services are seeking additional allocations of the limited spectrum to be able to provide new or expanded capabilities.

While the spectrum is limited, it is a resource that cannot be stored or conserved for future use. The same spectrum is potentially available at any particular instant in time. If the spectrum is not used at each point in time, it is a lost opportunity. The resource is susceptible to interference, whether intentional or unintentional, naturally occurring or man-made, which can nullify its utility. The usage of the limited spectrum needs to be appropriately managed so that all the intended services and applications can co-exist without harmful interference.

With the anticipated exponential increase in demand on the limited and scarce natural resource of spectrum (especially the RF spectrum), it is inevitable that all wireless users should use this resource most efficiently.

Many existing users of the RF spectrum (including aviation) will over time likely need to modernize their systems to improve their spectrum efficiency to enable the spectrum to meet additional future demands.

9.3 Spectrum Overview

For convenience sake, the entire spectrum has been segregated into bands of frequencies as indicated in Figure 56. Figure 57 expands on the classifications and identifies some example uses for how that spectrum is being used today.

Band		Frequency	Wavelength
Radio	HF	3 – 30 MHz	100 to 10 m
	VHF	30 – 300 MHz	10 to 1 m
	UHF	300 – 1000 MHz	1 to 0.3 m
	L	1 – 2 GHz	30 to 15 cm
	S	2 – 4 GHz	15 to 7.5 cm
	C	4 – 8 GHz	7.5 to 3.75 cm
	X	8 – 12 GHz	3.75 to 2.5 cm
	Ku	12 – 18 GHz	2.5 to 1.67 cm
	K	18 – 27 GHz	1.67 to 1.11 cm
	Ka	27 – 40 GHz	1.11 to 0.75 cm
	V	40 – 75 GHz	7.5 to 4 mm
	W	75 – 110 GHz	4 to 27 mm
	G	110 – 300 GHz	27 to 1 mm
Infrared		300 GHz – 430 THz	1 mm to 0.6 µm
Visible		430 – 790 THz	0.6 µm to 0.3 µm
UV		790 THz – 30 PHz	300 to 10 nm
X-Ray		30 PHz – 30 EHz	10 nm to 0.01 nm
Gamma-Ray		> 10 EHz	Less than 0.01 nm

Figure 56 – Electromagnetic Spectrum Band Designations

Band	Band Name	Frequency	Example Uses
TLF	Tremendously Low Frequency	< 3 Hz	Electronic noise
ELF	Extremely Low Frequency	3 - 30 Hz	Submarine communications
SLF	Super Low Frequency	30 - 300 Hz	Submarine communications
ULF	Ultra Low Frequency	300 - 3000 Hz	Submarine communications
VLF	Very Low Frequency	3 - 30 kHz	Submarine communications
LF	Low Frequency	30 - 300 kHz	AM long wave broadcasting (Europe), amateur radio
MF	Medium Frequency	300 - 3000 kHz	AM (medium wave) broadcasting, amateur radio
HF	High Frequency	3 - 30 MHz	Over the horizon aviation communications, shortwave broadcasts, over the horizon radar
VHF	Very High Frequency	30 - 300 MHz	Air-to-ground communications (118 to 136 MHz), VOR (112-118 MHz), ILS Localizer (108-112 MHz), ELT (121.5 MHz), FM radio, TV channels 2-13
UHF	Ultra High Frequency	300 – 1000 MHz	ILS Glideslope (328.6 to 335.4 MHz), ELT (406 MHz), UHF TV, microwave ovens, mobile phones
L	Long Wave	1 to 2 GHz	GPS (L1: 1575.42 MHz, L2: 1227.6 MHz, L5: 1176.45), GNSS, SATCOM (1530 – 1660 MHz)
S	Short Wave	2 to 4 GHz	Mobile satellite, amateur radio
C	Compromise between S and X Band	4 to 8 GHz	MLS, radio location, satellite
X	---	8 to 12 GHz	Weather radar, radio location
Ku	Kurz-under	12 to 18 GHz	SATCOM, space research
K	Kurz	18 to 27 GHz	Satellite, radio astronomy
Ka	Kurz-above	27 to 40 GHz	SATCOM, standard frequency and time signal
V	---	40 - 75 GHz	Space research, satellite
W	---	75 to 110 GHz	Space research, radio astronomy
G	---	110 to 300 GHz	Space research, radio astronomy
SHF	Super High frequency	3 – 30 GHz	SATCOM, MLS, Radio Altimeter (4.2 to 4.4 GHz), radars, AeroSat, satellite television, wireless LAN
EHF	Extremely High Frequency	30 – 300 GHz	Radio astronomy, microwave radio relay
THF or THz	Tremendously High Frequency or Terahertz	300 – 3000 GHz	Terahertz imaging

Figure 57 – Electromagnetic Spectrum Bands and Example Uses

9.4 Radio Frequency Allocations

Spectrum is a key element of wireless communications systems and needs to be managed with great care. The use of the radio spectrum is regulated, access is controlled, and rules for its use are enforced because of the possibilities of interference between uncoordinated uses.

The spectrum in the United States is managed and controlled by the National Telecommunications and Information Administration (NTIA) for federal users and the Federal Communications Commission (FCC) for non-federal users. Federal users include for example the aviation, national defense, law enforcement & security, transportation, etc. Non-federal users include businesses, state and local governments, as well as commercial and private users.

Spectrum in the United States relevant to civil aviation is sub-managed and controlled by the FAA (specifically the FAA Spectrum Engineering Services Office) within the spectrum allocation and conditions established by the NTIA. The FAA Spectrum Engineering Services Office works to secure, manage, and protect all civil aviation radio frequency spectrum resources.

Aviation Spectrum Resources, Inc. (ASRI) is responsible for managing the Aeronautical enroute VHF spectrum including 128.825 – 132.00 MHz and 136.500 – 136.975 MHz and the Long Distance Operational Control (LDOC) HF spectrum in the United States. This aeronautical spectrum is used by aircraft operators to fulfill their requirements for AOC communications. Management of these spectrum resources includes coordinating and licensing of approximately 5000 ground stations; 200 new assignments; 200 modifications, and 1000 license renewals per year.

The international spectrum is managed by a specialized agency of the United Nations called the International Telecommunications Union (ITU). In addition, a second specialized agency of the United Nations called the International Civil Aviation Organization (ICAO) is responsible for managing the aviation spectrum.

Internationally, the spectrum is allocated as part of periodic worldwide treaty conferences, called World Radio Conferences (WRC). The WRC is made of delegates from member states and supporting international agencies (e.g., ITU, ICAO).

The NTIA, FCC, FAA, ASRI, ICAO as well as other organizations work with the ITU to coordinate the shared global use of the radio spectrum that is allocated by the WRC. The allocations of the radio frequencies in the United States are depicted in Figure 58 below. As illustrated by the chart, very little of the radio frequency spectrum from 3 kHz to 300 GHz is not already allocated.

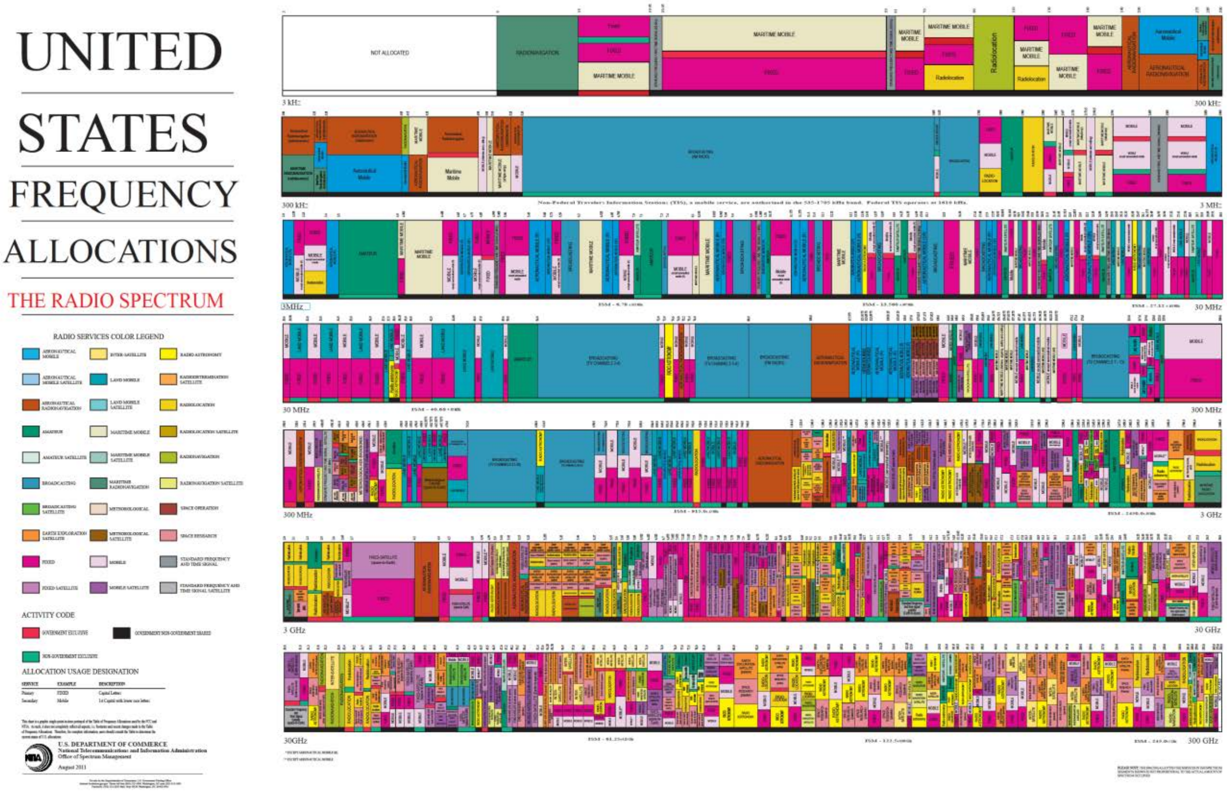


Figure 58 – Radio Frequency Allocations as of August 2011

[Reference: National Telecommunications & Information Administration (NTIA), http://www.ntia.doc.gov/files/ntia/publications/spectrum_wall_chart_aug2011.pdf]

9.5 Electromagnetic Radiation Effects

9.5.1 Ionizing / Non-Ionizing Radiation

At frequencies in the EM spectrum starting with ultra violet (UV) radiation and above as depicted in Figure 59, the ionizing radiation caused by the use of these frequencies can be hazardous to humans and other living organisms since the ions that are produced by ionizing radiation, even at low radiation powers, have the potential to cause DNA damage to living tissue potentially resulting in mutation, radiation sickness, cancer, and death. As such, the frequencies where there is ionizing radiation (including all of the bands including X-Rays, Gamma Rays, and the upper portion of UV bands) would not be good candidates for radiating signals to support air-to-air and air-to-ground wireless communications.

Ionizing radiation has sufficient energy to dislodge orbital electrons from atoms or molecules, whereas non-ionizing radiation does not. Ionizing radiation is hazardous to living organisms.

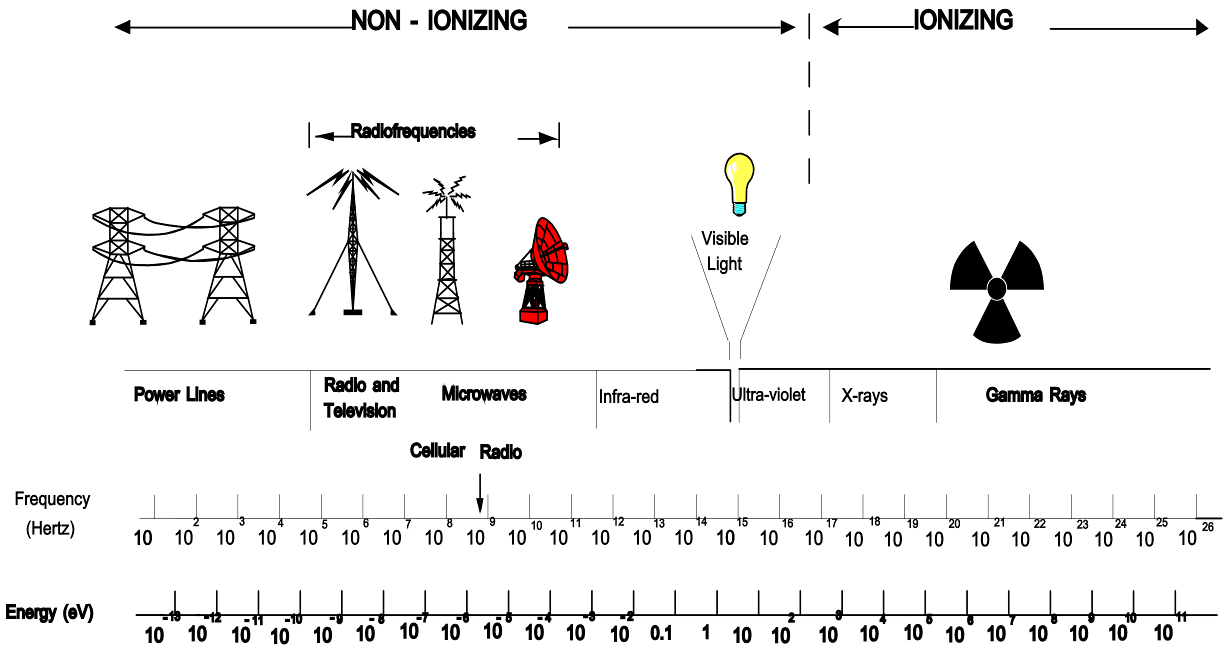


Figure 59 – Ionizing / Non-Ionizing Portions of Electromagnetic Spectrum

[Reference: Federal Communications Commission – Questions and Answers about Biological Effects and Potential Hazards of Radio Frequency Electromagnetic Fields, August 1999, page 3.]

9.5.2 Atmospheric Windows

The atmospheric attenuation of electromagnetic waves varies significantly with frequency. The earth's atmosphere, due to the many different gases and particles that it contains, absorbs many different wavelengths of electromagnetic radiation. The wavelengths that pass through the atmosphere, with lesser absorption constitute atmospheric windows that are often highly used for communications.

Electromagnetic radiation is reflected or absorbed mainly by several gases in the Earth's atmosphere, including water vapor, carbon dioxide, and ozone. Some radiation, such as that in the radio spectrum, infrared, and visible light regions, largely passes (i.e., is transmitted) through the atmosphere. Regions of the spectrum with wavelengths that can pass through the atmosphere are referred to as "atmospheric windows", as depicted in Figure 60. Another way to present the concept of atmospheric windows is consider the atmospheric opacity (see Figure 61), where having an atmospheric opacity much smaller than 100% for a signals of a given wavelength (or frequency) means that the atmosphere allows the signal to easily pass through it, and where the atmospheric opacity is relatively large or near 100% means that the atmosphere effectively blocks the signal.

Above 300 GHz, the absorption of electromagnetic radiation by Earth's atmosphere is so great that the atmosphere is effectively opaque, until it becomes transparent again in the near-infrared and optical window frequency ranges.

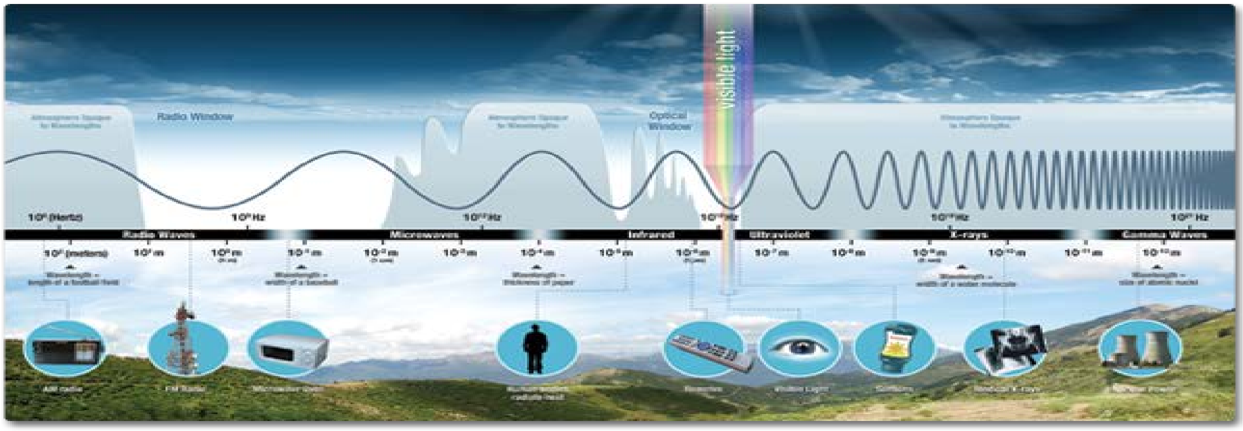


Figure 60 – Atmospheric Windows

[Reference: NASA from web site http://missionscience.nasa.gov/ems/01_intro.html.]

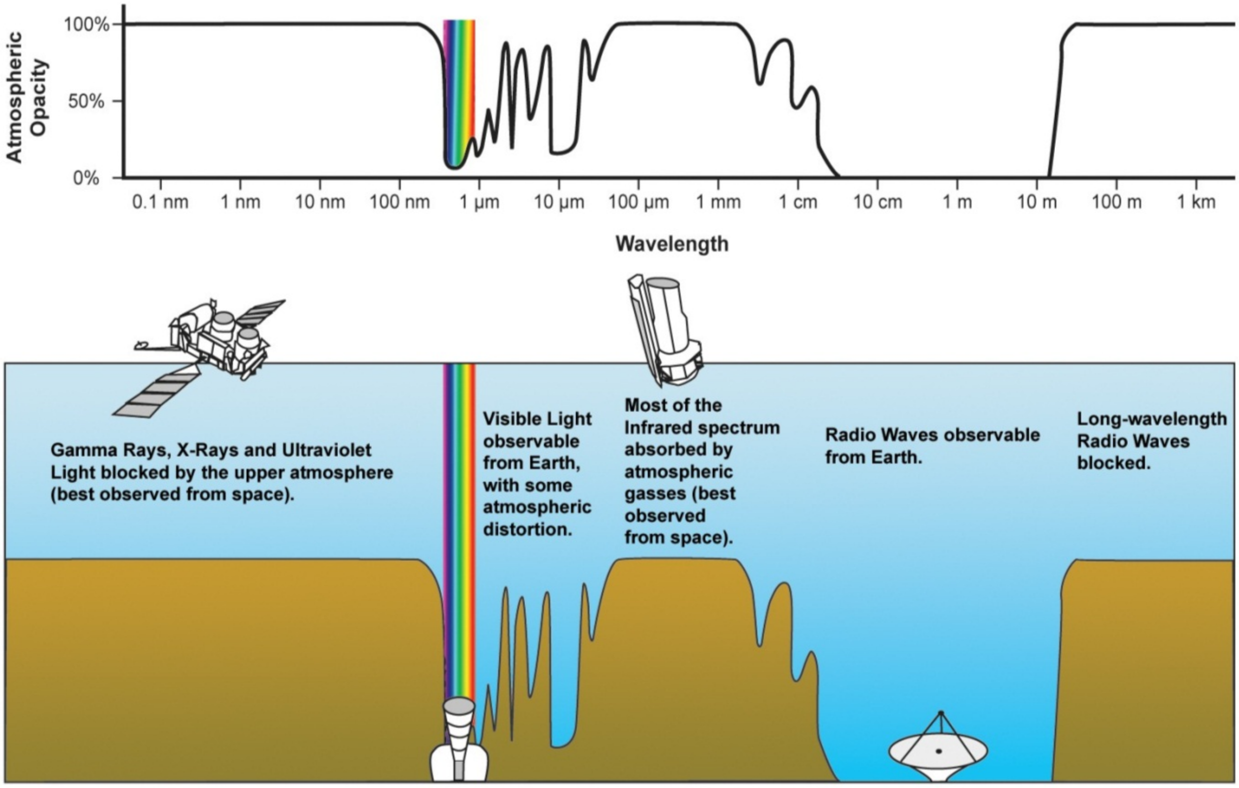


Figure 61 – Atmospheric Opacity

[Reference: NASA as posted by Wikipedia.]

Figure 62 below is a generalized diagram that shows the relative atmospheric radiation transmission of different wavelengths. The blue colored zones in the figure mark the minimal passage of the radiated signal, whereas the white areas denote atmospheric windows in which the radiated signal has much less interaction with the atmosphere, and hence has less atmospheric absorption.

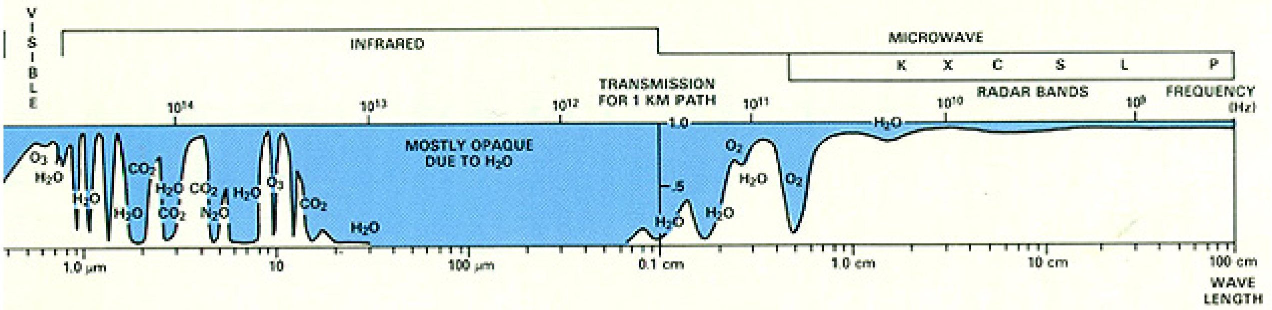


Figure 62 – Atmospheric Absorption

[Reference: Federation of American Scientists, The Remote Sensing Tutorial, http://www.fas.org/irp/imint/docs/rst/Intro/Part2_4.html]

Figure 63 below similarly shows the relative atmospheric attenuation due to gases and particles in the atmosphere in dB per kilometer for frequencies ranging from HF to UV. Frequencies in the HF to K band as well as frequencies in the infra-red and visible light regions have relatively low attenuation.

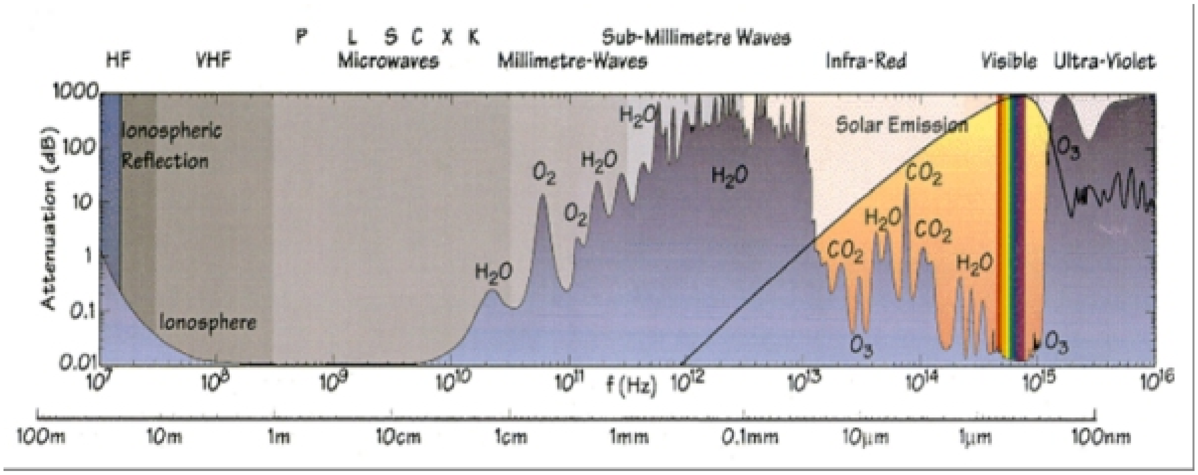


Figure 63 – Atmospheric Attenuation

[Reference: Credit to the European Space Agency (ESA), as cited from http://www.altimetry.info/html/alti/principle/frequencies/welcome_en.html]

9.5.3 Propagation of Electromagnetic Waves

[Reference: Communication Systems Engineering, Prentice-Hall, Inc., by John G. Proakis and Masoud Salehi, pages 15-21.]

The mode of propagation of electromagnetic waves in the atmosphere and free space can be divided into three propagation categories, including: 1) ground-wave, 2) sky-wave, and 3) line-of-sight (LOS). In the VLF and ELF frequency bands, where the wavelengths exceed 10 km, the earth and the ionosphere function as a waveguide for the propagation of the electromagnetic waves. In these frequency ranges, communication signals practically propagate around the entire earth. Thus, these frequency bands have been primarily used to provide navigational aids from short to ships around the world. The channel bandwidths available in these frequency bands are relatively small.

9.5.3.1 Ground Wave Propagation

Ground-wave propagation is the dominant mode of propagation for frequencies in the MF band (0.3 to 3 MHz). This is the frequency band used for AM and maritime radio broadcasts. In AM broadcasting, the range with ground-wave propagation, even with the more powerful radio stations is limited to ~100 miles. The reason is that atmospheric noise, main-made noise, and thermal noise from electronic components at the receiver are dominant disturbances.

9.5.3.2 Sky Wave Propagation

Sky-wave propagation results from signals being reflected (bent or refracted) by the ionosphere, which is that portion of the earth's atmosphere that consists of several layers of charged particles ranging from 30 to 250 miles above the earth. During the daytime hours, the heating of the lower atmosphere by the sun causes the formation of the lower layers at altitudes below 75 miles. These lower layers absorb frequencies below 2 MHz, thus severely limiting sky-wave propagation of AM radio broadcasts. However, during the night-time hours, the electron density in the lower layers of the ionosphere drops sharply which significantly reduces the frequency absorption that occurs during the daytime. As a consequence, powerful AM radio broadcast stations can propagate over large distances.

A frequent problem with propagation via sky wave propagation in the HF frequency range is signal multipath. Signal multipath occurs when the transmitted signal arrives at the receiver via multiple propagation paths at different times. Multipath generally results in inter-symbol interference in digital communication systems, and it causes signal fading when the signal components arrive via different propagation paths and add destructively.

Sky-wide ionospheric propagation ceases to exist at frequencies above approximately 30 MHz, which is at the high end of the HF band. However, ionospheric scatter propagation can occur at frequencies in the range of 30 MHz to 60 MHz. It is possible to communicate over distances of several hundred miles by use of tropospheric scattering at frequencies in the range of 40 MHz to 300 MHz. Tropospheric scatter results from signal scattering due to particles in the atmosphere at altitudes of 10 miles or less. Wireless communications systems that rely on ionospheric or tropospheric scattering to communicate over long ranges require a large amount of transmit power.

9.5.3.3 Line of Sight Propagation

For frequencies above 30 MHz, the dominant mode of propagation is line-of-sight (LOS), since such frequencies propagate through the ionosphere with relatively little loss. For terrestrial communication systems, the transmitter and receiver antennas must be in direct LOS with relatively little or no obstructions.

In general, the coverage area for LOS propagation is limited by the curvature of the earth. If the transmitting antenna is mounted at a height (*h*) feet above the surface of the earth, the distance (*d*) in miles to the radio horizon, assuming no physical obstructions such as mountains, buildings, or other structures is approximately:

LOS radio horizon: $d = \sqrt{2h}$

where: $d =$ LOS radio distance in miles

$h =$ Height above earth's surface in feet

The dominant noise limiting the performance of communications systems in the VHF and UHF frequency ranges is thermal noise generated in the receiver front end and cosmic noise picked up by the antenna.

9.5.4 Free Space Attenuation

Free space attenuation is commonly referred to as Free Space Path Loss (FSPL). FSPL is defined as the loss in signal strength of an EM wave from line-of-sight propagation of the signal in "free space" with no obstacles that cause reflection or diffraction of the EM wave. FSPL would occur in a vacuum under ideal conditions.

For an isotropic radiator (i.e., one that propagates the EM wave uniformly in all directions), the FSPL can be computed as:

$$FSPL = 20\log_{10}(D_{km}) + 20\log_{10}(f_{GHz}) + 92.45\,dB$$

where: $FSPL$ = Free Space Path Loss (in dB)

D_{km} = distance between transmit and receive antennas (in km)

f_{GHz} = transmit frequency (in GHz)

The above FSPL equation does not include factors such as the gain of the antennas used at the transmitter and receiver, atmospheric attenuation losses, or losses associated with transmiter and receiver hardware imperfections which are commonly included in a communications link budget. Atmospheric attenuation losses due primarily to standard atmospheric gases and weather effects are discussed in Section 9.5.5.

Figure 64 contains a plot of the FSPL signal attenuation for transmit frequencies ranging from 10 kHz to 10 THz and for communications LOS ranges (or distances) between transmit and receive antennas from 0.1 to 1000 km.

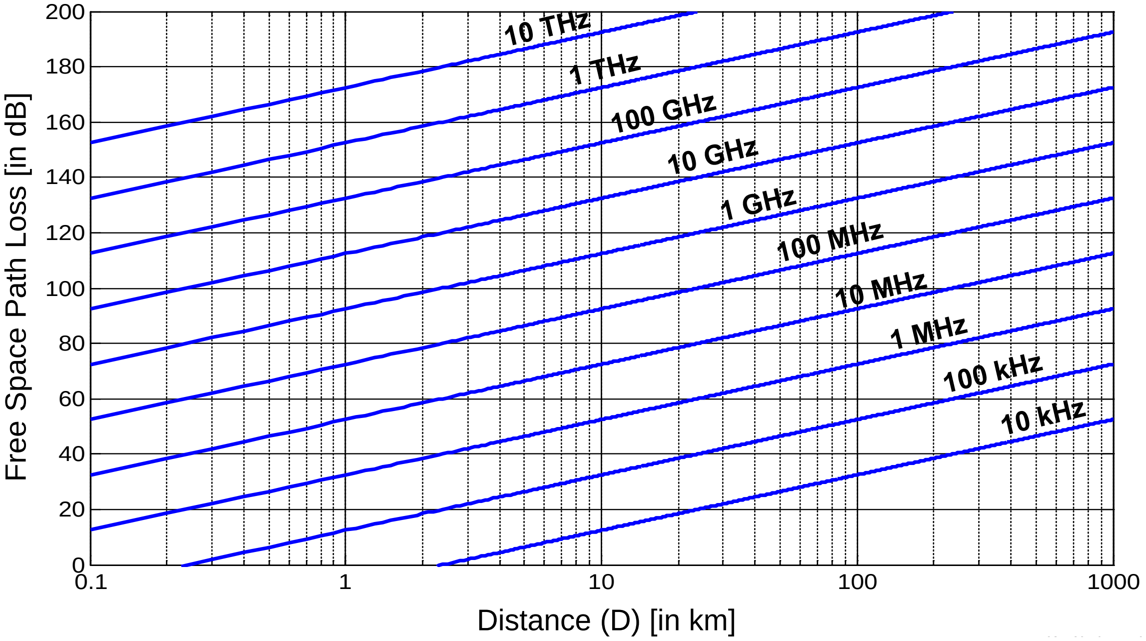


Figure 64 – Free Space Path Loss for Isotropic Radiator

9.5.5 Atmospheric Attenuation

The atmospheric attenuation of radio waves varies significantly with frequency. The specific attenuation due to dry air and water vapor, from sea level to an altitude of 10 km, can be estimated using algorithms documented in the International Telecommunication Union – Radio communication sector (ITU-R) Recommendation ITU-R P.676-9 entitled "Attenuation by atmospheric gases. Figure 65 shows the specific attenuation for signals at frequencies ranging from 1 to 350 GHz for dry air (red curve) and for water vapor with a density (ρ_{H_2O}) of 7.5 g/m^3 (blue curve) and the total of both (black curve).

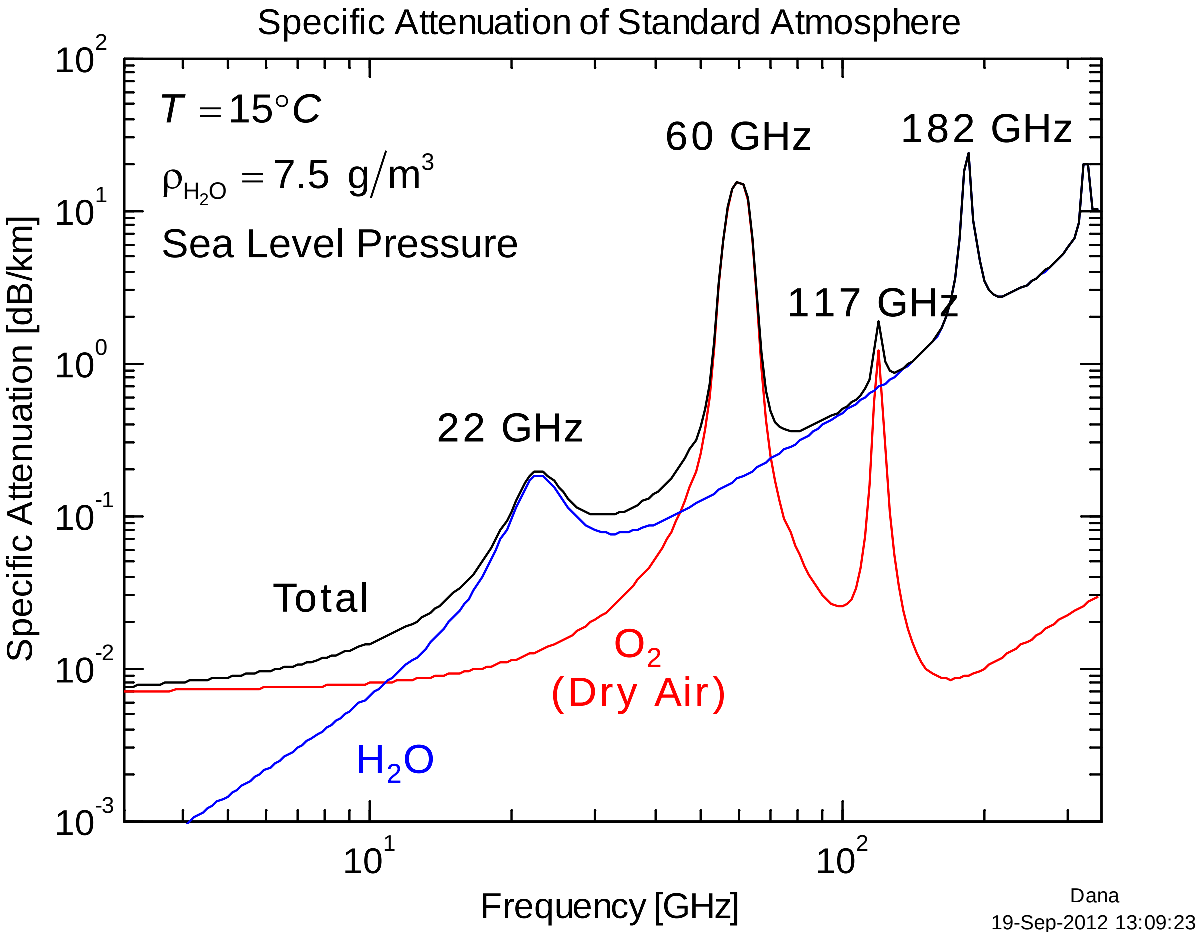


Figure 65 – Attenuation (in dB/km) Due to Atmospheric Gases

[Reference: Attenuation by Atmospheric Gases, Recommendation ITU-R Report P.676-9, dated 02/2012, Figure 5, as plotted by Roger Dana from Rockwell Collins.]

In addition to atmospheric gases, at frequencies of ~5 GHz and higher, other atmospheric conditions (including for example rain, fog, clouds, etc.) can significantly attenuate the signal and limit signal propagation ranges. Figure 66 illustrates the signal attenuation in dB/km due to various precipitation (rain) rates for frequencies in the range of 1 to 1000 GHz. Another source for signal attenuation as a function of rain rate is provided in Figure 67. Notice that rain can introduce high propagation losses (> 1dB per km) for frequencies at and above ~5 GHz.

Figure 68 illustrates the signal attenuation in dB/km due to both atmospheric gases and environmental conditions including rain and fog over the frequency range of 10 GHz to 1000 THz. At frequencies of the order of 100 GHz and above, attenuation due to fog and clouds may be significant. The liquid water density in fog is typically about 0.05 g/m^3 for medium fog (visibility of the order of 300 m) and 0.5 g/m^3 for thick fog (visibility of the order of 50 m). Thick fog yields an almost negligible attenuation at frequencies below 10 GHz. Contrast this situation to free space optical (FSO) systems. Since FSO optical signals have wavelengths on the same order of magnitude as the small fog and cloud particles, attenuations on the order of 200 dB/km can be experienced with heavy fog in the FSO transmission path.

Airborne dust, sand, and other small particles tend to have an effect similar to fog and clouds on the propagation of electromagnetic radiation. Such atmospheric obscurants affect infrared and optical signals much more than radio wave signals.

<u>Thus, to support communications that desire long range propagation through the atmosphere in the presence of rain and other environmental effects, it is desirable to select a frequency less than ~ 5 GHz and certainly less than 10 GHz to avoid high levels of attenuation.</u>

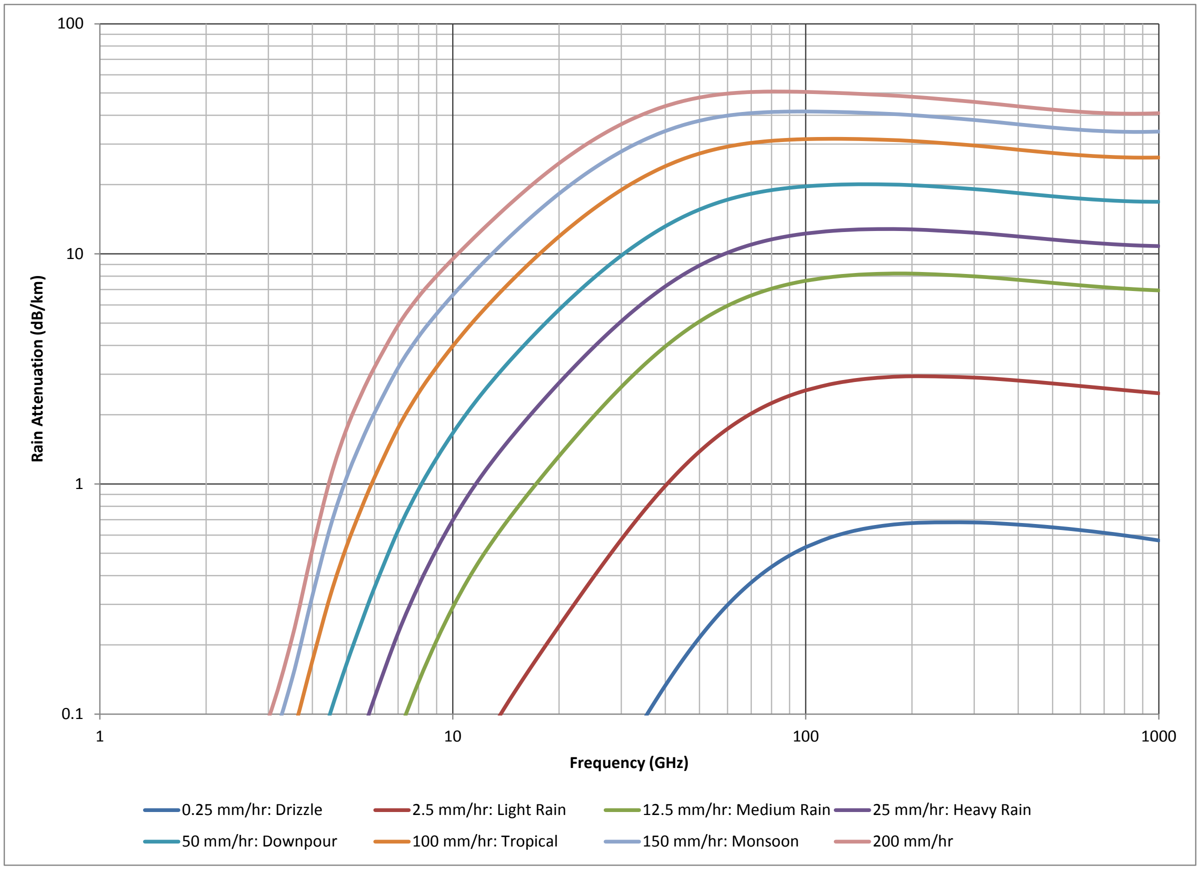
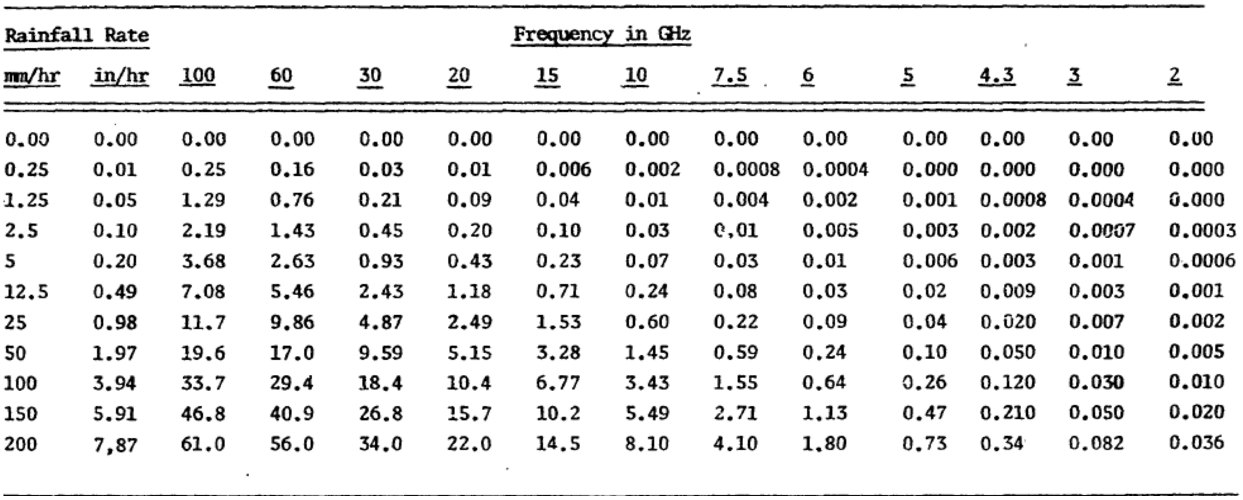


Figure 66 – Attenuation (in dB/km) Due to Various Rain Rates Plot

[Reference: "Specific attenuation model for rain for use in prediction methods," Recommendation ITU-R Report P.838-3, dated 2005.]



Rainfall Rate		Frequency in GHz											
mm/hr	in/hr	100	60	30	20	15	10	7.5	6	5	4.3	3	2
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.01	0.25	0.16	0.03	0.01	0.006	0.002	0.0008	0.0004	0.000	0.000	0.000	0.000
1.25	0.05	1.29	0.76	0.21	0.09	0.04	0.01	0.004	0.002	0.001	0.0008	0.0004	0.000
2.5	0.10	2.19	1.43	0.45	0.20	0.10	0.03	0,01	0.005	0.003	0.002	0.0007	0.0003
5	0.20	3.68	2.63	0.93	0.43	0.23	0.07	0.03	0.01	0.006	0.003	0.001	0.0006
12.5	0.49	7.08	5.46	2.43	1.18	0.71	0.24	0.08	0.03	0.02	0.009	0.003	0.001
25	0.98	11.7	9.86	4.87	2.49	1.53	0.60	0.22	0.09	0.04	0.020	0.007	0.002
50	1.97	19.6	17.0	9.59	5.15	3.28	1.45	0.59	0.24	0.10	0.050	0.010	0.005
100	3.94	33.7	29.4	18.4	10.4	6.77	3.43	1.55	0.64	0.26	0.120	0.030	0.010
150	5.91	46.8	40.9	26.8	15.7	10.2	5.49	2.71	1.13	0.47	0.210	0.050	0.020
200	7,87	61.0	56.0	34.0	22.0	14.5	8.10	4.10	1.80	0.73	0.34	0.082	0.036

Figure 67 – Attenuation (in dB/km) Due to Various Rain Rates

[Reference: Gierhart, G.D. and M.E. Johnson (1978), Propagation Model, DOT Report FAA-RD-77-129 as cited in " Aeronautical and Satellite Link Propagation Method," ITU Radio Communication Study Group Document 3K/21-E, June 11, 2012, Table 16.]

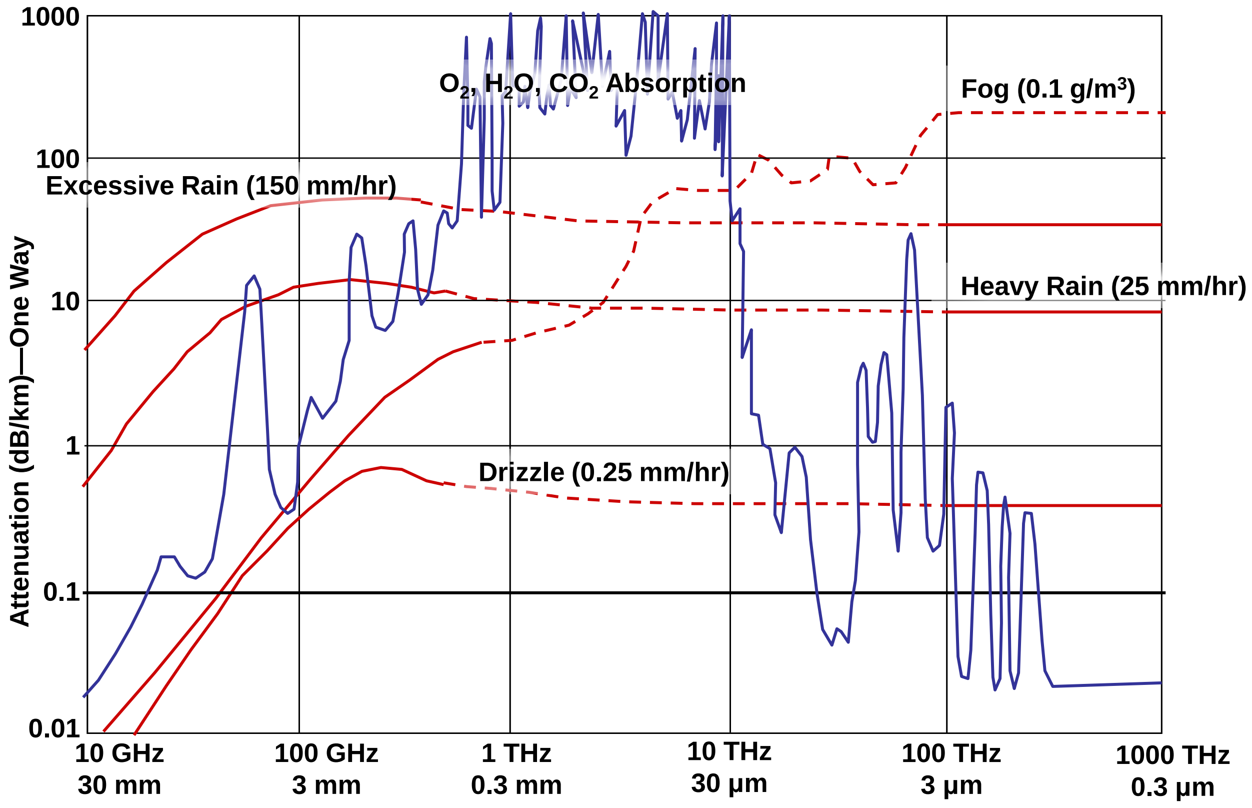


Figure 68 – Attenuation (in dB/km) Due to Atmospheric Gases and Conditions

[Reference: Lettington, A. H., Blankson, I. M., Attia, M., and Dunn, D., "Review of Imaging Architecture," Proceedings of SPIE 4719, 327-40, 2002.]

9.5.6 *Propagation Characteristics of Various Bands*

Figure 69 below summarizes the propagation characteristics of frequencies from Very Low Frequency (VLF) to Gamma Rays.

Band	**Frequency**	**Characteristics**
VLF	3 – 30 kHz	The earth and ionosphere act as a wave guide. Very limited BW for communications.
LF	30 – 300 kHz	The earth and ionosphere act as a waveguide. Waves can travel through the surface of large objects, including the earth as the earth acts like a conductor. Ionospheric effects can cause interference. Very limited BW for communications.
MF	0.3 – 3 MHz	Same as the above, but with less penetration of objects. Very limited BW for communications.
HF	3 – 30 MHz	Ionospheric propagation is available, so very long (beyond LOS) distance communication is possible. There is significant interference and fading that occurs through the shifting of the ionospheric layers and solar activity. Higher BW for communications than VLF to MF bands, but still low.
VHF	30 – 300 MHz	LOS communications with little atmospheric attenuation due to rain.
UHF	0.3 – 1 GHz	Similar to VHF.
L	1 – 2 GHz	Virtually no rain attenuation, but the ionosphere can introduce a rapid fading (referred to as ionospheric scintillation).
S	2 – 4 GHz	Inherently low background noise level. Less ionospheric effects than L band.
C	4 – 8 GHz	This spectrum is a heavily used for satellite communications. There is a modest amount of fading from rain and ionospheric scintillation. The large size of earth ground station antennas is a drawback.
X	8 – 12 GHz	Similar to C band, except more attenuation due to rain.
Ku	12 – 18 GHz	High attenuation due to rain. Band used for digital direct to home services such as DirecTV.
K	18 – 27 GHz	Similar to Ku band, but even higher attenuation due to rain.
Ka	27 – 40 GHz	Similar to K band, but even higher attenuation due to rain.
V	40 – 75 GHz	Very heavy attenuation due to rain.
W	75 – 110 GHz	Very heavy attenuation due to rain.
G	110 – 300 GHz	Very heavy attenuation due to rain.
EHF	30 – 300 GHz	Very heavy attenuation due to rain.
Infrared	300 GHz – 430 THz	Not capable of penetrating walls and other opaque objects or environmental obscurants such as dense fog, clouds, or rain. Eye safety is an area of significant concern, especially with frequencies near visible light.
Visible	430 – 790 THz	Not capable of penetrating walls and other opaque objects or environmental obscurants such as dense fog, clouds, or rain. Eye safety is an area of concern.
UV	790 THz – 30 PHz	Heavily attenuated by atmosphere. Higher UV frequencies have ionizing radiation hazardous to humans and other living organisms.
X-Rays	30 PHz – 30 EHz	Heavily attenuated by atmosphere. Ionizing radiation hazardous to humans and other living organisms.
Gamma Rays	Greater than 10 EHz	Heavily attenuated by atmosphere. Ionizing radiation hazardous to humans and other living organisms.

Figure 69 – Characteristics of the Various Frequency Bands

9.6 Summary of Spectrum Analysis for A-A & A-G Communications Suitability

Based upon spectrum analysis to identify suitable frequencies that have good propagation characteristics through the earth's atmosphere and bandwidth to meet the envisioned needs of NAS Air-to-Air and/or Air-to-Ground communications, the following frequency bands are deemed potential candidates:

For Air-to-Air communications: VHF, UHF, L-Band, S-Band, C-Band, and optical.

For Air-to-Ground communications: HF, VHF, UHF, L-Band, S-Band, C-Band, and optical.

For Communication with Satellites (or high flying communications platforms): In addition to the LOS bands from VHF to L-Band, additional bands that are suitable for communications with satellites either to support air-to-air and/or air-to-ground communications (either between the aircraft and the satellite, or between the ground network operating center and the satellite) include Ku band, K, Ka, V band, and potentially optical.

The rationale is that the propagation characteristics of the VHF to C band can support air-to-air and air-to-ground communications out to ~100 NM or more as is needed for line-of-sight (LOS) A-A and A-G applications. The propagation characteristics of infrared and optical communications are also possible (with technology maturation) at those ranges, with little to no atmospheric obscurants like fog, clouds, or rain and at shorter ranges with such obscurants. Infrared and optical could support very high bandwidth communications between, if information is available to point the highly directional antennas. Infrared was not selected as a strong candidate because of significant eye safety concerns, which is also a concern at optical frequencies. Frequencies higher than optical do not propagate well through the atmosphere and mostly consist of the portion of the electromagnetic spectrum with ionizing radiation whose emission would be harmful to all living organisms and thus has been ruled out as potential candidates. HF communications support A-G communications today at BLOS ranges. Below HF frequencies, BLOS communications are possible, but at very low bandwidths and have thus not deemed suitable for future NAS A-A or A-G communications.

For communications with relatively short propagation ranges through the atmosphere (as is the case for communications between a ground system and satellites and/or between an aircraft and satellites) communications are currently done in the Ku and Ka bands. With appropriate maturation of technology, this could be expanded to also include the K and V bands, as well as potentially also infrared and optical. Once again, infrared was rejected because of significant eye safety concerns. In addition, the K band, with high power ground transmitters, might be suitable for ground-to-aircraft communications. The K to V bands may also be suitable for very short A-A or A-G communications, including airport surface communications or very short range terminal area communications. Additionally, for relatively short horizontal propagation ranges for airport surface and terminal area applications, or shorter range A-A communications, X-band is also a possibility at nominal power levers, with longer range possible with high power transmissions.

10 IDENTIFICATION OF COMM. CANDIDATES AND QUANTIFICATION OF THEIR FUNCTIONAL ATTRIBUTES & CHARACTERISTICS

This section identifies candidates potentially suitable for future air-to-air and air-to-ground communications. The candidates identified have only passed an initial technical feasibility screening that the candidate could be reasonably expected to satisfy the anticipated communication needs for supporting ATM functions. Many of the candidates would require additional maturity prior to being suitable for supporting NAS operations.

In addition to initial technical feasibility, there are many other factors that influence the final candidate selection, including detailed technical feasibility assessment, being allocated the spectrum at both the national and international levels, cost benefits relative to all the alternatives, the transition path from operations today to operations in the future, the willingness of the alternative to be accepted by all stakeholders, etc.

The primary functional objective of the future aeronautical communication system being studied herein is to provide communications (voice and data link) in all air spaces (surface, terminal area, enroute, oceanic/remote, and polar) that provides sufficient communications performance to support ATM operations through 2062 and beyond.

While individual communication candidates need not fully support all the ATM requirements for all airspaces, an appropriate combination of communication links (formed from existing and/or proposed future candidates), must as a whole system support ATM operations.

The following subsections provide:

- identification of the A-A and A-G candidates (Section 10.1),
- quantification of the functional attributes and characteristics of the A-A and A-G candidates including an identification of a number of key technology enablers for the low TRL candidates (Section 10.2), and
- identification of how the candidates are or can be integrated in the future (Section 10.3).

The advantages and disadvantages of various bands of frequencies were discussed in Section 9. Additional advantages and disadvantages of the various candidates are identified in Section 10.2.

10.1 Identification of A-A and A-G Communications Candidates

Candidates were identified for A-A and A-G communications that may potentially satisfy the future NAS needs. All of the communications candidates identified could be grouped into one of the following basic categories:

- More efficiently use existing aviation communications spectrum (e.g., using higher order modulations)
- Leverage commercial communications networks to support NAS communications needs
- Reuse underutilized spectrum currently allocated to aviation (but not currently communications) to potentially support future NAS communication [e.g., MLS (C-Band) and DME (L-band), radar altimeter, ADF]
- Identify suitable new spectrum that could potentially be allocated to support NAS communications

Figure 70 and Figure 71 list the communications candidates identified for A-A and A-G communications, respectively.

A-A	Air-to-Air (A-A) Communications Candidates
1	VHF A-A
2	UHF A-A
3	L-Band A-A
4	S-Band A-A
5	C-Band A-A
6	X-Band A-A
7	Optical A-A
8	Hybrid RF/Optical A-A
9	LEO SATCOM A-A (One Hop through Satellite)
10	GEO SATCOM A-A (One Hop through Satellite)
11	MEO SATCOM A-A (One Hop through Satellite)
12	GEO + HEO SATCOM A-A (One Hop through Sat.)

Figure 70 – Air-to-Air Communications Candidates

A-G	Air-to-Ground (A-G) Communication Candidates
1	HF A-G
2	VHF A-G
3	UHF A-G
4	L-Band A-G
5	S-Band A-G
6	C-Band A-G
7	Optical A-G
8	Hybrid RF/Optical A-G
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)
10	DTV VHF/UHF Network
11	Cellular Network (e.g., Aircell)
12	LEO SATCOM Network (e.g., Iridium Next+)
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)
14	MEO SATCOM Network (e.g. GlobalStar+)
15	VHF A-A Hopping for long range A-G Com.
16	UHF A-A Hopping for long range A-G Com.
17	L-Band A-A Hopping for long range A-G Com.
18	X-Band A-G
19	GEO + HEO SATCOM Network

Figure 71 – Air-to-Ground Communications Candidates

Within each frequency band there are several alternatives that align with the 4 basic groups of alternatives identified earlier in this section. A brief description of the candidates is provided in the following subsections.

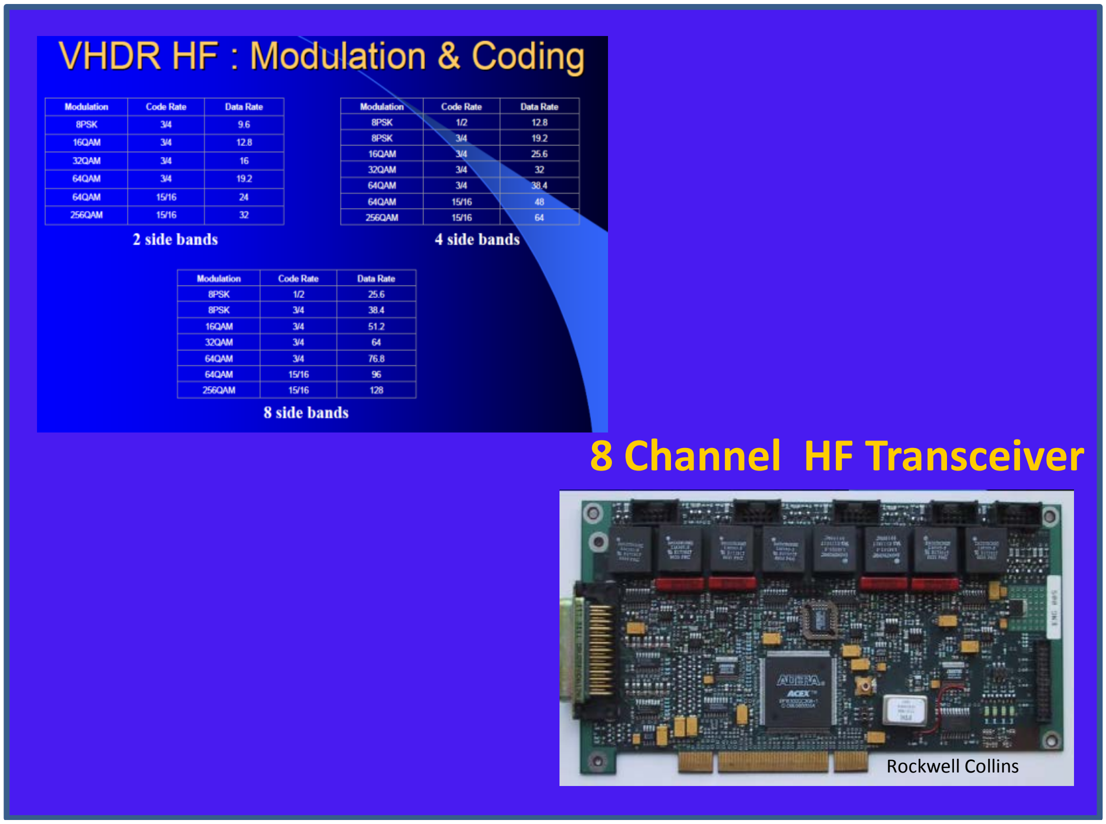
10.1.1 HF

Both A-A and A-G communications are possible with HF; although, HF was removed as an A-A future candidate because it did not meet the requirements for any of the future A-A applications identified in Section 13. HF was retained as an A-G candidate, as it is one of the few candidates that can cover oceanic, remote, and polar regions. The typical range for HF communications is several hundred miles to global depending on the RF power and ionospheric conditions as is described in Section 7.3.1. The availability of HF communications can be poor (e.g., typical 30% to nearly 100%) depending upon conditions.

HF is being used less today because of the availability of better performing SATCOM for long range A-G communications in oceanic, remote, and polar regions not covered by VHF communications. The characteristics and attributes of today's HF commercial communications were previously provided (see Section 7.3.1 and Figure 37).

The new technology trend is to aggregate channels (or bands) as one virtual channel to yield significantly higher data rates. Band aggregation is a trend in the cellular community (e.g., LTE and AWS as well with AT&T engineering smart phones with radios that aggregate disparate bands). Using channel aggregation of multiple HF channels and the use of higher order modulation constellations, much higher data rates are possible within the study modernization time horizon. Currently, through the aggregation of 3, 4, 6, or 8 independent 3 kHz HF channels and using higher order modulation constellations as high 256 QAM, Rockwell Collins Very High Data Rate (VHDR) multi-channel radio reaches rates as high as 128 kbps for long range HF communications. This "band aggregation" technology has been written into military standard (MIL-STD)-188-100. Use of a single tone has data rates between 75 and 2400 bps (3 kHz channel), using 256 QAM (per Appendix D of the MIL-STD) the data rate is up to 16 kbps (3 kHz channel), and using band aggregation in 3 kHz increments up to 24 kHz, data rates up to 120 kbps are achieved today. Research is being done by the Office of Naval Research (ONR) and Rockwell Collins whereby using bandwidths up to 48 kHz and 256 QAM, data rates of up to 240 kbps have been demonstrated. This is expected to increase 5X to 10X during the study modernization period. Figure 72 depicts the 8 channel VHDR HF transceiver and the data rates that can be achieved today using various modulations and code rates.

Channel aggregation technology is a trend that can be leveraged for future NAS communications (not just HF). This technology enables aggregation of multiple channels (non-contiguous) to develop one network socket capable of higher data rates. Others including AT&T are performing similar technology developments to address disparate cell bands. Such technology is expected to yield higher data rates over the NAS modernization period.



VHDR HF : Modulation & Coding

Modulation	Code Rate	Data Rate
8PSK	3/4	9.6
16QAM	3/4	12.8
32QAM	3/4	16
64QAM	3/4	19.2
64QAM	15/16	24
256QAM	15/16	32

2 side bands

Modulation	Code Rate	Data Rate
8PSK	1/2	12.8
8PSK	3/4	19.2
16QAM	3/4	25.6
32QAM	3/4	32
64QAM	3/4	38.4
64QAM	15/16	48
256QAM	15/16	64

4 side bands

Modulation	Code Rate	Data Rate
8PSK	1/2	25.6
8PSK	3/4	38.4
16QAM	3/4	51.2
32QAM	3/4	64
64QAM	3/4	76.8
64QAM	15/16	96
256QAM	15/16	128

8 side bands

8 Channel HF Transceiver

Figure 72 – Channel Aggregation Technology Applied to HF Transceiver

The benefit of HF communications is that it supports long range communications to be able to communicate with aircraft in oceanic, remote, and polar airspaces. The disadvantages of HF are the relatively small data rates relative to other alternatives, and limited number of users supported on a very limited number of channels. Future improvements may include more channel aggregation, improved modulation, and data acceleration. In the future HF ground operations could be seamlessly integrated in a way to be favorably interconnected to other network operations centers (SATCOM) for the request / forward of broadband data onto various L, Ku, and Ka SATCOM systems, a form of augmentation or hybridization to SATCOM.

10.1.2 VHF

Both A-A and A-G line of sight communications are possible in the VHF band. VHF communications are currently utilized in the 118 to 137 MHz, with 25 kHz bandwidths for voice and data communications as described in Section 7.3.2. 8.33 kHz is currently used for voice communications in Europe and could potentially be deployed in the NAS for both voice and data.

VDL Mode 2 has already been implemented on several thousand aircraft to transport ACARS messages and will support ATC CPDLC communications. Networks of ground stations provide VDL Mode 2 service deployed by ARINC and SITA with degrees of coverage for data and voice communication channels. The VDL Mode 2 Physical Layer uses a 25 kHz wide channel with a D8PSK modulation. The data rate is 31.5 kbps with a maximum range of ~200 nautical miles.

VDL Mode 3 has been defined to enable allocation of more VHF channels and to simplify the simultaneous use of voice and data communications. VDL-M3 divides each 25 kHz channel into

4 time division multiple access (TDMA) slots, each of which carries independent digital voice or data. Thus, VDL-M3 has the potential to quadruple the number of VHF channels and will allow simultaneous voice and data communications on the same 25 kHz frequency assignment. To date, VDL-M3 has not been implemented in the NAS, but it could be utilized in the future.

VDL Mode 4 has been defined and is being used in some other parts of the world (e.g., Sweden), which uses Gaussian frequency shift keying (GFSK) to transmit data in the 25 kHz channel at 19.2 kbps. VDL-M4 uses a self-organizing TDMA for the channel access, where transmitters autonomously select a private time slot for sending information (i.e., self-organizing) to avoid interfering with other transmissions.

Reuse into other VHF "Aviation" Frequencies

There is the potential to use the VHF VOR frequencies from 112 to 118 MHz to support future NAS communications. If VOR is de-commissioned or drawn down to a more minimal operating system, then this potentially frees up "aviation" spectrum that could be reused to support future A-A and/or A-G communications. One advantage of this is that the spectrum is adjacent to existing VHF communications frequencies, where it is relatively easy to accommodate with the ground and aircraft Tx/Rx and antennas.

There is also a potential to reuse some of the VHF ILS localizer frequencies in the 108 to 112 MHz band. While this is not in the current FAA navigation plan, it is possible that when multi-constellation/multi-frequency GNSS becomes available and it can support precision approach operations to Category I (or near Cat. I) minima, that this could reduce the need for ILS. It is not envisioned that the 108 to 112 MHz spectrum will become fully available in the study period for traditional A-A or A-G communications. However, it is expected to become more heavily used for the GPS/LAAS VHF Data Broadcast (VDB) navigation function which is a ground-to-aircraft broadcast of data. The VDB is just beginning to emerge today in the NAS, currently in the VOR band from 112 to 118 MHz, but it is expected in the long term to share the 108 to 112 MHz band with ILS localizer.

Improve VHF Efficiency

With future technologies that will become available during the modernization time horizon, it is believed that it will be possible to significantly increase the efficiency of the 25 kHz channels to gain a 2X to 4X data rate improvement than the 31.5 kbps data rate that is achieved using D8PSK in a 25 kHz channel. Furthermore, we believe that it will be possible to achieve data rates of ~33 kbps or higher within an 8.33 kHz channel. An example link budget that shows such data rate increases for VHF, as well as UHF, L-band, and C-band is given in Figure 73. Notice for VHF that the link budget shows a 75 kbps data rate in a 25 kHz channel, and a 33.3 kpbs in an 8.33 kHz channel. This link budget has taken advantage of technologies presented in Section 8 of this report, including for example very low installation loss (cables and connectors) resulting from smart antenna technologies. It has also been developed with a 6 dB link safety margin which is standard practice today for many aviation systems.

Link Type	**Cband G/G**	**Cband A/G**	**Lband A/G**	**UHF A/A-A/G**	**VHF A/A-A/G**	**VHF A/A-A/G**
Legacy Band	**MLS**	**MLS**	**DME**	**UHF TV**	**VHF Comm**	**VHF Comm**
Spectrum Low End (MHz)	**5031.00**	**5031.00**	**962.00**	**699.50**	**118.00**	**118.00**
Spectrum High End (MHz)	**5090.00**	**5090.00**	**1213.00**	**804.50**	**137.00**	**137.00**
Channel Spacing (KHz)	**1000**	**1000**	**2000**	**3000**	**8.33**	**25**
Available Channels	**60**	**60**	**126**	**36**	**2280**	**760**
Bandwidth (KHz)	**1000**	**1000**	**2000**	**3000**	**8.33**	**25**
Info Bits per Hz	**3.00**	**3.00**	**2.00**	**1.50**	**4.00**	**3.00**
Chan Info Bit Burst Rate (Kbps)	**3000**	**3000**	**4000**	**4500**	**33.333332**	**75**
Link Freq (MHz)	**5090.00**	**5090.00**	**1213.00**	**804.500**	**135.950**	**135.950**
Received Signal						
Required Symbol C/N (dB)	14.91	14.91	9.58	6.68	20.03	14.91
Required C/No (dB-Hz)	74.91	74.91	72.59	71.45	59.23	58.89
Receiver Characteristics						
Receiver Noise Figure (dB)	5.00	5.00	5.00	5.00	7.00	7.00
Cable & Connector Loss (dB)	1.00	1.00	1.00	1.00	1.00	1.00
Antenna VSWR	2.00	2.00	2.00	2.00	2.00	2.00
Antenna VSWR Loss (dB)	0.51	0.51	0.51	0.51	0.51	0.51
Antenna Gain (dB)	4.00	4.00	3.00	2.00	-1.00	-1.00
Equiv Rx Noise @ Antenna Input (dBm/Hz)	-169.26	-169.26	-169.26	-169.26	-166.75	-166.75
Channel Characteristics						
Environmental Noise (dBm/Hz)	-174.00	-174.00	-174.00	-174.00	-166.62	-166.62
Env + Equiv Rx Noise @ Antenna (dBm/Hz)	-168.00	-168.00	-168.00	-168.00	-163.68	-163.68
Desired Link Range (NM)	**5.00**	**30.00**	**100.00**	**100.00**	**100.00**	**100.00**
Path Loss (dB)	125.91	141.47	139.47	135.91	120.46	120.46
Total Effective Path Loss (dB)	128.42	143.98	142.98	140.42	127.97	127.97
Required Effective Radiated Power (dBm)	35.33	50.90	47.57	43.87	23.53	23.19
Transmitter Characteristics						
Cable & Connector Loss (dB)	1.00	1.00	1.00	1.00	1.00	1.00
Antenna VSWR	2.00	2.00	2.00	2.00	2.00	2.00
Antenna VSWR Loss (dB)	0.51	0.51	0.51	0.51	0.51	0.51
Antenna Gain (dB)	4.00	6.00	3.00	2.00	-1.00	-1.00
Desired dB Margin	**6.000**	**6.000**	**6.000**	**6.000**	**6.000**	**6.000**
Required Tx Power (dBm)	**32.85**	**46.41**	**46.09**	**43.38**	**26.04**	**25.70**
Required Tx Power (Watts)	**1.93**	**43.73**	**40.60**	**21.78**	**0.40**	**0.37**

Figure 73 – Example Future Comm. Link Budgets for VHF, UHF, L-Band, & C-Band

VHF Low Band

The VHF low band spectrum area is currently used by digital terrestrial television (DTV). These lower VHF frequency used for DTV are generally well below what most would consider for a viable aircraft antenna installation; however, there are techniques/maturing technologies for loading or folding an antenna to achieve reasonable antenna structures for the aircraft installation. If the communication system is ground transmit and aircraft receive-only system, then this problem may be less of an issue given the relatively higher radiated power from the transmitter.

Recently, portions of this lower VHF band have been reallocated to new channel spacings for digital public safety radio. It is very possible within the 50 year time frame the remaining band fragments may be reallocated once again or reused in part, possibly for aeronautical use (e.g., extension of the existing VHF aviation frequencies). These individual bands currently serve as terrestrial HD television channels and have excellent propagation properties. It is possible to leverage the existing commercial network to support ground-to-air communications. The DTV standard allows for the option of one high definition channel (19.3 Mbps) or optionally a number of lower definition sub-channels. The system and the standard also allow for an ancillary channel of about 1-Mbps running concurrently with the video injections. This ancillary channel may be used for other purposes (generally accessible as an Ethernet port available to a wide area network). The bandwidth may be scaled to consume a low-resolution DTV channel if desired for higher data channel bit rates. This is contractually and technically governed by the license holder of the station.

Digital Physical Layer Pipe (PLP) technology may be used to insert a secure proprietary air-mobile broadcast stream as an embedded ancillary data stream into the 8-VSB DTV broadcast. Currently there is experimentation with data delivery to ground mobile devices using 8-VSB with PLP; however the modulation type makes this is difficult to overcome deep fades. However, it is estimated that this technology could be used with specialized coding and Doppler correction to deliver robust air mobile data as the airborne problem does not have the deep fade issue. More research is needed for use as a future system.

The placement of these transmitters is typically in 50-200 mile cells concentrated in the most populated areas. This opportunity may be suited for providing aero data updates that have high tolerance to latency or availability (minutes to hours). Propagation is horizontally polarized reaching 100-150 NM (terrestrial) depending the band and transmitter power.

Graphical information such as weather and other data use may share the DTV transmission as an embedded PLP channel. This channel could complement other 2-way communications like VHF or AeroMACS.

Horizontal antenna polarization, size and Doppler may present technical challenges for the aircraft receiver system; however, this challenge can be addressed possibly sharing VDL as a dual-pol or steered array design. Providing continuous CONUS coverage will involve use of existing and additional transmitters.

10.1.3 UHF

Both A-A and A-G line of sight communications are possible in the UHF band. UHF alternatives may include being allocated portions of the unused TV broadcast frequencies, being allocated other frequencies (e.g., portion of the Milcom in the 225-400 MHz), leveraging the use of commercial networks, as well as using other aviation spectrum [e.g., ILS Glideslope (as reliance on ILS is reduced or possibly eliminated over the next 5 decades) and ADF]. Software radio technology could be useful in aggregating fragmented available band segments.

The most favorable UHF alternative would be to obtain a new spectrum allocation to support aeronautical A-A and A-G communications, such that it could be developed in a way that optimally met the aviation needs. The example UHF link budget given in Figure 73 (on page 126) is illustrative of the type of performance (data rate) and range that could be expected from this approach. However, there are other alternatives as identified below.

UHF High Band

Similar to VHF DTV band, however the shorter wavelength (0.5 meter) may enable a more realizable electronically steerable antenna (ESA) design perhaps including a broadband enough version to cover LDACS and UAT. The transmitter's antenna horizontal polarization would require a transmitter tower design update (undesirable) or a cross-polarized aircraft antenna if used with other vertical polarized services. The nose under the radar hood may be a candidate to install a tuned horizontal antenna.

As with VHF, digital Physical Layer Pipe (PLP) technology may be used to insert a proprietary air-mobile broadcast stream as an embedded ancillary data stream to the 8-VSB DTV broadcast. This virtual data pipe may be set up (coding and interleave) to deliver a robust mobile data channel (compensations required for air mobile use include any channel fading and Doppler). Doppler may be corrected using well known DSP algorithms technology or RF / IF compensation. A single quadrant (~ 4.8 Mbps) of the DTV broadcast may serve as a broadcast cell spanning 100-150 nm depending on transmitter power. Graphical information such as weather may share the DTV transmission as an embedded PLP channel. This channel could complement AeroMACS (airport vs. enroute), and LDACS or carry new data.

Horizontal antenna (smaller than VHF) polarization will present technical challenges for the aircraft system; however, this is seen as a technical challenge that can be overcome with steerable array (ESA) technology. Providing continuous CONUS coverage will involve use of existing and additional transmitters.

As possibly a more favorable option to reusing DTV technology would be to be allocated the band and design a new system using optimal channels and optimal modulation for aviation purposes. Each approach comes with its own costs and time. Over the period of 10-50 years, it is likely this band area will again be revisited possibly to the benefit of aeronautical use.

UHF Other

Within the UHF band area are 800 MHz segments used by Aircell (product name GoGo). Aircell supports existing air-to-ground options. It uses the TIA-856-A EVDO standard. This enables approximately 3 Mbps+ peak to an aircraft. A 3 MHz channel has been the primary channel until recently a second 1 MHz channel has been added to increase capacity. There may be future options with this service such as paring this service with a SATCOM service.

The broadband-oriented 3 MHz license (License C) was won by AC Bid Co. a subsidiary of Aircell. Aircell has deployed in-flight broadband using this license. (License C includes 849.0-850.5 MHz and 894.0-895.5 MHz; License D includes 850.5-851.0 MHz and 895.5-896.0 MHz).

10.1.4 L-Band

Both A-A and A-G line-of-sight communications are possible in the L-Band. Today, aviation is using 1030/1090 MHz for ATCRBS, TCAS, Mode S, ADS-B (both UAT and 1090 MHz). LDACS is expected to emerge to support A-G communications.

L-Band alternatives may include being more efficient with the existing L-Band spectrum, being allocated additional L-Band spectrum, as well as reusing other aviation spectrum [e.g., DME].

Aviation could more efficiently utilize the L-band spectrum. Two very inefficient uses of the spectrum are TCAS and SSRs. Reliance on these systems is anticipated to significantly decrease during the study modernization time horizon with ADS-B and other surveillance technologies like multilateration. It is anticipated that during a transition period, that TCAS and SSR interrogation rates will be significantly reduced (hybrid surveillance) and ADS-B will become the primary means of ground and aircraft surveillance. Furthermore, it is anticipated that ADS-B could be made more efficient by use of a self-organizing TDMA multiple access, rather than a probabilistic multiple access. Probabilistic multiple access requires the ADS-B surveillance systems to transmit at a much higher rate than necessary for the airborne and ground applications to accommodate message losses during collisions. Probabilistic multiple access does not efficiently utilize the available communications bandwidth.

The largest opportunity to reuse existing aviation spectrum in the L-band is the existing DME spectrum. It is believed that navigation and ADS-B surveillance will in the long term need a more capable terrestrial-based alternative to the highly capable GNSS Position/Navigation/Timing (PNT) source, which is often referred to as Alternative Position/Navigation/Timing (or APNT). It is believed that such a system will be developed within the study modernization time frame, and it likely will be implemented in a small portion of the existing DME spectrum (~15 to 30 MHz). The remaining DME spectrum may present a significant opportunity for the future A-A and A-G communications. The example link L-band budget given in Figure 73 (on page 126) is illustrative of the type of L-band performance (data rate) and range that could be expected from this approach.

10.1.5 S-Band

Both A-A and A-G communications are possible in the S-Band. The S band is used by weather radar, surface ship radar, and some communications satellites. The largest opportunity in the S-band to support future NAS communication needs is to leverage commercial services. The S-band is currently used by Sirius XM Radio to provide its Satellite Weather data casting service. If economically attractive, Sirius (or other commercial provider) could expand and enhance its services to support NAS A-G communications.

10.1.6 C-Band

Both A-A and A-G line-of-sight (LOS) communications are possible in the C-Band, albeit at a shorter range than VHF to S-Band LOS candidates.

Repurposing the aviation Microwave Landing System (MLS) C-band spectrum allocation for surface, terminal area, and potentially high bandwidth control non-payload communications (CNPC) links for UAS seems like the largest opportunities and they are in the process of being pursued. An example C-band link budget given in Figure 47 (on page 126) is illustrative of C-band performance (data rate) that can be achieved for short range (less than ~30 NM communications).

Within the study modernization period, C-Band links will become viable for not only airport A-G surface communications at busy airports (i.e., AeroMACS), but also terminal area A-G communications (e.g., out to at least 70 NM and more likely out to 100 NM or more). Because of the high bandwidth available and C-Band frequencies already allocated to the aviation community (i.e., the MLS allocation), portions of the C-Band is expected to become the CNPC link for UAS. While C-band frequencies are more attenuated by the atmosphere effects than VHF to S-Band frequencies, low cost electronically steered aircraft antennas and implementations that reduce the cable and connector losses (e.g., moving at least the radio front end very close to the antenna), C-band air-to-ground communications over a 100+ NM range will become available with reasonable transmit power.

C Radar Altimeter

People are evaluating if the C-band radar altimeter frequencies in the 4.2-4.4 GHz frequency range, could have the potential for jointly continuing to support the radar altimeter function plus future data communications. Of the 200 MHz, it is estimated that ~50 MHz may not be efficiently applied given technology today and that gap will likely grow over time. Some of the issues associated with alternate use of the radar altimeter spectrum include the potential jamming of the high integrity radar altimeter function that supports precision approach and landing as well as ground proximity warning functions, the narrow beam downward looking antenna compatibility with A-A or A-G communications, and the band access plan. The radar altimeter antenna generally only has an 80 degree beam width. It would likely need to be much larger to support A-A or A-G communications. Possible uses include airport and terminal area. Currently, opposition to this candidate exists and will likely remain so until a standard is developed that defines an acceptable joint use.

10.1.7 X-Band

Both A-A and A-G communications are possible in the X-Band. The band is currently utilized by the military for satellite communications and for a number of radar applications, including airborne Weather Radars (WxR). The largest NAS communications opportunity in the X-band is to develop a future system that could effectively leverage the on-aircraft WxR equipment and spectrum allocation not only for detecting atmospheric conditions, but also to support high bandwidth A-A communications. The X-band could also be used to support short range A-G LOS communications (e.g., surface high BW data link), but gaining an allocation for NAS communications is unlikely. The characteristics of the X-Band are similar to C-band, except with higher attenuation caused by rain.

10.1.8 Free Space Optical and Hybrid RF/Optical

Both A-A and A-G line-of-sight (LOS) communications are possible using free space optical and hybrid RF/optical communications. The use of free space optical or RF/optical is viewed as a more futuristic concept and is described in section 10.1.13.1 (page 138). There are a number of technologies that need to be matured and made more affordable to enable wide scale A-A and A-G communications (other than perhaps for gate link applications). However, the potentially large communications bandwidth and the availability of new spectrum to support wireless communications is a huge potential opportunity.

10.1.9 Cellular Networks

While unlikely to fully meet all the aviation requirements for high criticality ATM applications, commercial cellular networks may be able to support A-A and A-G communications for some applications. The communications would be LOS from cell towers.

LTE / Cellular

Though not exclusive, LTE technology is generally associated with several band areas generally land mobile or “mobile” band applications (700, 1700, 1900 MHz) or even military bands. The LTE standard has many favorable cellular access attributes and has been researched for air mobile. Low spectrum reuse factor 1:1 may provide issues at altitude where the aircraft generally would have visibility of many towers at once. Hand-off district is about 26 miles requiring modification to the MAC layers to handle aircraft visibility to LOS (100+ NM). Additionally the Doppler eventually becomes problematic above 120 km/hr.

Given these issues it may still be possible to develop a new network implementation where an air mobile band is acquired or identified, LTE towers are set at optimal aeronautical distances, radio equipment is compensated for Doppler, and optimal cross polarized or directional antennas are used. It may be easier to find a one-way spectrum block (e.g., 20 MHz Block-D @700 MHz) to broadcast only to aircraft, augmenting today's enroute VHF and VDL communications. Additionally "band aggregation", a technology and process of taking several disparate bands and processing / working them into one virtual band, may be an option given the fading availability of 6 MHz channels. AT&T has developed this cell phone technology to perform this with its disparate cell bands.

Advanced Wireless Service (AWS) - "Mobile" RF bands

NTIA's designation of "mobile" does not exclude airmobile. A future service provider within 10 to 20 years could plausibly include services to aircraft. Broadcast, multicast, unicast data, graphics, and weather data may be included in such communications.

Consolidation of service providers and regional licenses may provide CONUS access. Band areas today include: AWS 1710-1755 MHz uplink mobile client-to-tower and 2110-2155 MHz downlink tower-to-mobile client. Ten, 20 MHz blocks are currently owned and operated by T-Mobile, Verizon, SpectrumCo, Metro PCS, Cingular, Cricket, and Barat (U.S. Cellular).

10.1.10 Terrestrial K to W Band Communications

Terrestrial high bandwidth K to potentially W band links will become a feasible NAS candidate within the 50 year modernization period. Some may come from commercial links, per the Ku link identified in the FCC notice discussed in the following paragraph. Others may come from dedicated aviation links in the K to W bands for short range (e.g., airport surface) links to support very high bandwidth communications. As indicated in Section 9, frequencies in the K to W band are susceptible to significant atmospheric attenuation due to environmental effects. However, if a 200 MHz allocation were available in the K to W band areas and a link budget could be closed, data rates of 500+ Mbps could be achieved. Much of the state of the art in signaling is more difficult to do in these higher RF bands because of the current semiconductor limitations which are expected to be matured over the years. Currently, we would likely be limited to simple Amplitude Shift Keying (ASK) or Phase Shift Keying (PSK) modulations, which are less spectral efficient than other modulation alternatives.

Ku Air-to-Ground

A recent FCC notice of proposed rulemaking (NPRM) was issued in May 2013. The FCC proposes to establish a new terrestrial-based air-to-ground mobile service in the 14.0-14.5 GHz (500 MHz bandwidth per site) of the Ku band. Plans are to provide multi megabyte connectivity to each aircraft. The basis for the NPRM comes from a petition from Qualcomm requesting to establish a new air-to-ground service. A competitive bid for 2 licensed bands is being recommended. There remains Satellite Industry Association (SIA) opposition due to the possibility of generating interference to the SATCOM community in the same band. The use of spatial diversity is what is planned to reduce or eliminate interference concerns. This commercial network is planned to have high availability and integrity and serve all aspects of the cabin and may in the future support ATM-related A-G communications. The directional Ku band aircraft antenna is anticipated to be ~20 cm square, which is compatible with small and large aircraft.

10.1.11 *SATCOM (LEO / MEO / GEO / HEO)*

Both A-A and A-G communications are possible using SATCOM. SATCOM offers potentially worldwide coverage with Low Earth Orbit (LEO) satellites and Medium Earth Orbit (MEO) satellites. Geostationary (GEO) SATCOM satellites typically offer coverage below ~70 degrees latitude. Combinations of GEO and High Earth Orbit (HEO) satellites may also be considered to obtain polar coverage. The minimum number of satellites necessary to obtain this global coverage and the approximate round trip signal latency (not including processing latency) associated with communicating with LEO, MEO, and GEO satellites is indicated in Figure 74. For polar coverage from HEO satellites, 3 or more satellites are needed for north polar coverage with high availability.

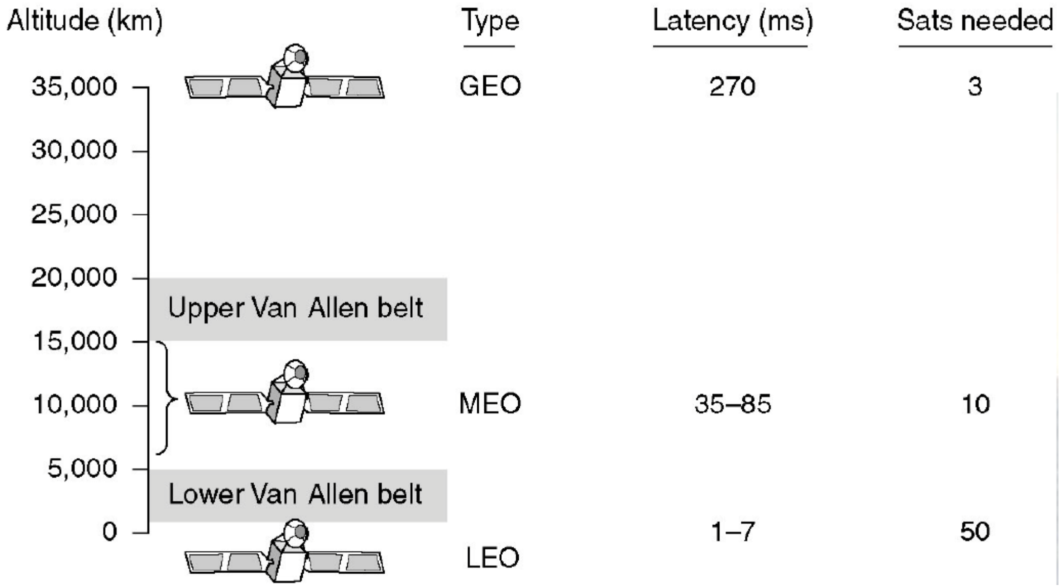


Figure 74 – SATCOM Round Trip Latency & Minimum Number of Satellites Needed for Global Coverage

[Reference: "Doppler-Aided Channel Estimation in Satellite Communication Base on Frequency-domain Equalization," 2013 IEEE iCNS Conference, by C. Tang.]

10.1.11.1 Air-to-Air SATCOM

A-A communications between any aircraft in the world is possible using SATCOM. There are two candidates.

<u>A-A Using SATCOM</u>

The first air-to-air candidate uses SATCOM satellites (e.g., Iridium, Iridium Next, future generations) to communicate by voice or data though a satellite, to a ground network operations center which in turn may use switch technology to vector the transaction to another aircraft. An advantage of this approach is satellite simplicity. The disadvantages include the latency and additional bandwidth "cost" of downlinking the transaction to the NOC routing it, and then uplinking it back to the satellite for delivery to the aircraft. This system can reach beyond the line of sight to connect A-A anywhere world-wide.

A-A "one hop" through SATCOM Satellite

As a future candidate, it is possible to directly route air-to-air transactions "one hop" through SATCOM satellite. See Figure 75 for an illustration of this candidate A-A communications concept, which is potentially applicable to LEO, MEO, and GEO satellite. New Ka band satellites including those from Viasat, Hughes Inmarsat GX, and others will or now contain digital buses and IP switches on-board the satellite enabling direct peer-to-peer connectivity without the necessity for going through a ground network operations center (NOC). This capability is essentially a smart IP router. Today's Ka band satellites are generally fixed terrestrial use; however, the trend toward on-board IP switches is a likely indicator of what is planned for 4th and 5th generation mobile Ka satellites (as well as other satellites) in the future. Broadband peer to peer may not directly alleviate traffic issues of VHF; however, it would enable a number of potential future applications that involve transfer of large amounts of data among aircraft (e.g., the exchange of graphical weather information collected from weather radar). This candidate trend potentially offers high data rate A-A communications in the future (~10+ years).

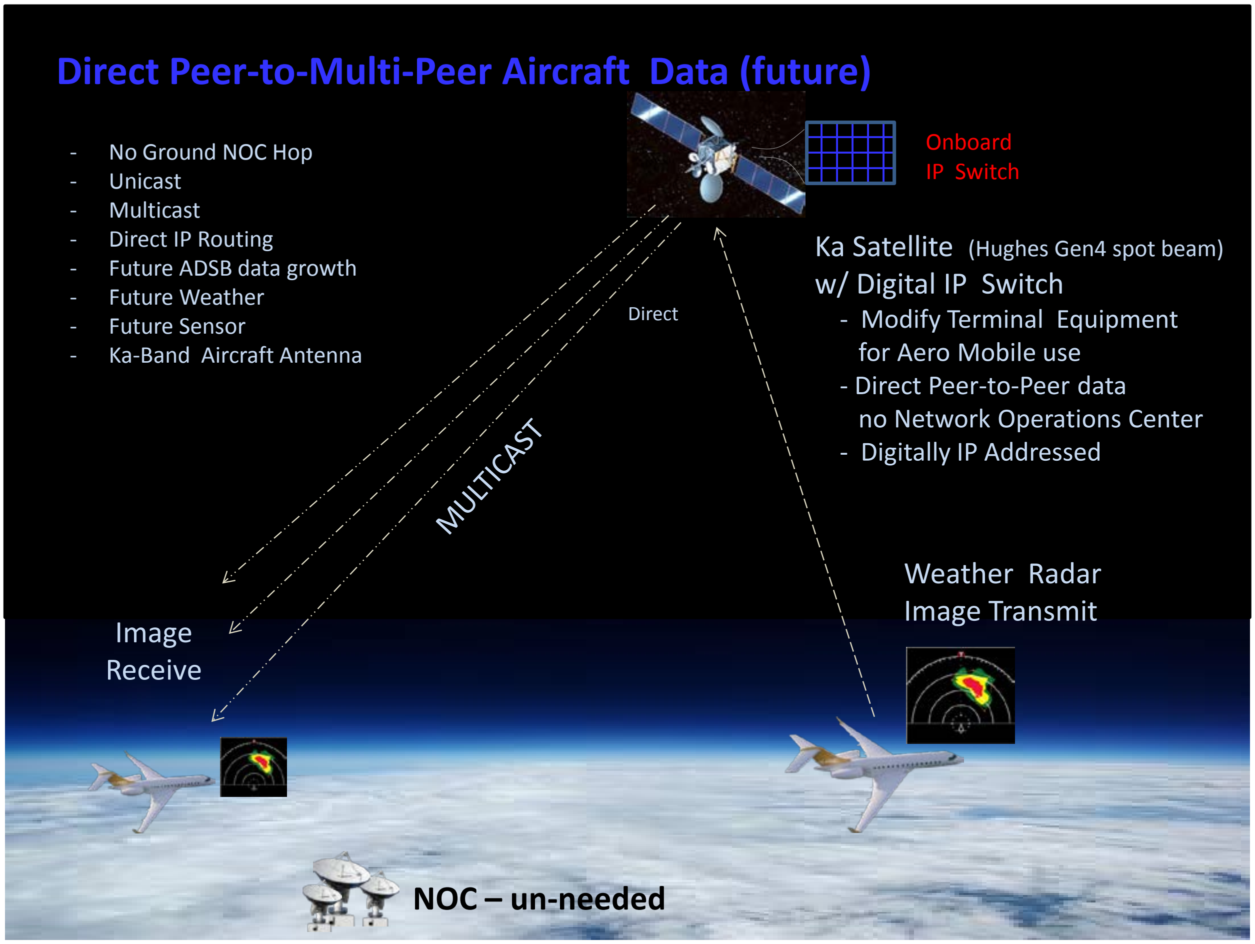


Figure 75 – Direct A-A SATCOM

10.1.11.2 Air-to-Ground SATCOM

Worldwide A-G communications are done today using SATCOM systems. For example, Inmarsat already provides aero information services at contracted or per minute cost to client.

In the future, the data communications capabilities will continue to improve over time. SATCOM satellites tend to last ~10 to 15 years. During the 50 year modernization period, there will be 3 to 5 new generations of SATCOM systems, each predicted to offer more communications capability than the previous generation.

LEO

As an example, Iridium (LEO) is currently in the process of upgrading to a next-generation satellite constellation named “Iridium NEXT.” NEXT is being developed with an improved data communications system. A comparison of the current Iridium services and the anticipated expanded Iridium NEXT services was given in Figure 41 (on page 81). Iridium NEXT is expected to include legacy voice service with improved voice quality and a variety of L-band data services with rates ranging from 2.4 kbps to 1.5 Mbps, using bandwidth-on-demand. System latency today is ~1 to 20 seconds depending on packet size. This is expected to be reduced in the future.

GEO

This concept is much the same as described in the LEO definition however generally higher data rates are available, but with more latency (e.g., round trip through the GEO satellite may be approach 700 ms). This technology is slated to become part of an augmented system with Inmarsat’s “Global eXpress” Ka band satellite. The L-band system will provide backup to the Ka in the event or rain fades or other detrimental precipitation.

MEO

This concept is much the same as described in the LEO definition however with more latency (e.g., round trip through the MEO satellite may be approach 200 ms).

GEO/HEO

The concept calls for combining GEO satellites and augmenting them with High Earth Orbit (HEO) satellites to obtain polar coverage. 3 HEO satellites are needed to obtain good coverage availability over the north polar regions with limited coverage of the south polar regions. Additional HEO satellites would be needed to obtain high availability coverage for both north and source. The latency performance of this candidate is similar to GEO performance, with the bandwidth similar to MEO performance.

Ku

Various services, antenna and terminals are used today for one and 2-way data communications (e.g., Rockwell Collins, Panasonic, Jet Blue, Live TV). These systems have 128 kbps uplink; 500 kbps to 5 Mbps downlink on business jets is typical today with a 12” antenna. Higher performance can be achieved with larger antenna (e.g., ~3’x6’) which are installed on larger aircraft. Large antenna associated with gain and directivity requirements of this band inhibits use on small aircraft fuselages below 6.5 feet. The Ku band SATCOM is currently not used for ATM communications. The potential exists for using the Ku and higher band communications hybrid with other data links (see additional candidates in section 10.1.13).

Ka

Future Inmarsat GX will become commercially available with the planned 2015 launch, one and 2-way data, streaming media, with ~43 Mbps per platform. Global coverage to 70 degrees N/S latitude will be achieved with handoff between 3 satellites. Antenna transmit directivity requirements generally offset wavelength benefit. Issues include the large antenna size which will limit usability to medium and large aircraft. Rain fade reduces stand-alone availability requiring augmentation with another link (e.g. L-band). Applications include passenger wireless, TV, Connected IFE, crew applications, and Electronic Flight bag (EFB).

10.1.11.3 ADS-B Satellite Based Air-to-Ground Surveillance

Satellite-based ADS-B is an expected capability that will fill the surveillance gap in oceanic, remote, and polar regions where installing a terrestrial based ground infrastructure is impractical.

Air Traffic Service Providers would like to receive accurate and timely aircraft surveillance information to control aircraft in regions where it is difficult to install and maintain a ground network of ADS-B ground stations including oceanic, remote, and polar regions. In such regions, satellites are expected to use to receive aircraft surveillance information and relay it to ATC. There are two primary candidates being considered for utilizing satellites to obtain ADS-B surveillance information from aircraft outside the coverage region of an ADS-B ground station network: (1) installing Mode-S 1090ES and UAT ADS-B receivers directly onto the satellites, and (2) installing a converter function on the aircraft that utilizes the ADS-B OUT surveillance information from the on-aircraft systems and appropriately convert the surveillance information for transmission to the satellites. For the former technique, the satellite systems would receive and consolidate the ADS-B signals prior to transmission to the ground, whereas in the latter technique, the satellite would function as a “bent pipe” to retransmit the surveillance information received from the aircraft such that it can be received by the ground. With both of these candidates, the satellite ground stations would receive and consolidate the traffic surveillance information transmitted by the satellites and provide the information to Air Traffic Control and other users. ADS capable satellites can be used to augment the ADS-B ground receiver networks to provide worldwide surveillance coverage.

Satellite operator Iridium, through its new joint venture Aireon LLC, is planning to put ADS-B receivers on its next-generation satellite constellation (Iridium Next) as hosted payloads, aimed at bringing global, real-time aircraft surveillance for Air Navigation Service Providers (ANSPs) as depicted in Figure 76 and Figure 77. The ADS-B receiver payloads are expected to be mounted on each Iridium NEXT satellite. They will operate independently and perform the communications associated with routing ADS-B surveillance information separately from the other missions of the spacecraft.

The Iridium network enables signals to be relayed from any point on the globe to a central ground location in Tempe, AZ (USA) in near real-time, with back-up locations in Alaska and Norway. The near real-time nature of relaying ADS-B surveillance data through the Iridium network is critical to achieving radar-like surveillance in remote regions that will enable reduced oceanic separation minima down to ~15 NM (Nautical Miles) for aircraft equipped with appropriate communication and navigation avionics, which could be very beneficial for improving operational efficiency.

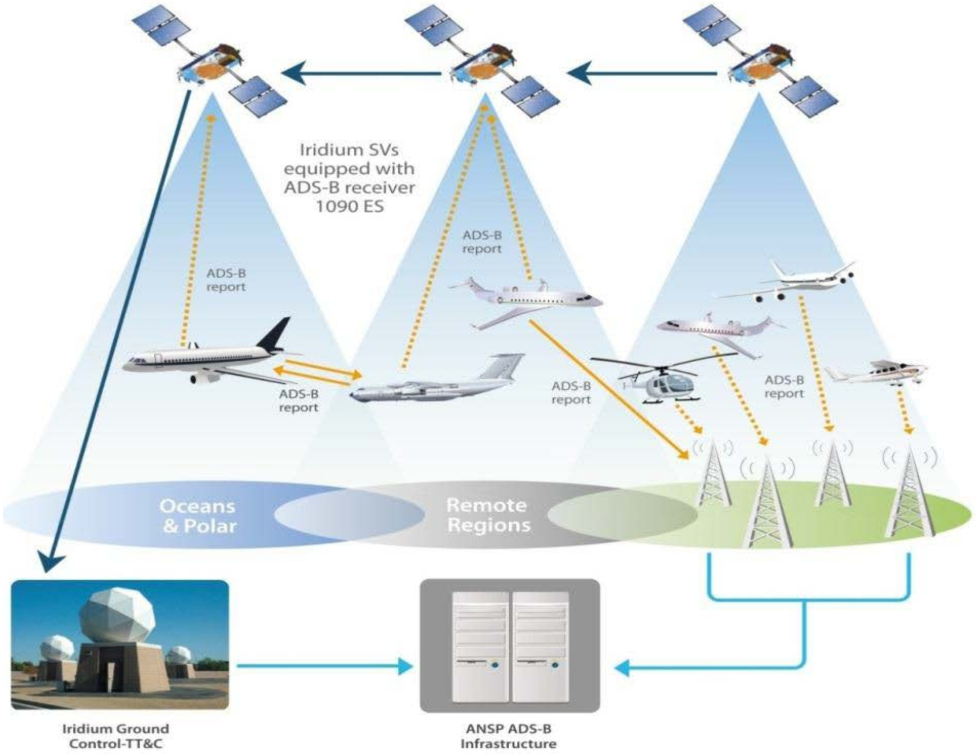


Figure 76 – Global Aircraft Surveillance using Space Based ADS-B Receivers

[Reference: "Iridium Now & Next, IDG Aero SATCOM Seminar – Stockholm, Sweden, March 9, 2012, by Jeffrey White, page 23.]

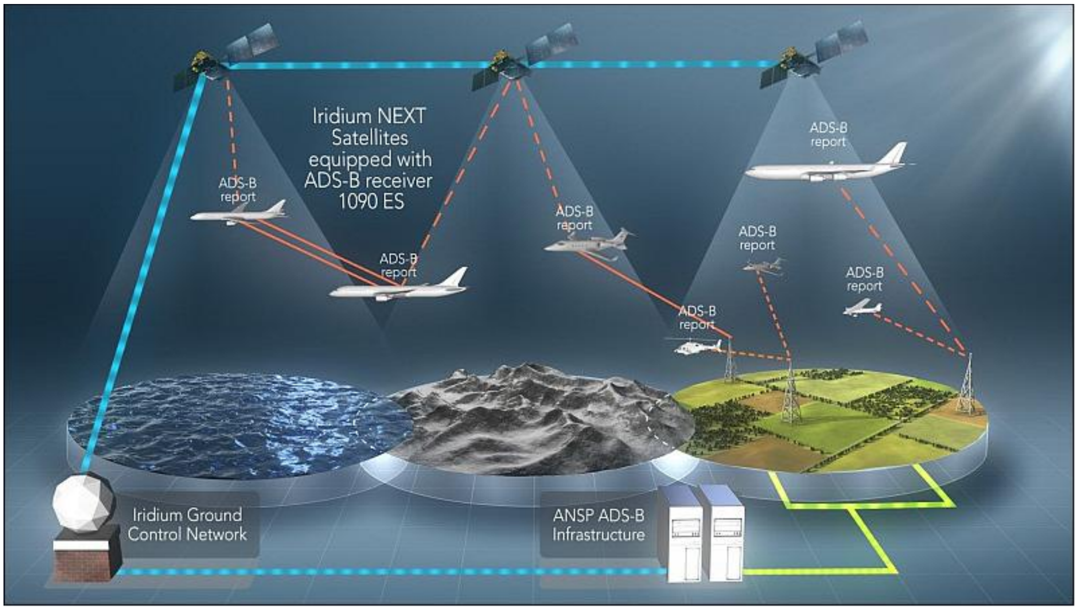


Figure 77 – Iridium Space-based ADS-B Concept of Operations

[Reference: https://directory.eoportal.org/web/eoportal/satellite-missions/i/iridium-next, image credit Aireon.]

10.1.12 Aircraft-to-Aircraft Hopping (relays) for A-G Communications

A-G communications between any aircraft and ATC (or AOC) is possible using LOS communications to aircraft within the LOS of the ground network and then using aircraft-to-aircraft hopping (or relaying) of the communication with suitably positioned aircraft until the communication reaches its destination. This candidate, while not intended to be a primary mode of operation, is envisioned to be a feasible, low cost, reduced capability backup long range communication means suitable for communicating with aircraft in oceanic, remote, and polar regions, should the future primary A-G communications (likely SATCOM) become unavailable. Currently, use of HF is the aeronautical communications A-G "safety" link for A-G with aircraft in oceanic, remote, and polar regions. This candidate would potentially allow removing HF equipment from aircraft (including its associated high cost, size, power, and weight) and ground infrastructure, and utilizing a LOS link (e.g., VHF, UHF, and L-band). The disadvantages of this candidate is that aircraft positions may not be such that the communications can be routed to a very remote aircraft at all times and it would utilize available bandwidth planned for domestic enroute, terminal, and surface operations (e.g., VHF) to support reaching remote aircraft. The characteristics and attributes of this candidate are exactly the same as the A-G communications using the LOS communications candidate (e.g., VHF, UHF, and L-Band), except the latency would be higher depending upon the number of hops required to get to the destination. It is likely that the latency of a communication could be designed to be less than 1 or 2 seconds per hop, which is acceptable for oceanic/remote/polar operations.

10.1.13 Additional Forward Looking Candidate Concepts

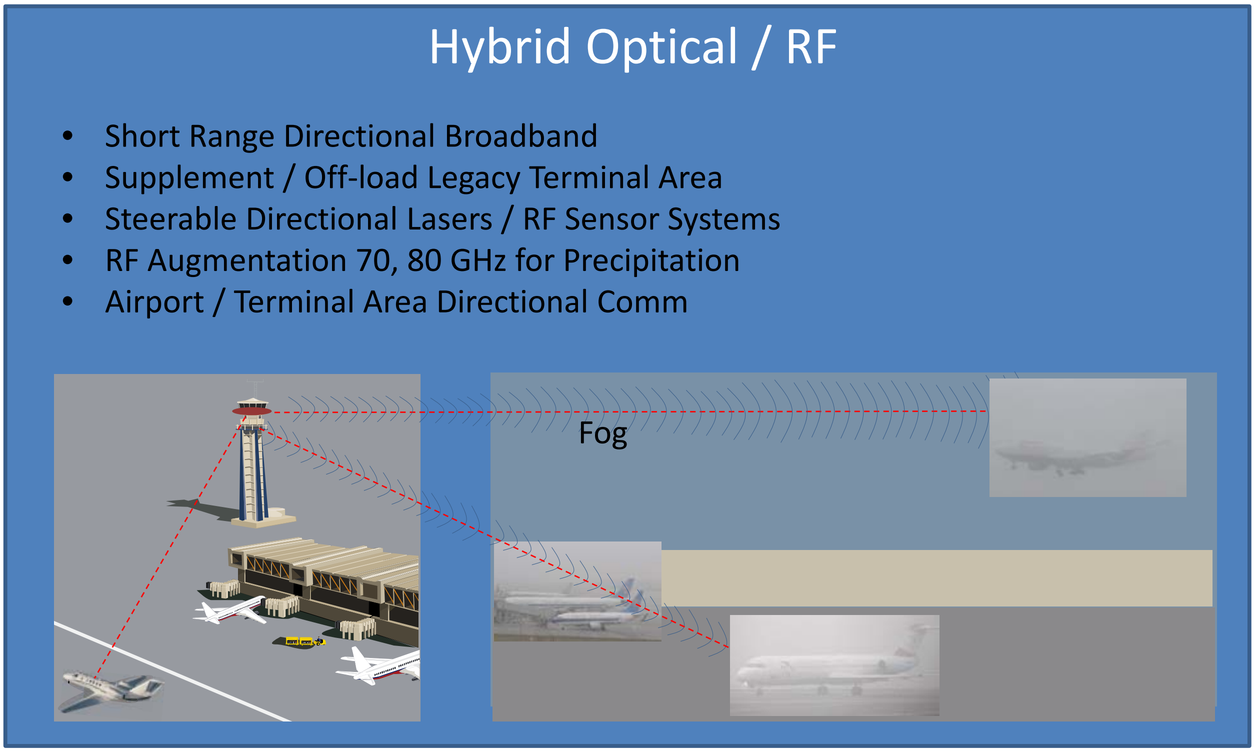
The following list contains several additional novel ideas identified for potentially supporting aeronautical A-A or A-G data exchange. The ones in highlighted in "**blue**" are perhaps considered having highest potential impact for leading the NAS into the future. These candidates are advanced forward looking concepts and additional maturation would be needed to make such concepts feasible.

- **Hybrid RF/Optical Hybrid**
- Augment VHF with GEO SATCOM
- Augment VHF with LEO (or MEO) SATCOM
- Augment 1090ES with SATCOM
- Augment VHF with Ku / Ka SATCOM
- **Hybrid Ku / Ka SATCOM and VHF/VDL**
- Terrestrial Ku (A-G) / Ku Ka (SATCOM)
- AeroMACS Augmented with Broadband Terrestrial Network or SATCOM
- Ku (Air-to-Ground) Augmented with SATCOM
- SATCOM – Future Generation: Bandwidth and QOS On Demand

All of the above forward looking concepts are briefly introduced in the subsections below.

10.1.13.1 Hybrid RF / Optical

Figure 78 depicts the robust hybrid RF/optical link candidate that may be possible on the airport surface and in the terminal area. Perhaps beginning with the gate link area for up and down loading passenger manifests and meal orders and IFE related media uploads. Smaller aircraft may be disadvantaged with broadband such as SATCOM due to large antenna and systems so the process of up and downloading at the gate a 1-Gbps – 100 Gbps speed over the study period could be a real opportunity with multiple robust optical / RF links. The emerging optic technology requires reduced size multiple directive movable antenna transceivers (gate-to-aircraft and tower-to-aircraft) which over the study period may play a role to relieve RF spectrum issues. Links to aircraft on the runway and taxi area may be used for gate change information and Flight Operational Quality Assurance (FOQA) data, system health, and maintenance information. The main advantage is the directionality of these may in the future allow vastly more connections.



Hybrid Optical / RF

- Short Range Directional Broadband
- Supplement / Off-load Legacy Terminal Area
- Steerable Directional Lasers / RF Sensor Systems
- RF Augmentation 70, 80 GHz for Precipitation
- Airport / Terminal Area Directional Comm

Figure 78 – Hybrid RF / Optical Candidate

This candidate can leverage the better attributes of laser or directional optical comm in the airport environment where congested communications is common. Optical comm not only offers high speed method for communication but it provides a very unique characteristics of being highly directional so it may be re-used over and over – a characteristics more difficult for RF to match given its wave properties.

Preferably, rather than just optical is to use a hybrid optical / RF link. The proposed concept is to use of a parallel mmWave system (70 or 80 GHz, for example) to augment the optical link in the event of fog or rain for short distance augmentation. The RF link may also be used as a control link for maintaining pointing of the optical system.

Candidates that incorporate optical communication offer a number of potential advantages; however, they also have a number of significant challenges. Optical communications potentially can offer very high bandwidths, but the drawbacks include the following.

- Need clear line of sight between the transmitter and the receiver. There are potential concerns with objects (e.g., aircraft fuselage / tail / landing gear, other aircraft, terrain, buildings) blocking the line of sight.
- Susceptible to scattering disruptions due to common atmospheric conditions like fog, dust, heavy rain, snow, or clouds, in the path between the transmitter and the receiver
- Directional antennas are needed to point the aircraft optical antenna, that may need to address factors of light refraction
- Antennas are more susceptible to typically encountered conditions (e.g., water vapor due to condensation or rain, dirt/contamination on the antenna)
- Traditionally, the cost of such optical antennas have been significantly higher than RF alternatives, but that may change in the future

10.1.13.2 Augment VHF with GEO SATCOM

Augmenting VHF with SATCOM is a means to extend the reach of the VHF and VDL services to reach globally and deliver high BW data from requests received on VHF. Extra data capacity spanning 100's of kbps to 43 Mbps. This requires larger high gain antenna and augmentation to L-band system for high availability. Cost and antenna size may still be problematic for small aircraft; however, value to mid to large aircraft should remain very strong though next generations of satellites 4, 5, 6, and beyond over the study period as systems become more broadband include onboard spacecraft switches and processing for managing bandwidth resources and on-demand concepts. As a prediction for mapping these technology trends into next generation services, each of the network providers will see the value in enabling greater connectivity options to their hardware services enabling innovative systems including augmented systems, hybrid band system systems, and bandwidth on demand options. Connectivity between services should develop over time as well.

An example of a future application could be a small aircraft's request for timely animated weather data though either a VHF or Iridium augmentation depending on the aircraft location. The graphical responses may be too large for either basic off-board services to carry practically or economically but the response may be IP forwarded to a Ka band NOC and delivered to a Ka band receive-only antenna which may concurrently be receiving cabin television too. The Ka band antenna may be a smaller variety as it performs a "receive-only" function (the other half of a Ka transmit is generally too large for a small aircraft). Thus a small (12" conformal) Ka electronic scanned array (ESA) receive-only aircraft may request on VHF and receive the information on Ka on its receive-only antenna. This futuristic system may fit practically on any aircraft (including most small aircraft) and leverages the best of both worlds of VHF and SATCOM links to bring tremendous new broadband benefit to aircraft.

10.1.13.3 Augment VHF with LEO OR MEO SATCOM

The description of this candidate is similar to that in the preceding section (10.1.13.2), except rather than using GEO satellite it would use either a LEO or MEO. Data capacity for today's systems range from up to 1.5 Mbps for the LEO and this will increase in the future. Data acceleration is possible for 5X greater effective capacity. Cost may continue to be a factor; however the global value proposition will continue to become stronger.

10.1.13.4 Augment 1090ES with SATCOM

The description of this candidate is similar to that in Section 10.1.13.2, but applied to extending 1090ES data (e.g., ADS-B and other aircraft data) to global for A-A applications. The likely application is to improve flight efficiency in oceanic, remote, and polar regions by receiving A-A data (e.g., ADS-B) at longer ranges using SATCOM. It would require additional services, and cost may be a factor.

10.1.13.5 Augment VHF with Ku / Ka SATCOM

The description of this candidate is similar to that in Section 10.1.13.2. Additional SATCOM system for extending VHF services to reach globally. Extra data capacity can be achieved spanning 100's kbps to 5 Mbps. This candidate requires a larger high gain antenna. Access may be limited on ground with tropical weather. L-band may be a better choice. Cost may be a factor.

10.1.13.6 Hybrid Ka and VHF/VDL

A potential future state may include a split (hybrid) system for transmitting on one system and receiving on another. The benefit is the potential for a smaller antenna system for smaller aircraft. Today's Ku and Ka band fuselage transmit antenna are large driven primarily due to the transmit directivity factor (maintaining tight enough beam to avoid inter-satellite interference). Fuselage antenna may be up to 3 feet x 6 feet in size to maintain a G/T of 11.5 dB in association with a 49 dBw satellite for example. Aircraft fuselage sizes of smaller business jet classes range from 5.0 feet to 6.5 feet in diameter, most of which cannot accommodate a 3'x6' broadband antenna like this. A future concept of hybridizing may help this by splitting transmit and receive into two technologies. The alternative transmit system may be associated with a lower-bit-rate channel (L-band with omni-directional antenna) and the receive system may be associated with a conformal Ku or Ka technology. As an example, the use of L-band [e.g., Iridium using omni-directional antenna] as the off-board link and Ku or Ka as the onboard link may be used to complete the IP circuit. As a pair, this antenna system is physically smaller. As a hybrid these two systems are a bit more integrated as a total network than simply using two 2-way systems. This configuration is not commercially available yet and generally a research item. However as satellites become more network IP oriented and as next generation satellites include multiple bands L/Ku, L/Ka (Inmarsat GX) for example, the advantages of hybrid bands will become possible to better serve the small aircraft antenna problem and not simply used for redundancy or backup but for a split IP circuit of transmit and receive.

10.1.13.7 Terrestrial Ku (A-G) / Ku Ka (SATCOM)

Figure 79 depicts a future concept that would primarily use a terrestrial broadband system like Qualcomm's newly proposed Ku air-to-ground link (w/ secure tunneling) to forward and receive IP data requests. Additionally, for aircraft capable of installing a receive Ku or Ka band SATCOM system, larger data returns may be "order wired" or forwarded to one of one or more future mobile GEO sat system for faster (50 Mbps peak returns), for lower latency graphics downloads, motion media (radar sequences etc.) would be possible. The final ruling for this FCC spectrum NPRM is approaching.

As satellites increase bit rates through higher order modulation, channel bonding, data acceleration, more bands per orbit slot, etc., the 47 Mbit per second peak per platform (today's peak capability) enabling availability / access to an order of magnitude greater as bit rates on 500+ Gbps on gen-5 satellites arrive in under 15 years and even higher with gen-6 satellites after that.

Terrestrial client based satellite networks will eventually introduce low cost Ku or Ka mobile services (hand-off) for SUVs and trucks for DTV first then as steerable antenna array technology improves, other options for the forward link will be evaluated. This commercial broadband technology will lead the way for aero mobile applications with different requirements but similar broadband mobile needs. Ku or Ka is seen as displacing the broadcast DTV due to cost – it costs significantly less to broadcast from a satellite than to deliver a broadcast though disparate cell towers. Cell towers do not have the physical coverage for continuous DTV QoS. In summary, Ku and particularly Ka (20-30 GHz shorter wave length band /smaller receive antenna) technology may trend / find regional mobile broadcast applications.

By adding secure digital Physical Layer Pipe (PLP) type technology to each of these commercial communications methods (future Ku air-to-ground, existing / future Mobile SATCOM) the augmentation / combination of these communications systems may offer substantial bandwidth for application growth opportunities associated with VHF, VDL, AeroMACS, ADS-B, LDACS in CONUS, regional, and global areas.

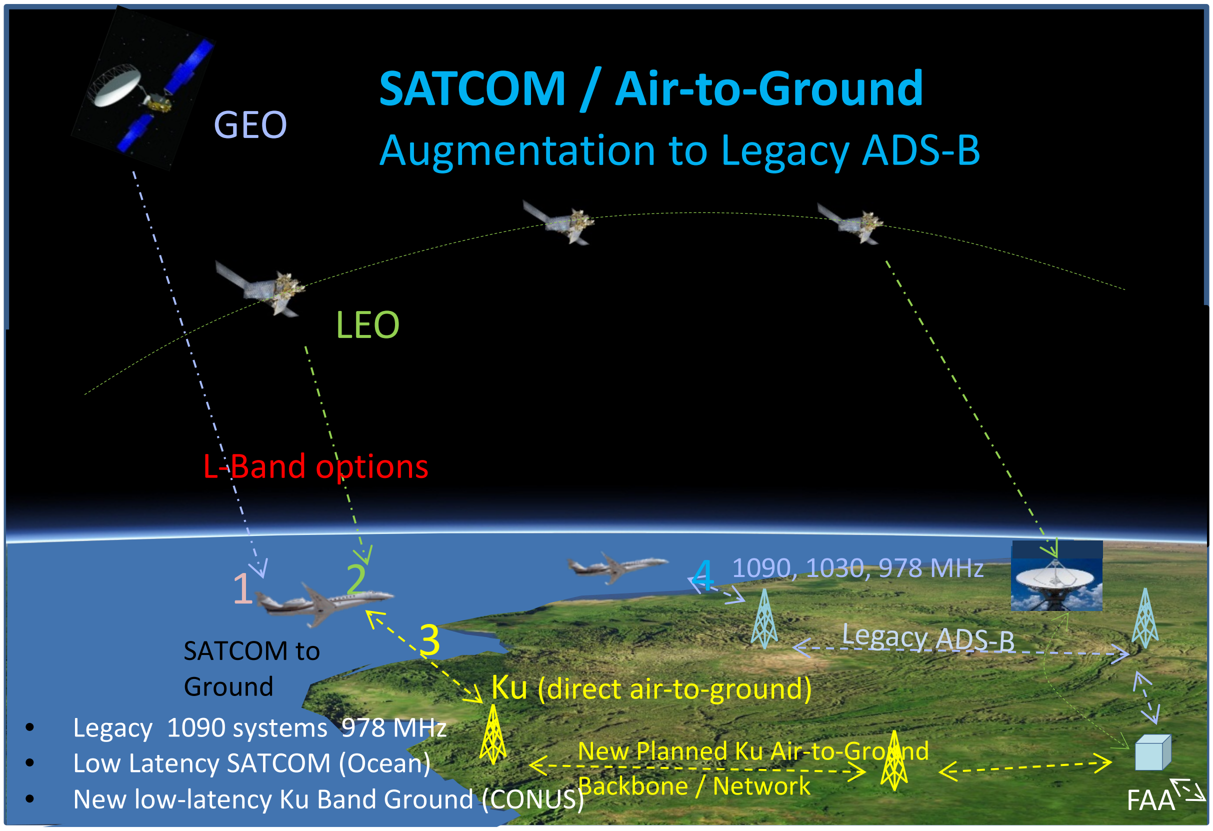


Figure 79 – Ku Air-to-Ground Terrestrial Network

10.1.13.8 AeroMACS Augmented with Broadband Terrestrial Network or SATCOM

This concept would augment or extend AeroMACS benefits to aircraft out of range of the C-band data link using a broadband terrestrial network (e.g., like the Ku band described in the previous section) or SATCOM (e.g., Inmarsat GX), similar to the concept described in Section 10.1.13.2 for VHF.

10.1.13.9 Ku (Air-to-Ground) Augmented with SATCOM

This new concept would use Qualcomm's newly proposed Ku air-to-ground link (see Section 10.1.13.7) to conduct IP data requests and to forward content to a secondary Ku or Ka SATCOM system to further offload the air-to-ground link. Possibilities include request and delivery of animated graphical weather data. An example would be requesting (order wire) weather data via the Ku air-to-ground path and receiving continuous massive data updates though the augmented Ku path where the K-band GEO antenna might be a simpler receive-only system (TV or data) on a commercial aircraft. L, Ku, or Ka may be used to provide Global or regional connectivity service beyond air-to-ground reach.

10.1.13.10 SATCOM – Future Generation: Bandwidth and QOS On Demand

As next generation satellites assume more on board switching and processing during the next 10 to 50+ years, it is envisioned that mobile clients (aircraft) will be able to supply report bandwidth schedules and needs to an on-board satellite processor. The powerful combination of having both a software radio on board the aircraft uniquely working together to manage resource with an intelligent processing system onboard the satellite for managing bandwidth and traffic resources will enable optimal flexible management of simultaneous IP traffic and streaming media, secure IP tunneling, and high reliability air data services on the same satellite and same transponders.

10.2 Functional Attributes and Characteristics of the A-A and A-G Candidates

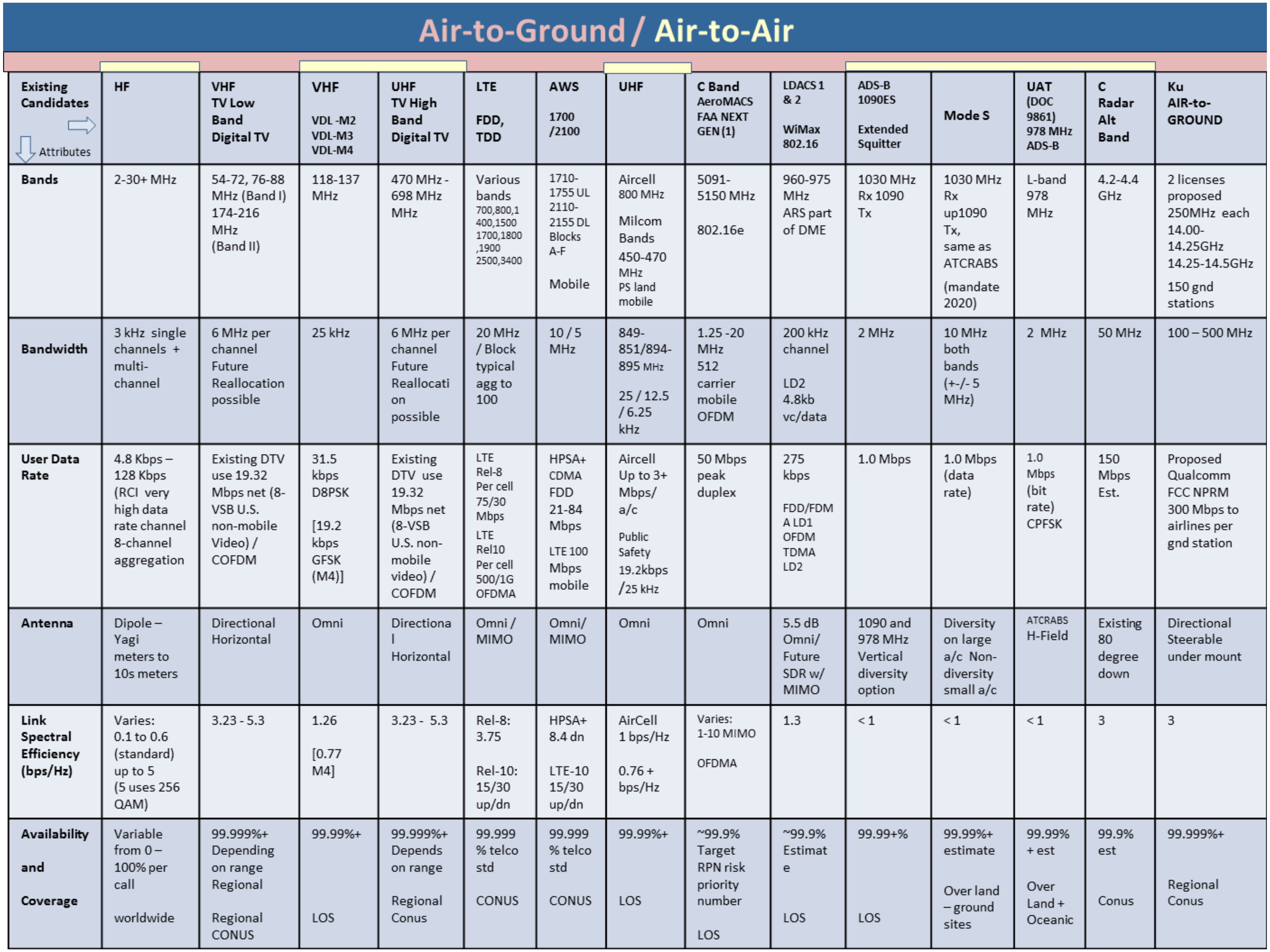
10.2.1 Existing Candidates

The functional attributes and characteristics of the existing A-A and A-G communication candidates have been quantified as summarized in Figure 80 to Figure 83 (starting on page 143). The candidates are listed at the tops of the figures. On Figure 80 and Figure 81, A-A candidates are indicated by a "yellow" colored bar marking at the top of the figure above the candidate, and A-G candidates are indicated by a "red" bar. The existing/emerging SATCOM candidates are presented on Figure 82 and Figure 83.

In general, the figures go across starting on the left at the lower frequency candidates and moving toward the right are higher frequency candidates. The lists of attributes and characteristics for each candidate includes the band, bandwidth, data rate, antenna characteristics, spectral efficiency, availability, latency, communications range, capacity, advantages/disadvantages (or strengths and weaknesses), vulnerabilities, new capabilities, and Technology Readiness Level (TRL). Since the list of attributes is long, the quantification of a given candidate extends over two figures. Thus, for a given candidate, the tabulation of attributes extends across two adjacent figures (i.e., Figure 80 and Figure 81 quantify one set of candidates, and Figure 82 and Figure 83 quantify a second set).

10.2.2 Low TRL Future Candidates

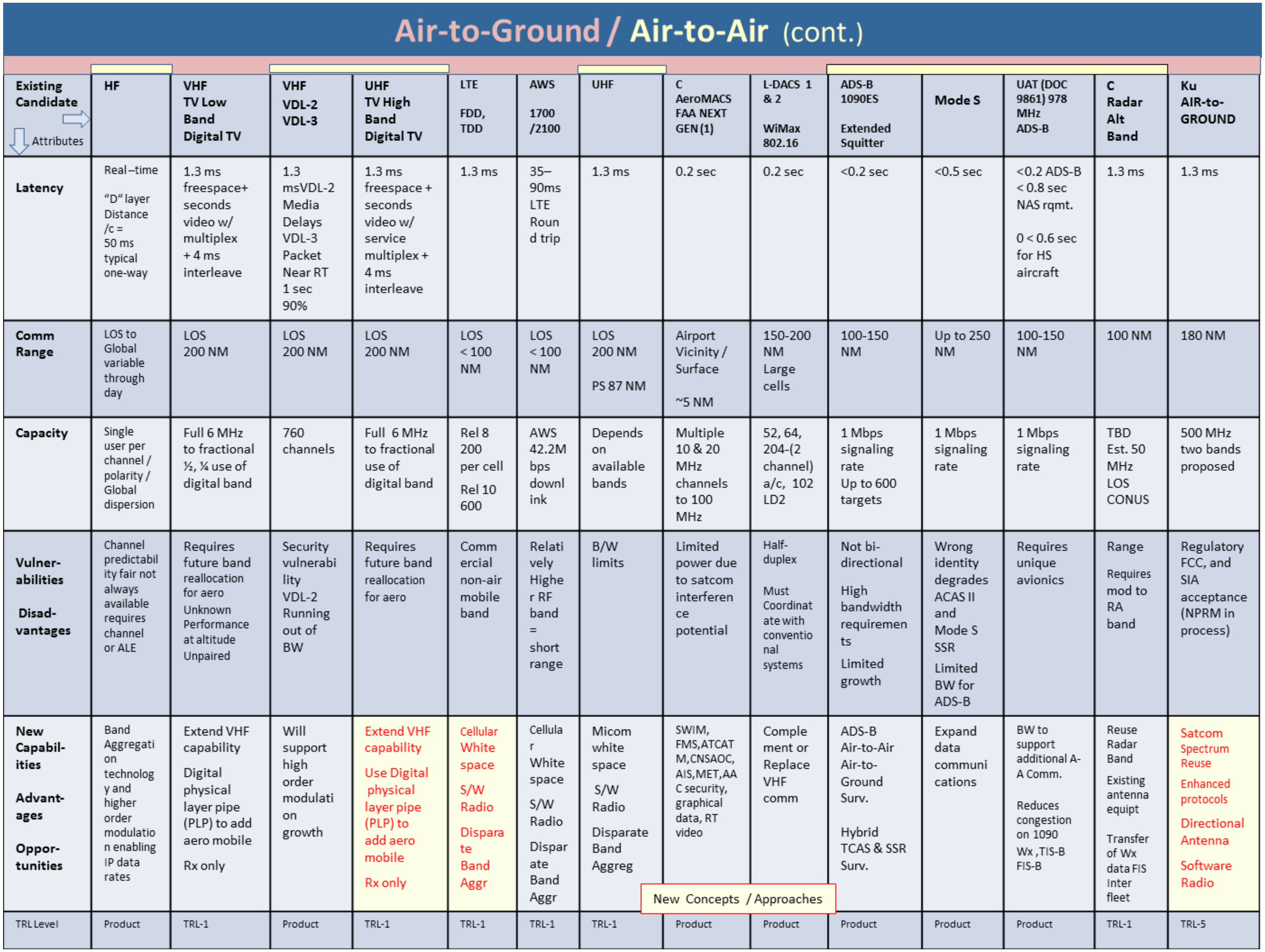
Figure 84 (on page 147) identifies the most important technology enablers necessary to mature for the low Technology Readiness Level (TRL) candidates and indicates the significant communication systems benefit that may be realized from the future candidate.



Air-to-Ground / Air-to-Air

Existing Candidates ⇨ ⇩ Attributes	HF	VHF TV Low Band Digital TV	VHF VDL -M2 VDL-M3 VDL-M4	UHF TV High Band Digital TV	LTE FDD, TDD	AWS 1700 /2100	UHF	C Band AeroMACS FAA NEXT GEN (1)	LDACS 1 & 2 WiMax 802.16	ADS-B 1090ES Extended Squitter	Mode S	UAT (DOC 9861) 978 MHz ADS-B	C Radar Alt Band	Ku AIR-to-GROUND
Bands	2-30+ MHz	54-72, 76-88 MHz (Band I) 174-216 MHz (Band II)	118-137 MHz	470 MHz - 698 MHz MHz	Various bands 700,800,1 400,1500 1700,1800 ,1900 2500,3400	1710-1755 UL 2110-2155 DL Blocks A-F Mobile	Aircell 800 MHz Milcom Bands 450-470 MHz PS land mobile	5091-5150 MHz 802.16e	960-975 MHz ARS part of DME	1030 MHz Rx 1090 Tx	1030 MHz Rx up1090 Tx, same as ATCRABS (mandate 2020)	L-band 978 MHz	4.2-4.4 GHz	2 licenses proposed 250MHz each 14.00-14.25GHz 14.25-14.5GHz 150 gnd stations
Bandwidth	3 kHz single channels + multi-channel	6 MHz per channel Future Reallocation possible	25 kHz	6 MHz per channel Future Reallocation possible	20 MHz / Block typical agg to 100	10 / 5 MHz	849-851/894-895 MHz 25 / 12.5 / 6.25 kHz	1.25 -20 MHz 512 carrier mobile OFDM	200 kHz channel LD2 4.8kb vc/data	2 MHz	10 MHz both bands (+-/- 5 MHz)	2 MHz	50 MHz	100 – 500 MHz
User Data Rate	4.8 Kbps – 128 Kbps (RCI very high data rate channel 8-channel aggregation	Existing DTV use 19.32 Mbps net (8-VSB U.S. non-mobile Video) / COFDM	31.5 kbps D8PSK [19.2 kbps GFSK (M4)]	Existing DTV use 19.32 Mbps net (8-VSB U.S. non-mobile video) / COFDM	LTE Rel-8 Per cell 75/30 Mbps LTE Rel10 Per cell 500/1G OFDMA	HPSA+ CDMA FDD 21-84 Mbps LTE 100 Mbps mobile	Aircell Up to 3+ Mbps/ a/c Public Safety 19.2kbps /25 kHz	50 Mbps peak duplex	275 kbps FDD/FDM A LD1 OFDM TDMA LD2	1.0 Mbps	1.0 Mbps (data rate)	1.0 Mbps (bit rate) CPFSK	150 Mbps Est.	Proposed Qualcomm FCC NPRM 300 Mbps to airlines per gnd station
Antenna	Dipole – Yagi meters to 10s meters	Directional Horizontal	Omni	Directional Horizontal	Omni / MIMO	Omni/ MIMO	Omni	Omni	5.5 dB Omni/ Future SDR w/ MIMO	1090 and 978 MHz Vertical diversity option	Diversity on large a/c Non-diversity small a/c	ATCRABS H-Field	Existing 80 degree down	Directional Steerable under mount
Link Spectral Efficiency (bps/Hz)	Varies: 0.1 to 0.6 (standard) up to 5 (5 uses 256 QAM)	3.23 - 5.3	1.26 [0.77 M4]	3.23 - 5.3	Rel-8: 3.75 Rel-10: 15/30 up/dn	HPSA+ 8.4 dn LTE-10 15/30 up/dn	AirCell 1 bps/Hz 0.76 + bps/Hz	Varies: 1-10 MIMO OFDMA	1.3	< 1	< 1	< 1	3	3
Availability and Coverage	Variable from 0 – 100% per call worldwide	99.999%+ Depending on range Regional Regional CONUS	99.99%+ LOS	99.999%+ Depends on range Regional Conus	99.999 % telco std CONUS	99.999 % telco std CONUS	99.99%+ LOS	~99.9% Target RPN risk priority number LOS	~99.9% Estimate LOS	99.99+% LOS	99.99%+ estimate Over land – ground sites	99.99% + est Over Land + Oceanic	99.9% est Conus	99.999%+ Regional Conus

Figure 80 – Functional Attributes &Characteristics of Existing Candidates (1 of 4)

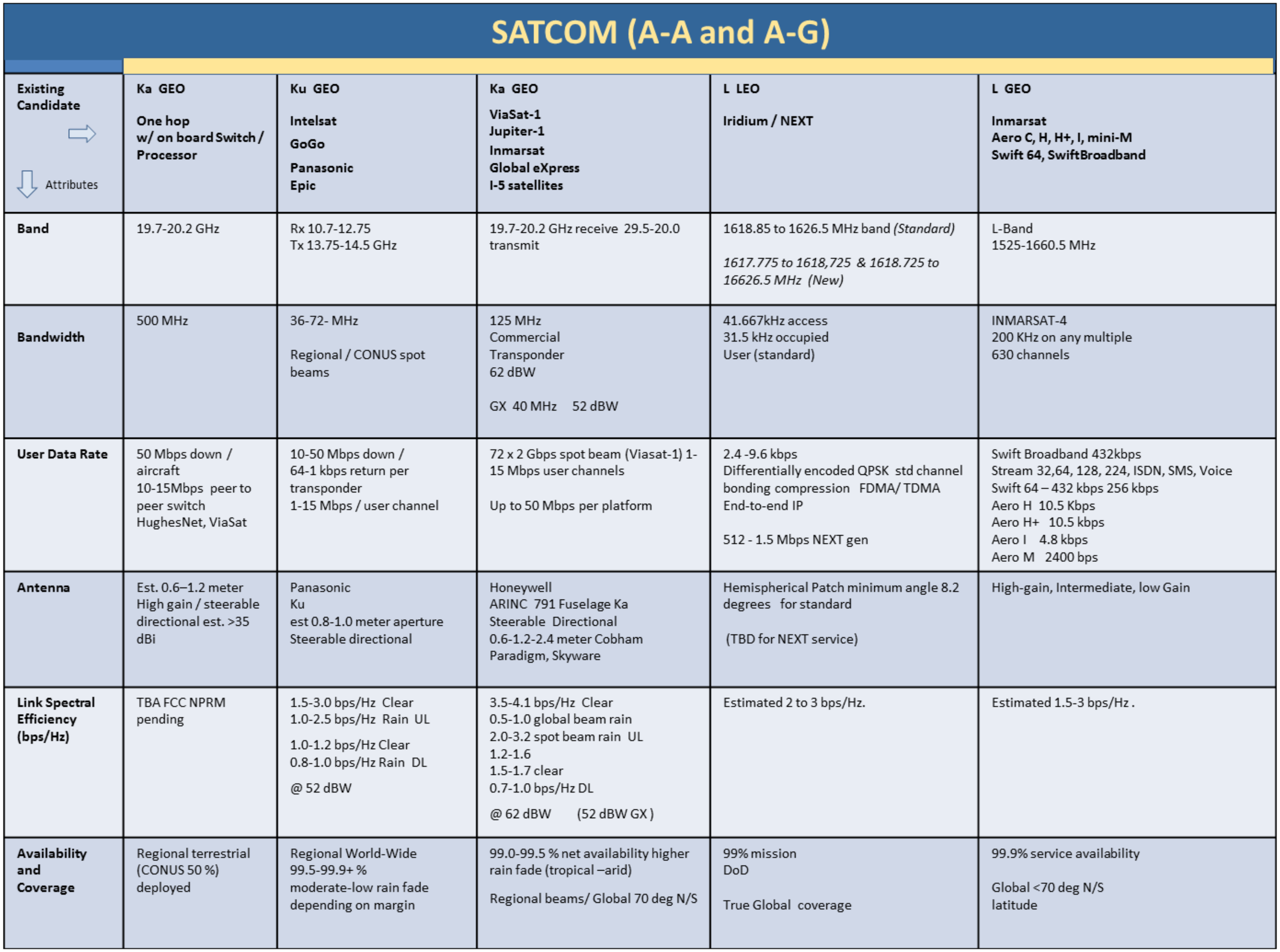


Air-to-Ground / Air-to-Air (cont.)

Existing Candidate ⇨ / ⇩ Attributes	HF	VHF TV Low Band Digital TV	VHF VDL-2 VDL-3	UHF TV High Band Digital TV	LTE FDD, TDD	AWS 1700 /2100	UHF	C AeroMACS FAA NEXT GEN (1)	L-DACS 1 & 2 WiMax 802.16	ADS-B 1090ES Extended Squitter	Mode S	UAT (DOC 9861) 978 MHz ADS-B	C Radar Alt Band	Ku AIR-to-GROUND
Latency	Real –time "D" layer Distance /c = 50 ms typical one-way	1.3 ms freespace+ seconds video w/ multiplex + 4 ms interleave	1.3 msVDL-2 Media Delays VDL-3 Packet Near RT 1 sec 90%	1.3 ms freespace + seconds video w/ service multiplex + 4 ms interleave	1.3 ms	35–90ms LTE Round trip	1.3 ms	0.2 sec	0.2 sec	<0.2 sec	<0.5 sec	<0.2 ADS-B < 0.8 sec NAS rqmt. 0 < 0.6 sec for HS aircraft	1.3 ms	1.3 ms
Comm Range	LOS to Global variable through day	LOS 200 NM	LOS 200 NM	LOS 200 NM	LOS < 100 NM	LOS < 100 NM	LOS 200 NM PS 87 NM	Airport Vicinity / Surface ~5 NM	150-200 NM Large cells	100-150 NM	Up to 250 NM	100-150 NM	100 NM	180 NM
Capacity	Single user per channel / polarity / Global dispersion	Full 6 MHz to fractional ½, ¼ use of digital band	760 channels	Full 6 MHz to fractional use of digital band	Rel 8 200 per cell Rel 10 600	AWS 42.2M bps downlink	Depends on available bands	Multiple 10 & 20 MHz channels to 100 MHz	52, 64, 204-(2 channel) a/c, 102 LD2	1 Mbps signaling rate Up to 600 targets	1 Mbps signaling rate	1 Mbps signaling rate	TBD Est. 50 MHz LOS CONUS	500 MHz two bands proposed
Vulner-abilities **Disad-vantages**	Channel predictability fair not always available requires channel or ALE	Requires future band reallocation for aero Unknown Performance at altitude Unpaired	Security vulnerability VDL-2 Running out of BW	Requires future band reallocation for aero	Commercial non-air mobile band	Relatively Higher RF band = short range	B/W limits	Limited power due to satcom interference potential	Half-duplex Must Coordinate with conventional systems	Not bi-directional High bandwidth requirements Limited growth	Wrong identity degrades ACAS II and Mode S SSR Limited BW for ADS-B	Requires unique avionics	Range Requires mod to RA band	Regulatory FCC, and SIA acceptance (NPRM in process)
New Capabil-ities **Advant-ages** **Oppor-tunities**	Band Aggregation on technology and higher order modulation enabling IP data rates	Extend VHF capability Digital physical layer pipe (PLP) to add aero mobile Rx only	Will support high order modulation growth	Extend VHF capability Use Digital physical layer pipe (PLP) to add aero mobile Rx only	Cellular White space S/W Radio Disparate Band Aggr	Cellular White space S/W Radio Disparate Band Aggr	Micom white space S/W Radio Disparate Band Aggreg	SWIM, FMS,ATCAT M,CNSAOC, AIS,MET,AAC security, graphical data, RT video	Complement or Replace VHF comm	ADS-B Air-to-Air Air-to-Ground Surv. Hybrid TCAS & SSR Surv.	Expand data communications	BW to support additional A-A Comm. Reduces congestion on 1090 Wx ,TIS-B FIS-B	Reuse Radar Band Existing antenna equipt Transfer of Wx data FIS Inter fleet	Satcom Spectrum Reuse Enhanced protocols Directional Antenna Software Radio
TRL Level	Product	TRL-1	Product	TRL-1	TRL-1	TRL-1	TRL-1	Product	Product	Product	Product	Product	TRL-1	TRL-5

New Concepts / Approaches

Figure 81 – Functional Attributes &Characteristics of Existing Candidates (2 of 4)



SATCOM (A-A and A-G)

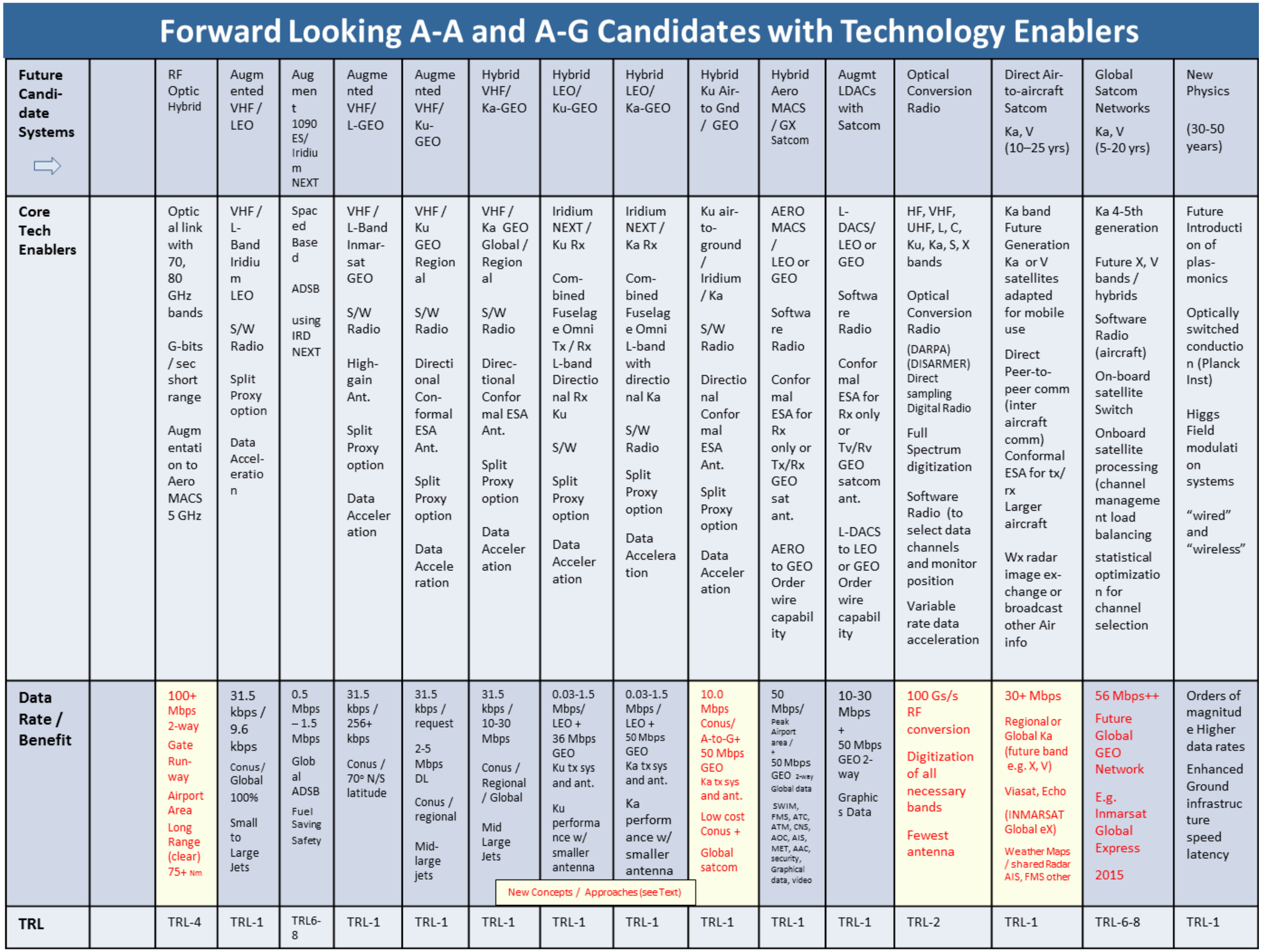
Existing Candidate ⇨ ⇩ Attributes	**Ka GEO** **One hop w/ on board Switch / Processor**	**Ku GEO** **Intelsat** **GoGo** **Panasonic Epic**	**Ka GEO** **ViaSat-1** **Jupiter-1** **Inmarsat Global eXpress I-5 satellites**	**L LEO** **Iridium / NEXT**	**L GEO** **Inmarsat Aero C, H, H+, I, mini-M Swift 64, SwiftBroadband**
Band	19.7-20.2 GHz	Rx 10.7-12.75 Tx 13.75-14.5 GHz	19.7-20.2 GHz receive 29.5-20.0 transmit	1618.85 to 1626.5 MHz band *(Standard)* *1617.775 to 1618,725 & 1618.725 to 16626.5 MHz (New)*	L-Band 1525-1660.5 MHz
Bandwidth	500 MHz	36-72- MHz Regional / CONUS spot beams	125 MHz Commercial Transponder 62 dBW GX 40 MHz 52 dBW	41.667kHz access 31.5 kHz occupied User (standard)	INMARSAT-4 200 KHz on any multiple 630 channels
User Data Rate	50 Mbps down / aircraft 10-15Mbps peer to peer switch HughesNet, ViaSat	10-50 Mbps down / 64-1 kbps return per transponder 1-15 Mbps / user channel	72 x 2 Gbps spot beam (Viasat-1) 1-15 Mbps user channels Up to 50 Mbps per platform	2.4 -9.6 kbps Differentially encoded QPSK std channel bonding compression FDMA/ TDMA End-to-end IP 512 - 1.5 Mbps NEXT gen	Swift Broadband 432kbps Stream 32,64, 128, 224, ISDN, SMS, Voice Swift 64 – 432 kbps 256 kbps Aero H 10.5 Kbps Aero H+ 10.5 kbps Aero I 4.8 kbps Aero M 2400 bps
Antenna	Est. 0.6–1.2 meter High gain / steerable directional est. >35 dBi	Panasonic Ku est 0.8-1.0 meter aperture Steerable directional	Honeywell ARINC 791 Fuselage Ka Steerable Directional 0.6-1.2-2.4 meter Cobham Paradigm, Skyware	Hemispherical Patch minimum angle 8.2 degrees for standard (TBD for NEXT service)	High-gain, Intermediate, low Gain
Link Spectral Efficiency (bps/Hz)	TBA FCC NPRM pending	1.5-3.0 bps/Hz Clear 1.0-2.5 bps/Hz Rain UL 1.0-1.2 bps/Hz Clear 0.8-1.0 bps/Hz Rain DL @ 52 dBW	3.5-4.1 bps/Hz Clear 0.5-1.0 global beam rain 2.0-3.2 spot beam rain UL 1.2-1.6 1.5-1.7 clear 0.7-1.0 bps/Hz DL @ 62 dBW (52 dBW GX)	Estimated 2 to 3 bps/Hz.	Estimated 1.5-3 bps/Hz .
Availability and Coverage	Regional terrestrial (CONUS 50 %) deployed	Regional World-Wide 99.5-99.9+ % moderate-low rain fade depending on margin	99.0-99.5 % net availability higher rain fade (tropical –arid) Regional beams/ Global 70 deg N/S	99% mission DoD True Global coverage	99.9% service availability Global <70 deg N/S latitude

Figure 82 – Functional Attributes &Characteristics of Existing Candidates (3 of 4)

SATCOM (A-A and A-G) (cont.)

Existing Candidates ⇨ ⇩ Attributes	**Ka** **GEO** **One Hop w/ on board Switch / Processor**	**Ku** **GEO** **Intelsat** **GoGo** **Panasonic** **Epic**	**Ka** **GEO** **ViaSat-1** **Jupiter-1** **Inmarsat** **Global eXpress** **I-5 satellites**	**L** **LEO** **Iridium / NEXT**	**L** **GEO** **Inmarsat** **Aero C, H, H+, I, mini-M** **Swift 64, SwiftBroadband**
Latency	350 ms one way + transceiver and NOC systems	400-600 ms	400-600 ms	270-390 ms voice 427 ms – 1.7 sec circuit data 1 sec 100 bytes Larger packets up to20 sec SBD	SB 1200-3500 ms Inmarsat-2 Global beam Inmarsat-3 Global + 7 spots Inmarsat-4 Global + 19 / 200
Comm Range	Geo Sat Regional Illumination (1000s km) of individual 100s km spot beams	GEO sat Regional Beam 1000s km	Global Express (L/Ka) 8000 Nm each satellite Viasat, Jupiter (fixed) GEO sat 100s km's spot , 2000 main	LEO sat Regional Beams, Global network	Global Beam Approximately 120 degrees longitude
Capacity	>100 Gbps Jupiter 1 Viasat small spot beam (100s km)	10-50 Mbps/ 2Mbps x 15 IP network multiplex = 75 to 375 clients a/c	50 Mbps /2Mbit x 15 IP network multiplex factor = 375 clients a/c	1100 x 3kHz voice channels per satellite spot x 66 sat (standard) Iridium NEXT (TBA)	Inmarsat-4 680 x 200kHz data channels x 3 global spacecraft
Vulnerabilities **Disadvantages**	Ka Transmit requires large antenna area May be unsuitable for smaller aircraft	Moderate Security larger antenna may not be suitable for smaller aircraft regional coverage 5-60 minute handoff outage	Moderate Security Large antenna Rain fade (outages) L-band I-4 backup Service limited to 70 latitude <45 sec handoff outage	Moderate Security Cost - Higher equipment and service cost	Moderate Security Cost – Higher equipment and service cost
New Capabilities/ Opportunity **Advantages**	Trend to onboard switches Inmarsat mobile, Hughes , Viasat fixed . Enables air-to-air via one hop . Future WxR information, Inter-fleet data, FMS, long range ADS-B.	FMS, weather data augmentation to cabin broadband Use software radio to add available transponder on same or adjacent satellite Use conformal directional ESA	FMS, weather data augmentation to cabin broadband Use SDR to pick regional transponders Use conformal directional ESA	FMS, weather Land / ocean New NEXT satellites - higher speed L-band 256k – 1.5 Mbps True global availability w/ minimal antenna for small aircraft Global ADS (Iridium NEXT)	Legacy band widths and data rates 356k +
TRL Level	TRL-5	Product	TRL-6-8 New Concepts / Approaches	Product (standard IRIDIUM) TRL-6-8 (IRIDIUM NEXT)	Product

Figure 83 – Functional Attributes &Characteristics of Existing Candidates (4 of 4)



Forward Looking A-A and A-G Candidates with Technology Enablers

Future Candidate Systems ⇨		RF Optic Hybrid	Augmented VHF / LEO	Augment 1090 ES/ Iridium NEXT	Augmented VHF/ L-GEO	Augmented VHF/ Ku-GEO	Hybrid VHF/ Ka-GEO	Hybrid LEO/ Ku-GEO	Hybrid LEO/ Ka-GEO	Hybrid Ku Air-to Gnd / GEO	Hybrid Aero MACS / GX Satcom	Augmt LDACs with Satcom	Optical Conversion Radio	Direct Air-to-aircraft Satcom Ka, V (10–25 yrs)	Global Satcom Networks Ka, V (5-20 yrs)	New Physics (30-50 years)
Core Tech Enablers		Optical link with 70, 80 GHz bands G-bits / sec short range Augmentation on to Aero MACS 5 GHz	VHF / L-Band Iridium LEO S/W Radio Split Proxy option Data Acceleration	Spaced Based ADSB using IRD NEXT	VHF / L-Band Inmarsat GEO S/W Radio High-gain Ant. Split Proxy option Data Acceleration	VHF / Ku GEO Regional S/W Radio Directional Conformal ESA Ant. Split Proxy option Data Acceleration	VHF / Ka GEO Global / Regional S/W Radio Directional Conformal ESA Ant. Split Proxy option Data Acceleration	Iridium NEXT / Ku Rx Combined Fuselage Omni Tx / Rx L-band Directional Rx Ku S/W Split Proxy option Data Acceleration	Iridium NEXT / Ka Rx Combined Fuselage Omni L-band with directional Ka S/W Radio Split Proxy option Data Acceleration	Ku air-to-ground / Iridium / Ka S/W Radio Directional Conformal ESA Ant. Split Proxy option Data Acceleration	AERO MACS / LEO or GEO Software Radio Conformal ESA for Rx only or Tx/Rx GEO sat ant. AERO to GEO Order wire capability	L-DACS/ LEO or GEO Software Radio Conformal ESA for Rx only or Tv/Rv GEO satcom ant. L-DACS to LEO or GEO Order wire capability	HF, VHF, UHF, L, C, Ku, Ka, S, X bands Optical Conversion Radio (DARPA) (DISARMER) Direct sampling Digital Radio Full Spectrum digitization Software Radio (to select data channels and monitor position Variable rate data acceleration	Ka band Future Generation Ka or V satellites adapted for mobile use Direct Peer-to-peer comm (inter aircraft comm) Conformal ESA for tx/ rx Larger aircraft Wx radar image ex-change or broadcast other Air info	Ka 4-5th generation Future X, V bands / hybrids Software Radio (aircraft) On-board satellite Switch Onboard satellite processing (channel management load balancing statistical optimization for channel selection	Future Introduction of plas-monics Optically switched conduction (Planck Inst) Higgs Field modulation systems “wired” and “wireless”
Data Rate / Benefit		100+ Mbps 2-way Gate Run-way Airport Area Long Range (clear) 75+ Nm	31.5 kbps / 9.6 kbps Conus/ Global 100% Small to Large Jets	0.5 Mbps – 1.5 Mbps Global ADSB Fuel Saving Safety	31.5 kbps / 256+ kbps Conus / 70º N/S latitude	31.5 kbps / request 2-5 Mbps DL Conus / regional Mid-large jets	31.5 kbps / 10-30 Mbps Conus / Regional / Global Mid Large Jets	0.03-1.5 Mbps/ LEO + 36 Mbps GEO Ku tx sys and ant. Ku performance w/ smaller antenna	0.03-1.5 Mbps / LEO + 50 Mbps GEO Ka tx sys and ant. Ka performance w/ smaller antenna	10.0 Mbps Conus/ A-to-G+ 50 Mbps GEO Ka tx sys and ant. Low cost Conus + Global satcom	50 Mbps/ Peak Airport area / + 50 Mbps GEO 2-way Global data SWIM, FMS, ATC, ATM, CNS, AOC, AIS, MET, AAC, security, Graphical data, video	10-30 Mbps + 50 Mbps GEO 2-way Graphics Data	100 Gs/s RF conversion Digitization of all necessary bands Fewest antenna	30+ Mbps Regional or Global Ka (future band e.g. X, V) Viasat, Echo (INMARSAT Global eX) Weather Maps / shared Radar AIS, FMS other	56 Mbps++ Future Global GEO Network E.g. Inmarsat Global Express 2015	Orders of magnitude Higher data rates Enhanced Ground infrastructure speed latency
TRL		TRL-4	TRL-1	TRL6-8	TRL-1	TRL-1	TRL-1	TRL-1	TRL-1	TRL-1	TRL-1	TRL-1	TRL-2	TRL-1	TRL-6-8	TRL-1

New Concepts / Approaches (see Text)

Figure 84 – Technology Enablers & Benefit of Low TRL Future Candidates

10.3 Identification of How Candidates Are or Can Be Integrated in the Future

The future NAS will have operational requirements for which the individual or integrated A-A and A-G communication candidates need to collectively meet the operational, performance, and safety requirements.

Today's A-G communications systems (VHF, HF, and SATCOM) a combination of LOS communications (VHF), BLOS long range communications (HF), and SATCOM (essentially global coverage or at least coverage below 70 degrees latitude) together form a communications system network such that communications with ATC is available in all airspaces. It is envisioned that a similar requirement will be imposed on the future airspace. Data communications also support surveillance functions today (SSR transponders).

Today's A-A communication systems are rather limited to relatively short range LOS, and include TCAS and VHF common traffic advisory frequency (CTAF).

Over the NAS modernization timeframe, the communications associated with CNS functions need to be supported aligned with the intended operations in the various airspaces. Figure 85 identifies the airspaces where a given candidate provides a level of service that is expected to be commensurate with the required communications performance necessary to support some ATM-relevant communications. This figure is a notional simplification. Some candidates can support ATM applications in other airspace (e.g., MEO SATCOM can also support communications in surface and terminal environments).

		Airspace				
#	Communications Candidates	Surface	Terminal	En Route	Oceanic/Remote	Polar
A-A	Air-to-Air (A-A) Communications Candidates					
1	VHF A-A	X	X	X	X	X
2	UHF A-A	X	X	X	X	X
3	L-Band A-A	X	X	X	X	X
4	S-Band A-A	X	X	X	X	X
5	C-Band A-A	X	X	X	X	X
6	X-Band A-A	X	X	X	X	X
7	Optical A-A	X	X	X	X	X
8	Hybrid RF/Optical A-A	X	X	X	X	X
9	LEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	X
10	GEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	
11	MEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	X
12	GEO + HEO SATCOM A-A (One Hop through Sat.)	X	X	X	X	X
A-G	Air-to-Ground (A-G) Communication Candidates					
1	HF A-G				X	X
2	VHF A-G	X	X	X		
3	UHF A-G	X	X	X		
4	L-Band A-G	X	X	X		
5	S-Band A-G	X	X	X		
6	C-Band A-G	X	X	X		
7	Optical A-G	X	X			
8	Hybrid RF/Optical A-G	X	X	X		
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)	X	X	X		
10	DTV VHF/UHF Network	X	X	X		
11	Cellular Network (e.g., Aircell)	X	X	X		
12	LEO SATCOM Network (e.g., Iridium Next+)	X	X	X	X	X
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)			X	X	
14	MEO SATCOM Network (e.g. GlobalStar+)			X	X	X
15	VHF A-A Hopping for long range A-G Com.				X	X
16	UHF A-A Hopping for long range A-G Com.				X	X
17	L-Band A-A Hopping for long range A-G Com.				X	X
18	X-Band A-G	X	X			
19	GEO + HEO SATCOM Network	X	X	X	X	X

Figure 85 – Notional Communication Candidates by Potential Airspace Applicability

10.3.1 Integration of A-A Communications Candidates

It is envisioned that A-A communications will be supported by at least one of the first 5 communication candidates (including VHF, UHF, L-band, S-band, C-band). Candidates 6 to 12 (X-band, optical, hybrid RF/optical, and SATCOM candidates) could potentially provide higher bandwidth A-A communications, but they are not robust enough from an environmental standpoint (i.e., could be lost in certain atmospheric conditions that are expected to regularly occur within the airspace). The optical candidate could not stand alone as the sole A-A communications candidate, as it would not be practical to be able to point the optical antennas without knowledge of aircraft positions, since free space optical communications have such a narrow beam width.

Candidates 6 to 12 in the right conditions can enable operational concepts (e.g., communicating graphical weather) that would not be practical in the NAS with low bandwidth communications.

Furthermore, candidates 9 to 12 (SATCOM candidates) would have latency and update rates that would not meet the needs for many ADS-B enabled on-aircraft traffic applications and TCAS (eventually ACAS-X) collision avoidance systems.

It is envisioned that having redundant ADS-B communication links (e.g., 1030 and 1090 MHz whereby aircraft transmit periodically on both links, perhaps in a simple alternating pattern) would be a good integration strategy for the future NAS. Such an integration strategy would help improve the robustness of ADS-B to better deal with unintentional jamming that may occur, for instance, with a stuck transmitter.

Thus, the long range future NAS A-A candidate integration strategy will likely include at least one of the first 5 candidates (likely L-Band to support ADS-B / TCAS), plus one or more high bandwidth A-A communication links (candidates 6 to 12). The final A-A candidates integration strategy will be based upon a cost benefits case, assuming that all the operational, safety, and regulatory requirements can be satisfied.

10.3.2 Integration of A-G Communications Candidates

It is envisioned that A-G communications will be supported by several LOS communication candidates (alternatives 2 to 11, 18) including VHF, UHF, L-band, S-band, C-band, and/or X-band). One or more of candidates 6 to 11 and 18 (optical, hybrid RF/optical, C-band, X-band, and potentially broadband terrestrial LOS networks) may be implemented to provide higher bandwidth capabilities.

It is anticipated that ATC communications for domestic enroute, terminal area, and surface will be primarily delivered by a dedicated aeronautical-only service to meet the aeronautical requirements (e.g., robustness, integrity, availability, security, etc.). That service will likely be provided using an appropriate combination of VHF, UHF, L-band, S-band, and/or C-band communication links. It is envisioned that one or more high bandwidth communication link will be integrated into NAS communications to support advanced ATM operations. The candidates that might provide this higher bandwidth link include candidates 7 to 11 and 18 (optical, hybrid RF/optical, X-band, or other terrestrial high BW link). Some of the commercial links may only provide “advisory” information (e.g., weather) rather than ATC clearances, because they may not by meet the aeronautical requirements for more important ATM communications. Other integration strategies may enable the delivery of the information using a less robust commercial link, but may provide robustness (e.g., integrity, security, etc.) verification information on a lower bandwidth dedicated aviation link.

It is anticipated that the primary ATC and AOC communications for oceanic, remote, and polar airspaces will primarily be delivered using SATCOM (candidates 12-14 and 19). It is envisioned that one or more BLOS backup terrestrial communication candidate will be needed to support critical aeronautical applications in the oceanic, remote, and polar airspaces. That backup will likely come from HF or a link that leverages A-A LOS hopping to obtain BLOS communications (candidates 1, and 15 to 17).

Thus, the long range future NAS A-G candidate integration strategy will likely include an optimum mix of dedicated aviation links (e.g., HF, VHF, L-band, C-band, optical, etc. per candidates 1 to 8, plus candidate 18) plus a set of commercial links that provide high bandwidth domestic and remote/oceanic/polar communications (candidates 9 to 14, and 19). Candidates 15 to 17 potentially may become feasible alternatives to HF, to provide long range BLOS communications to backup SATCOM. The final A-G communications integration strategy will be based upon a cost benefits case, assuming that all the operational, safety, and regulatory requirements can be satisfied.

11 EMERGING ADS-B/ADS-R/TIS-B, 1090 SPECTRUM CONGESTION, & WAYS TO IMPROVE ADS-B SYSTEM & COST EFFECTIVENESS

The 1090 MHz spectrum has been used for many years to support Secondary Surveillance Radar (SSR) surveillance and TCAS. Its use is emerging to support aircraft reporting of their position via ADS-B, as well as supporting the correspondingly emerging ADS-R and TIS-B ground surveillance services.

Due to the numerous systems competing for 1090 MHz spectrum, along with the potential growth of air traffic in the future that will contribute more 1090 MHz users to the environment, the possibility exists that the 1090 MHz frequency will be congested to the point that existing and future systems will not meet their required performance levels. This could result in ADS-B services on 1090 MHz not being able to support planned or future ADS-B applications required for the NAS transition to NextGen and beyond. In addition, existing surveillance (SSR) and collision avoidance (TCAS) systems could be degraded such that they would no longer be able to fully support their operational missions.

This section of the report: 1) describes the emerging ADS-B, ADS-R, and TIS-B surveillance systems and identifies the quality of service required for the air-to-air and air-to-ground data links associated with these systems, 2) presents an analysis of the ability of the 1090 MHz spectrum to meet the ADS-B air-to-air data communication update interval requirements under various traffic growth rate assumptions, 3) presents an analysis of the ability of the 1090 MHz spectrum to meet the TCAS performance requirements under various traffic growth rate assumptions, 4) identifies ADS-B/ ADS-R /TIS-B system concerns, potential system improvements that should be considered over the modernization time horizon, and potential ways that ADS-B could be made more cost effective, and 5) presents emerging and future ADS-B IN applications. These five topic areas are presented below in subsections 11.1 to 11.5, respectively.

11.1 Emerging ADS-B / ADS-R / TIS-B Surveillance Systems

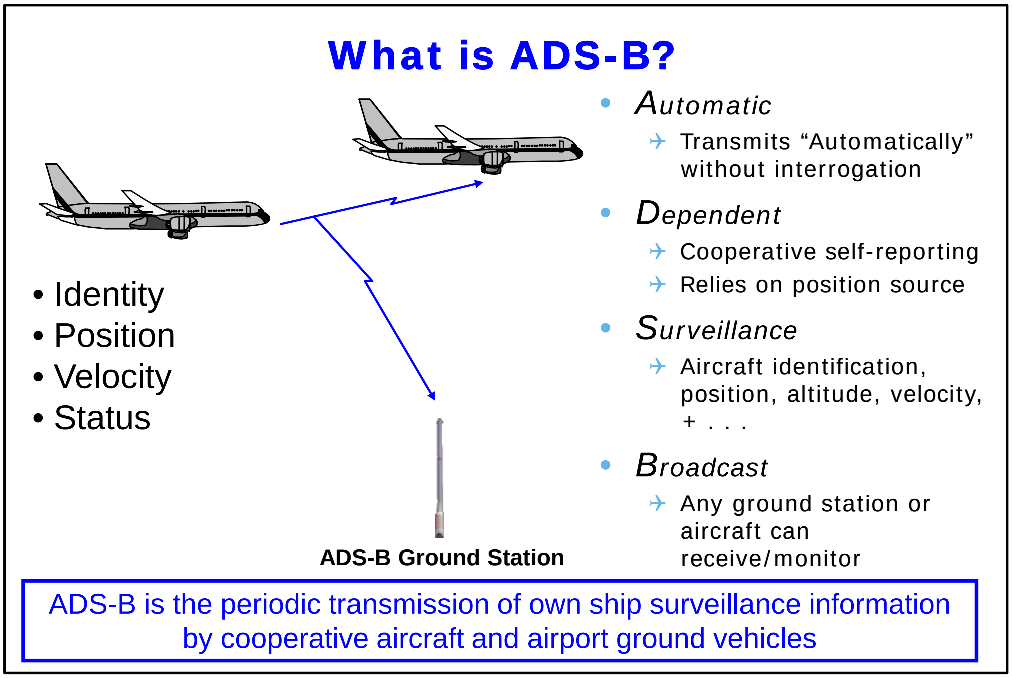
ADS-B is an integral system in plans for upgrading the aviation infrastructure around the world to support enhanced aircraft operations. In the United States, ADS-B along with companion systems of Automatic Dependent Surveillance-Rebroadcast (ADS-R) and Traffic Information Services-Broadcast (TIS-B) are important systems that are part of the Federal Aviation Administration’s (FAA) plan to overhaul the National Airspace Air Transportation System, which is referred to as NextGen (short for Next Generation). NextGen has been architected to improve the safety, efficiency, capacity, security, and environmental friendliness of the air transportation system through the use of advanced operational procedures enabled by combining ADS-B with better navigation, communications, and information management systems. As part of the transformation to NextGen, the FAA plans to transition from using radar to using ADS-B as its primary means of Air Traffic Control surveillance post 2020 and approve ADS-B enabled on-aircraft applications that support reduced aircraft spacing and delegated separation. Similarly in Europe, ADS-B is viewed as an integral system to enable the Single European Sky Air Traffic Management Research (SESAR) initiatives for improving the air transportation system in Europe.

11.1.1 Automatic Dependent Surveillance – Broadcast (ADS-B)

11.1.1.1 ADS-B Overview

ADS-B is an emerging air traffic surveillance technology that enables suitably equipped aircraft and airport ground vehicles to be tracked by: 1) air traffic controllers without the need for conventional radar, and 2) pilots of other aircraft that are equipped with ADS-B receive equipment. ADS-B traffic surveillance information transmitted by equipped aircraft and airport ground vehicles (referred to as ADS-B OUT) is expected to replace radar as the primary source of traffic surveillance used by air traffic controllers to control aircraft worldwide. Equally important, ADS-B will enable a broad range of on-aircraft applications (referred to as ADS-B IN) that will allow pilots to more safely and efficiently operate their aircraft at reduced distances from other traffic.

More accurate than radar, ADS-B systems determine their own ship surveillance information very precisely using Global Navigation Satellite System (GNSS) receivers (or in the future, other suitable position source like APNT) installed on the aircraft or vehicle. With a more precise understanding of the location of aircraft and operationally relevant airport ground vehicles, the air transportation system can be designed to make better use of the airspace. ADS-B is a lower cost surveillance technology than radar and it enables both pilots and Air Traffic Controllers (ATC) to "see" and control aircraft with more precision over a far larger portion of the earth than has ever been possible before. See Figure 86.



What is ADS-B?

- Identity
- Position
- Velocity
- Status

ADS-B Ground Station

- *Automatic*
  - ✈ Transmits "Automatically" without interrogation
- *Dependent*
  - ✈ Cooperative self-reporting
  - ✈ Relies on position source
- *Surveillance*
  - ✈ Aircraft identification, position, altitude, velocity, + . . .
- *Broadcast*
  - ✈ Any ground station or aircraft can receive/monitor

ADS-B is the periodic transmission of own ship surveillance information by cooperative aircraft and airport ground vehicles

Figure 86 – ADS-B Overview

Figure 87 illustrates the concept of operations for ADS-B, which supports operations during all flight phases. ADS-B equipped aircraft and airport ground vehicles use GNSS receivers (or in the future potentially other approved source) to derive precise position and velocity state information, which is augmented with other aircraft/vehicle parameters and transmitted during all phases of operation including oceanic/remote, enroute, terminal, and airport surface operations. This surveillance information is broadcast periodically from aircraft. These transmissions are received and processed by ADS-B ground/satellite system receivers and the surveillance information can be used to support Air Traffic Control Services. The broadcast surveillance information can also be received by ADS-B receivers installed on other aircraft and airport ground vehicles and be used for on-aircraft/vehicle traffic applications. See Figure 88.

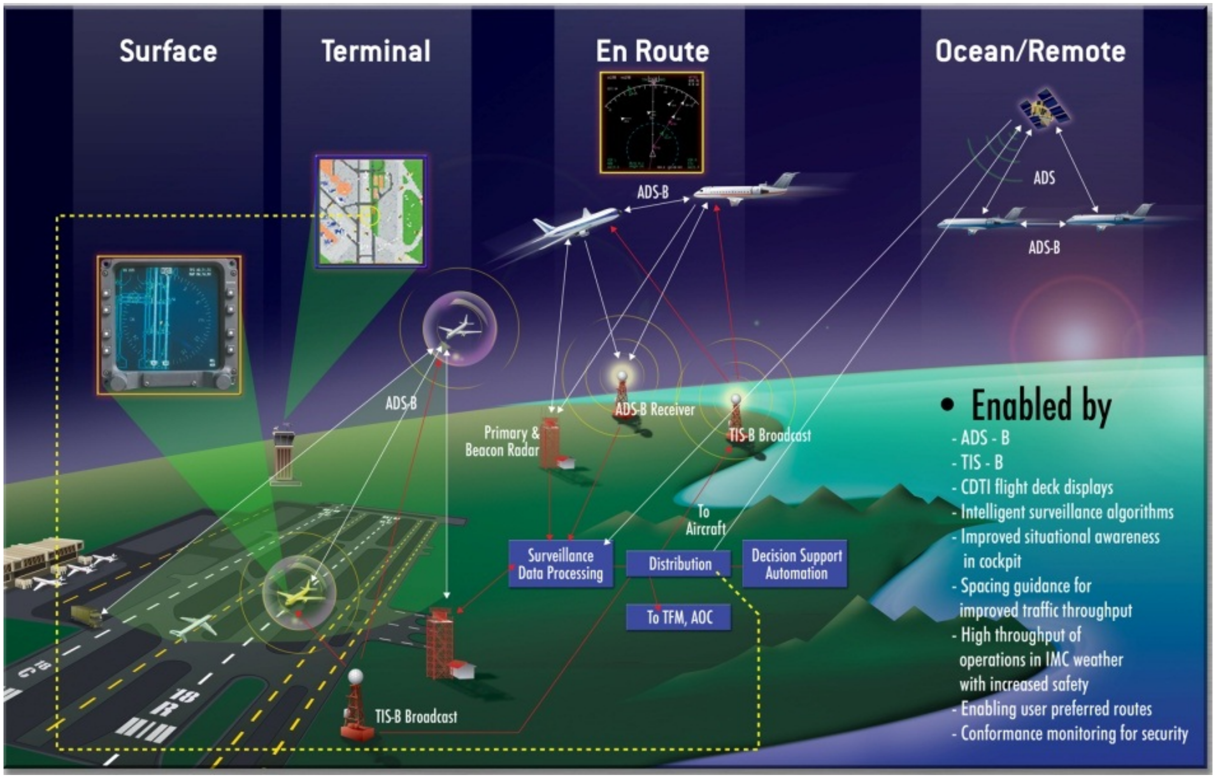
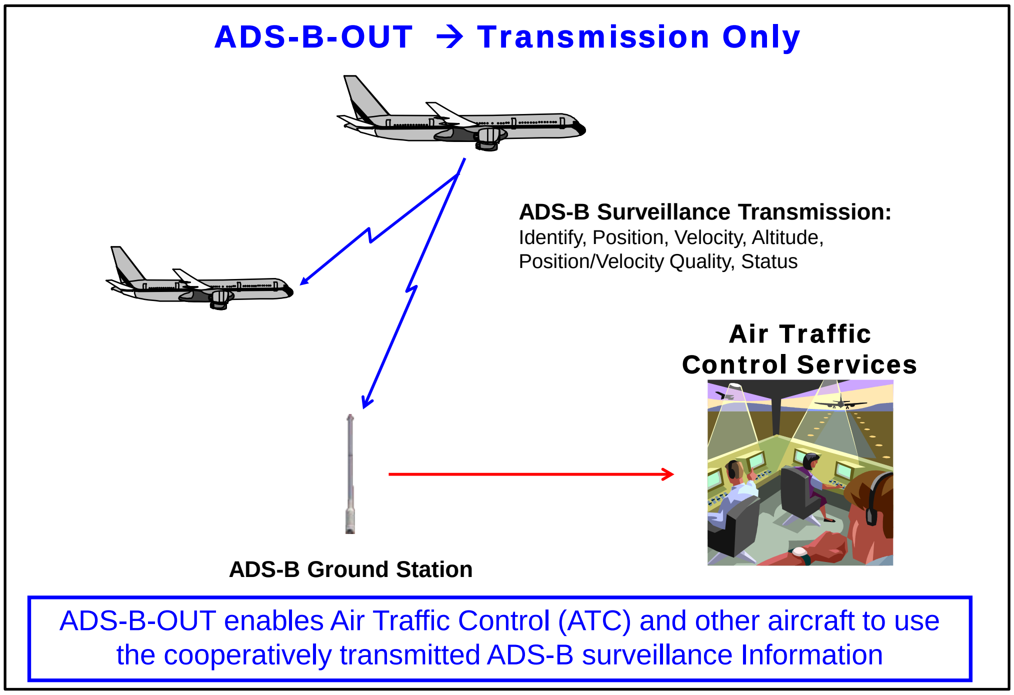


Figure 87 – ADS-B Supports Operations During All Flight Phases



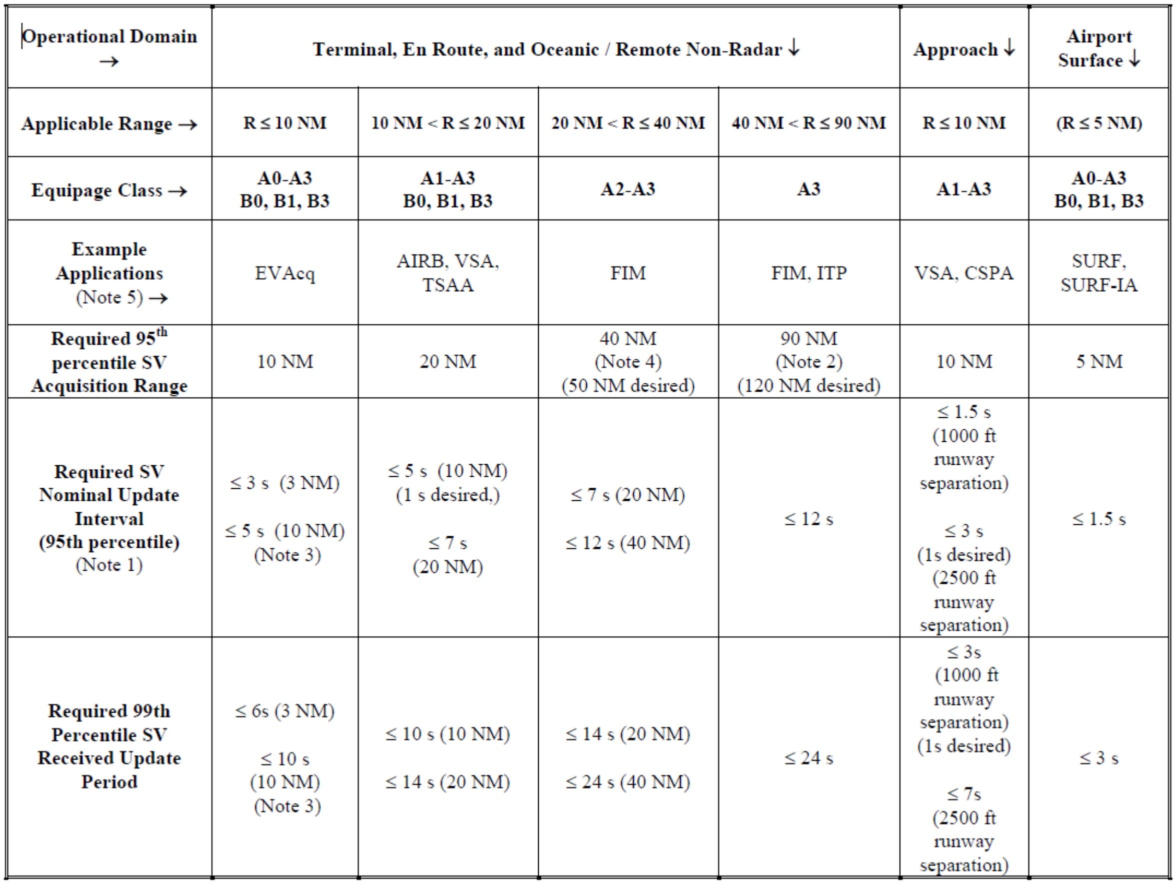
ADS-B-OUT enables Air Traffic Control (ATC) and other aircraft to use the cooperatively transmitted ADS-B surveillance Information

Figure 88 – ADS-B Out: Self Reporting of Aircraft Surveillance Information

11.1.1.2 ADS-B Quality of Service

The Required Communications Performance (RCP) quality of service for ADS-B is as follows [Reference: RTCA/DO-338 MASPS for ADS-B Traffic Surveillance Systems and Applications (section 3.4.3.6 {pages 136-139}), and RTCA/DO-260B MOPS for 1090 MHz Extended Squitter ADS-B and TIS-B Services (section 2.2.5.2 {pages 189-196}].

- Integrity: 10^{-5} per hour
- Availability: 0.9995 per flight hour
- Continuity: 2e-4 per flight hour
- Update Interval: Dependent upon range and equipment classification as indicated in Figure 89
- Range: 90 NM (see Figure 89)
- Transmit Latency: 100 milliseconds (Position Message)



Operational Domain →	**Terminal, En Route, and Oceanic / Remote Non-Radar ↓**				**Approach ↓**	**Airport Surface ↓**
Applicable Range →	**R ≤ 10 NM**	**10 NM < R ≤ 20 NM**	**20 NM < R ≤ 40 NM**	**40 NM < R ≤ 90 NM**	**R ≤ 10 NM**	**(R ≤ 5 NM)**
Equipage Class →	**A0-A3 B0, B1, B3**	**A1-A3 B0, B1, B3**	**A2-A3**	**A3**	**A1-A3**	**A0-A3 B0, B1, B3**
Example Applications (Note 5) →	EVAcq	AIRB, VSA, TSAA	FIM	FIM, ITP	VSA, CSPA	SURF, SURF-IA
Required 95th percentile SV Acquisition Range	10 NM	20 NM	40 NM (Note 4) (50 NM desired)	90 NM (Note 2) (120 NM desired)	10 NM	5 NM
Required SV Nominal Update Interval (95th percentile) (Note 1)	≤ 3 s (3 NM) ≤ 5 s (10 NM) (Note 3)	≤ 5 s (10 NM) (1 s desired,) ≤ 7 s (20 NM)	≤ 7 s (20 NM) ≤ 12 s (40 NM)	≤ 12 s	≤ 1.5 s (1000 ft runway separation) ≤ 3 s (1s desired) (2500 ft runway separation)	≤ 1.5 s
Required 99th Percentile SV Received Update Period	≤ 6s (3 NM) ≤ 10 s (10 NM) (Note 3)	≤ 10 s (10 NM) ≤ 14 s (20 NM)	≤ 14 s (20 NM) ≤ 24 s (40 NM)	≤ 24 s	≤ 3s (1000 ft runway separation) (1s desired) ≤ 7s (2500 ft runway separation)	≤ 3 s

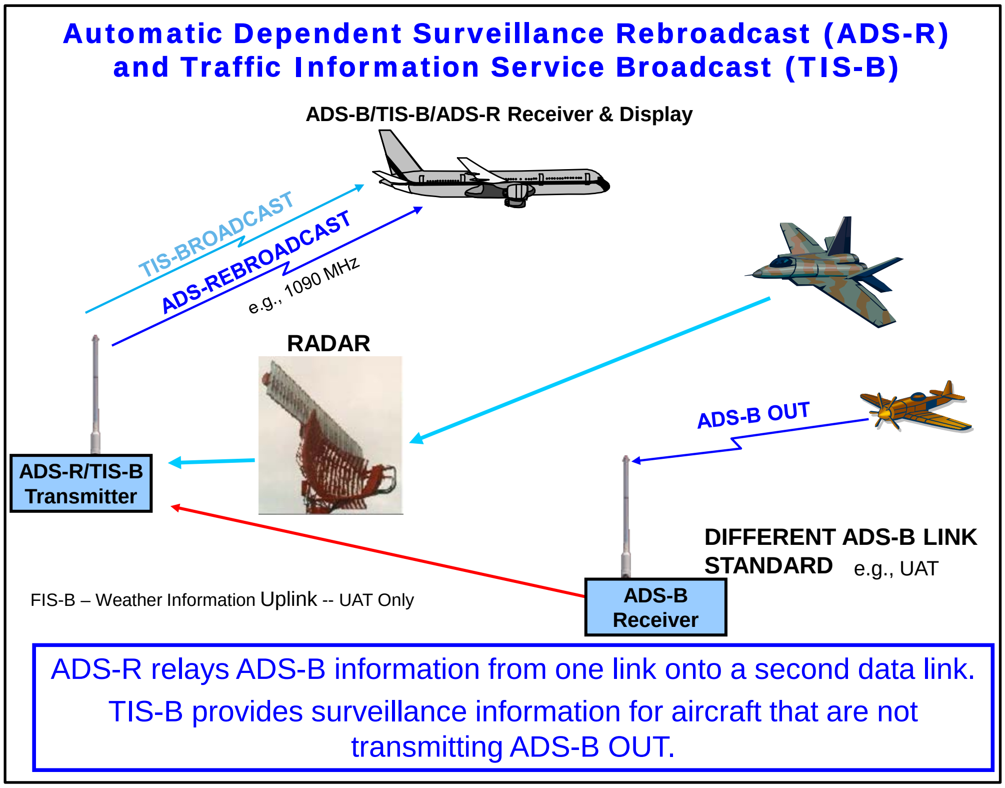
Figure 89 – ADS-B Air-to-Air Range and Update Interval Requirements

[Reference: RTCA/DO-338 MASPS for ADS-B Traffic Surveillance Systems and Applications, Table 3-35, page 129.]

11.1.2 Automatic Dependent Surveillance – Rebroadcast (ADS-R)

11.1.2.1 ADS-R Overview

Automatic Dependent Surveillance – Rebroadcast (ADS-R) is a ground-based traffic information service that relays ADS-B information transmitted by an aircraft or airport ground vehicle using one ADS-B link technology (e.g., UAT) and received by the ground station for subsequent rebroadcast for use by an aircraft or vehicle using another ADS-B link technology (e.g., 1090ES). As shown in Figure 90, the ADS-R system receives ADS-B transmissions by active ADS-B equipped aircraft and continuously monitors the presence of proximate aircraft with differing ADS-B links. When such aircraft are in proximity of each other, the ADS-R system instructs ADS-B ground stations within range of both aircraft to rebroadcast surveillance information received on one link frequency to aircraft on the other link frequency (e.g., UAT to 1090ES and vice versa). The ADS-R multilink gateway service is a companion to the Traffic Information Services-Broadcast (TIS-B) service [described in Section 11.1.3] for providing ADS-B IN aircraft with a complete set of traffic surveillance information for all aircraft.


Automatic Dependent Surveillance Rebroadcast (ADS-R) and Traffic Information Service Broadcast (TIS-B)

ADS-R relays ADS-B information from one link onto a second data link.

TIS-B provides surveillance information for aircraft that are not transmitting ADS-B OUT.

Figure 90 – ADS-B and TIS-B Services

11.1.2.2 ADS-R Quality of Service

The Required Communications Performance (RCP) quality of service for ADS-R is as follows [Reference: RTCA/DO-338 MASPS for ADS-B Traffic Surveillance Systems and Applications (section 3.1.4.3.2 {pages 69-72} and section 3.3.1.3 {page 108}]:

- Integrity: 10^{-5} per message
- Service Availability: 0.999

- Continuity: Not specified in RTCA/DO-338
- Update Interval – Depends upon Service Provided as follows:
  - 2 seconds (95%) within Surface Service Volume for the ADS-R service, which is defined as traffic within 5 NM horizontally and within +/- 2000 feet vertically of each client.
  - 5 seconds (95%) within Terminal Area Service Volume for the ADS-R service, which is defined as traffic within 15 NM horizontally and within +/- 5000 feet vertically of each client.
  - 10 seconds (95%) within Enroute Service Volume for the ADS-R service, which is defined as traffic within 15 NM horizontally and within +/- 5000 feet vertically of each client.
- ADS-R System Latency: 1.1 seconds
- ADS-R Transmit Latency: 100 milliseconds (Position Message)

11.1.3 Traffic Information Services – Broadcast (TIS-B)

11.1.3.1 TIS-B Overview

Not all aircraft will be broadcasting their position via ADS-B. Such conditions may occur for aircraft that are either not ADS-B equipped or in conditions where the ADS-B OUT equipment installed on an aircraft is not operational. Traffic Information Service – Broadcast (TIS-B) is a ground-based traffic information service that fills this traffic surveillance information gap by broadcasting traffic surveillance information for those aircraft/vehicles that are not broadcasting ADS-B surveillance information and for which ground surveillance information is available, such that ADS-B IN equipped aircraft have a complete set of traffic surveillance information for aircraft in their vicinity.

TIS-B receives traffic surveillance information from available non-ADS-B surveillance systems, including radar, Airport Surface Detection Systems (e.g., ASDE-X), and multilateration systems. This surveillance information is processed and correlated with traffic surveillance information that is received via ADS-B. The TIS-B system uses this information to transmit traffic surveillance information for non-ADS-B-equipped aircraft/vehicles to active ADS-B IN users. The TIS-B service is complementary to the ADS-R service and the ADS-B OUT surveillance information provided by other aircraft in order to allow ADS-B IN users to have a complete picture of the nearby traffic without duplication. As of this writing, TIS-B is being implemented by the FAA as described above. In the future, the TIS-B system may be upgraded to provide one or more other modes of operation, including for example: 1) a full traffic mode whereby all traffic known to the TIS-B system in a region is broadcast, or 2) a best available traffic surveillance mode whereby TIS-B will transmit known traffic surveillance information in the conditions where either: a) no ADS-B OUT information is being broadcast directly by a given traffic vehicle, or b) higher quality traffic surveillance information is known by the TIS-B system than is being broadcast by the traffic vehicle on ADS-B OUT.

11.1.3.2 TIS-B Quality of Service

The Required Communications Performance (RCP) quality of service for TIS-B is as follows [Reference: RTCA/DO-338 MASPS for ADS-B Traffic Surveillance Systems and Applications (section 3.1.4.3.1 {pages 66-69} and section 3.3.1.5 {page 109})]:

- Integrity: 10^{-5} per message
- Service Availability: 0.999
- Continuity: Not specified in RTCA/DO-338
- Update Interval – Depends upon Service Provided as follows:
  - 2 seconds (95%) within TIS-B Surface Service Volume, which is defined as traffic within 5 NM horizontally and within +/- 2000 feet vertically of each client.
  - 6 seconds (95%) within TIS-B Terminal Area Service Volume, which is defined as traffic within 15 NM horizontally and within +/- 3500 feet vertically of each client.
  - 12.1 seconds (95%) within TIS-B Enroute Service Volume, which is defined as traffic within 15 NM horizontally and within +/- 3500 feet vertically of each client.
- TIS-B System Latency: 1.525 seconds
- TIS-B Transmit Latency: 100 milliseconds (Position Message)

Note: The vertical service volume for TIS-B and ADS-B services in the Terminal Area and Enroute are defined differently as indicated.

11.2 ADS-B [1090ES] Performance Assessment with Increasing Traffic Levels

ADS-B performance for a range of possible future traffic levels was assessed and the results have been documented in the FAA's "1090 MHz Spectrum Mitigation Alternatives Analysis – Interim Report," v1.0 (dated August 23, 2012). The information in this subsection has been extracted from this report which predicts that without other mitigations that ADS-B performance on 1090 MHz is predicted not to meet the required air-to-air update rate performance in the NAS (without mitigation) by as early as 2020, assuming a 2.5% year-over-year traffic growth rate.

ADS-B air-to-air performance has been assessed in terms of meeting the required 95% update interval achieved at a given receiver under various environmental and operating conditions. For the purposes of the analysis that is presented in this subsection, the required update intervals for various operating ranges were based on the RTCA Minimum Aviation System Performance Standards (MASPS) for ADS-B Traffic Surveillance Systems and Applications (ATSSA) and are shown in Figure 91 below.

Range (R)	**R ≤ 10 NM**	**10 < R≤ 20 NM**	**20 <R≤ 40 NM**	**40 <R≤ 60 NM**	**60 <R≤ 90 NM**
95% Update Interval	3 sec	7 sec	12 sec	12 sec	12 sec

Figure 91 – ADS-B Air-to-Air Update Interval Requirements

[Reference: 1090 MHz Spectrum Mitigation Alternatives Analysis – Interim Report, by the FAA, v1.0, August 23, 2012, page 12.]

For the 1090ES link, there are multiple equipage classes permitted for use in the NAS, which are described in RTCA DO-260B. For analysis results presented later in this section, two general equipage scenarios were evaluated including:

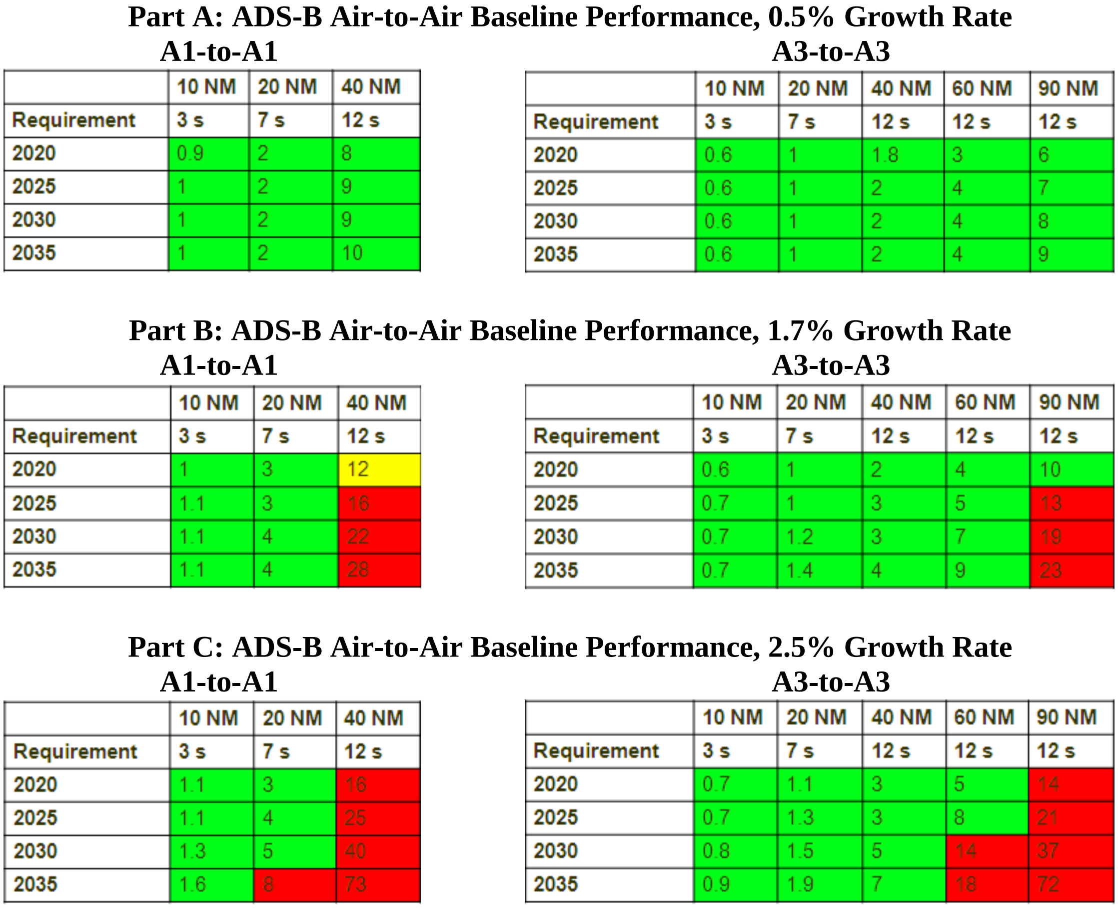
- A1-to-A1: This scenario consists of aircraft pairs where both broadcasting and receiving aircraft are equipped with A1-class avionics that utilize an embedded tracking capability.

Each aircraft is also assumed to employ antenna diversity and dual full receiver/decoder chains. Since no Air-to-Air applications currently defined or being developed for use by the General Aviation community require operation beyond 40 NM, only operating ranges of 10 NM through 40 NM are assessed for A1-to-A1. Although the required maximum range for A1-to-A1 in the ATSSA MASPS is 20 NM, A1-equipped aircraft in the future may wish to participate in applications which may require them to receive updates from aircraft out to 40 NM.

- A3-to-A3: This scenario consists of aircraft pairs where both broadcasting and receiving aircraft are equipped with A3-class avionics that utilize an embedded tracking capability and more advanced decoding techniques. Each aircraft is also assumed to employ antenna diversity and dual full receiver/decoder chains. All ranges are assessed for A3-to-A3.

ADS-B air-to-air performance was assessed using a tool developed by Johns Hopkins University Applied Physics Laboratory (JHUAPL). This tool simulates the operational characteristics of a “victim” ADS-B receiver in order to evaluate ADS-B receive performance in the presence of interference.

Figure 92 presents the results from the assessment of ADS-B air-to-air performance for the two air-to-air equipage scenarios (A1-to-A1 and A3-to-A3) with yearly traffic growth rates of 0.5%, 1.7%, and 2.5%. Each cell in the figure is color-coded to highlight whether the results met the minimum requirement for that operating range: “Green” indicates the requirement was surpassed; “Yellow” indicates a borderline condition, where performance fell within +/- 10% of the minimum requirement; and “Red” indicates a definite failure to meet the minimum requirement (i.e., missed meeting the minimum requirement by more than 10%).



Part A: ADS-B Air-to-Air Baseline Performance, 0.5% Growth Rate

A1-to-A1

	10 NM	20 NM	40 NM
Requirement	3 s	7 s	12 s
2020	0.9	2	8
2025	1	2	9
2030	1	2	9
2035	1	2	10

A3-to-A3

	10 NM	20 NM	40 NM	60 NM	90 NM
Requirement	3 s	7 s	12 s	12 s	12 s
2020	0.6	1	1.8	3	6
2025	0.6	1	2	4	7
2030	0.6	1	2	4	8
2035	0.6	1	2	4	9

Part B: ADS-B Air-to-Air Baseline Performance, 1.7% Growth Rate

A1-to-A1

	10 NM	20 NM	40 NM
Requirement	3 s	7 s	12 s
2020	1	3	12
2025	1.1	3	16
2030	1.1	4	22
2035	1.1	4	28

A3-to-A3

	10 NM	20 NM	40 NM	60 NM	90 NM
Requirement	3 s	7 s	12 s	12 s	12 s
2020	0.6	1	2	4	10
2025	0.7	1	3	5	13
2030	0.7	1.2	3	7	19
2035	0.7	1.4	4	9	23

Part C: ADS-B Air-to-Air Baseline Performance, 2.5% Growth Rate

A1-to-A1

	10 NM	20 NM	40 NM
Requirement	3 s	7 s	12 s
2020	1.1	3	16
2025	1.1	4	25
2030	1.3	5	40
2035	1.6	8	73

A3-to-A3

	10 NM	20 NM	40 NM	60 NM	90 NM
Requirement	3 s	7 s	12 s	12 s	12 s
2020	0.7	1.1	3	5	14
2025	0.7	1.3	3	8	21
2030	0.8	1.5	5	14	37
2035	0.9	1.9	7	18	72

Figure 92 – Predicted 1090 MHz ADS-B Air-to-Air Update Rate as a Function of Airborne Equipment, Range, and Traffic Growth Rate

[Reference: 1090 MHz Spectrum Mitigation Alternatives Analysis – Interim Report, by the FAA, v1.0, August 23, 2012, page 14.]

The results presented in Figure 92 indicate that the 1090 MHz spectrum will not meet the ADS-B air-to-air link update rate requirements (without mitigation) as early as 2020 with a 2.5% yearly traffic growth rate.

11.3 TCAS Performance Assessment with Increasing Traffic Levels

TCAS performance for a range of possible future traffic levels was assessed and the results have been documented in the FAA's "1090 MHz Spectrum Mitigation Alternatives Analysis – Interim Report," v1.0 (dated August 23, 2012). The information in this subsection has been extracted from this report which predicts that without other mitigations that TCAS performance is predicted to not meet the desired performance in the NAS by 2035 with only a 2.5% yearly traffic growth rate.

TCAS performs its collision avoidance function by actively interrogating nearby transponder-equipped aircraft with Mode S and ATCRBS Mode C altitude interrogations, using existing ATCRBS and Mode S signal formats. TCAS tracks ATCRBS-equipped aircraft in its vicinity via a "whisper-shout" power management technique, and Mode S-equipped aircraft using the Mode S squitter for acquisition and discretely addressed interrogations. TCAS also interrogates Mode S-equipped aircraft at different rates based on their collision threat potential.

TCAS determines which transponder-equipped aircraft are a threat based on proximity and direction of flight. Depending on the class of TCAS equipment, the system will issue traffic warnings, up/down maneuver instructions, and/or coordinated advisories. TCAS-issued warnings can be in the form of traffic advisories (TAs) for potential threats, or resolution advisories (RAs) for imminent threats of collision.

A basic performance characteristic of TCAS is called the Risk Ratio, which is defined in terms of the probability of mid-air collision with and without TCAS:

$$\text{Risk Ratio} = \frac{\text{Probability of Near Mid-Air Collision (NMAC) with TCAS}}{\text{Probability of NMAC without TCAS}}$$

The widely accepted goal for the TCAS Risk Ratio is a value of 0.1 or smaller. The risk ratio is comprehensive of all effects, including a surveillance component and a logic component. To achieve the risk ratio of 0.1, TCAS is designed to issue an RA when an intruding aircraft's tau value (time-to-go to Closest Point of Approach) falls below a defined threshold, dependent on the own ship aircraft's altitude, as follows:

< 1000 ft (AGL):	N/A
1000 - 2350 ft:	15 seconds
2350 - 5000 ft:	20 seconds
5000 - 10000 ft:	25 seconds
10000 - 20000 ft:	30 seconds
20000 - 42000 ft:	35 seconds
> 42000 ft:	35 seconds

The aforementioned FAA report stated that TCAS performance can be characterized in terms of the likelihood of having an intruder in track within a sufficient time span so that the appropriate Traffic Advisory (TA) and/or Resolution Advisory (RA) can be issued if required. The likelihood of having an intruder successfully in track by the time an RA needs to be issued must be at least 90% for all expected closing speeds. For the analysis, the likelihood of having an intruder successfully in track by the time a TA needs to be issued was also assessed. Although there does not appear to be a minimum requirement for this performance measure, for this analysis presented here, the same value was applied that was used for the RA case, i.e. 90%.

For the purposes of this analysis presented herein, the northeastern corridor of the U.S. (stretching from the Washington, DC to the Boston, MA metro areas) was assumed to be geographically the worst case environment relative to the impact on spectrum congestion, due to its high density of air traffic, TCAS equipage, and number of operating SSRs. This environment was used as the basis for assessing the TCAS technical performance. Other operating environments, such as busy airport surface areas, may present unique challenges from a spectrum congestion perspective not encountered in high density enroute airspace. Additional analysis of such environments should also be done.

TCAS performance was assessed using a tool developed by MIT Lincoln Laboratory and the results are presented in Figure 93. Each cell is color-coded to highlight whether the results met the minimum requirement for that operating range: “Green” indicates the requirement was surpassed; “Yellow” indicates a borderline condition, where performance fell within +/- 10% of the minimum requirement; and “Red” indicates a definite failure to meet the minimum requirement (i.e., missed meeting the minimum requirement by more than 10%).

Part A: TCAS Baseline Performance, 0.5% Growth Rate

Probability of Track for RA

Closing Speed	368 kts	523 kts	600 kts	780 kts	800 kts	1000 kts	1200 kts
2020	1	1	1	1	1	1	1
2025	1	1	1	1	1	1	0.999
2030	1	1	1	1	1	1	0.999
2035	1	1	1	1	1	1	0.999

Probability of Track for TA

Closing Speed	368 kts	523 kts	600 kts	780 kts	800 kts	1000 kts	1200 kts
2020	1	1	1	1	1	0.999	0.998
2025	1	1	1	1	1	0.999	0.997
2030	1	1	1	1	1	0.999	0.997
2035	1	1	1	1	1	0.999	0.996

Part B: TCAS Baseline Performance, 1.7% Growth Rate

Probability of Track for RA

Closing Speed	368 kts	523 kts	600 kts	780 kts	800 kts	1000 kts	1200 kts
2020	1	1	1	1	1	1	0.999
2025	1	1	1	1	1	0.999	0.998
2030	1	1	1	1	1	0.999	0.996
2035	1	1	1	1	1	0.998	0.994

Probability of Track for TA

Closing Speed	368 kts	523 kts	600 kts	780 kts	800 kts	1000 kts	1200 kts
2020	1	1	1	1	1	0.998	0.994
2025	1	1	1	0.999	0.999	0.997	0.990
2030	1	1	1	0.999	0.999	0.994	0.982
2035	1	1	1	0.999	0.998	0.992	0.973

Part C: TCAS: TCAS Baseline Performance, 2.5% Growth Rate

Probability of Track for RA

Closing Speed	368 kts	523 kts	600 kts	780 kts	800 kts	1000 kts	1200 kts
2020	1	1	1	1	1	0.999	0.998
2025	1	1	1	1	1	0.998	0.995
2030	1	1	1	0.999	0.999	0.996	0.989
2035	1	1	1	0.998	0.998	0.992	0.975

Probability of Track for TA

Closing Speed	368 kts	523 kts	600 kts	780 kts	800 kts	1000 kts	1200 kts
2020	1	1	1	0.999	0.999	0.997	0.990
2025	1	1	1	0.999	0.998	0.993	0.978
2030	1	1	1	0.997	0.996	0.985	0.952
2035	1	1	0.999	0.993	0.992	0.966	0.901

Figure 93 – Predicted TCAS Performance as a function of Aircraft Speed and Traffic Growth Rate

[Reference: 1090 MHz Spectrum Mitigation Alternatives Analysis – Interim Report, by the FAA, v1.0, August 23, 2012, pages 15-16.]

While TCAS use is heavy for the baseline analysis, the report claimed that a 40% reduction in the 1090 MHz utilization by TCAS can be realized if all aircraft currently required to carry TCAS II are required to carry TCAS Hybrid Surveillance. Figure 94 illustrates the concept of Hybrid Surveillance. When an intruder aircraft is far from being a threat, it is primarily passively tracked using ADS-B surveillance information received from that aircraft, with its ADS-B position being validated once per minute using active TCAS interrogations. When the intruder is a near threat in altitude or range, but not both, it is tracked using ADS-B, with its ADS-B position being validated once every 10 seconds or less often depending on range and range closure rate using active TCAS interrogations. When the intruder is a near threat in altitude and range, ADS-B is no longer used, and it is tracked exclusively using active TCAS interrogations once per second.

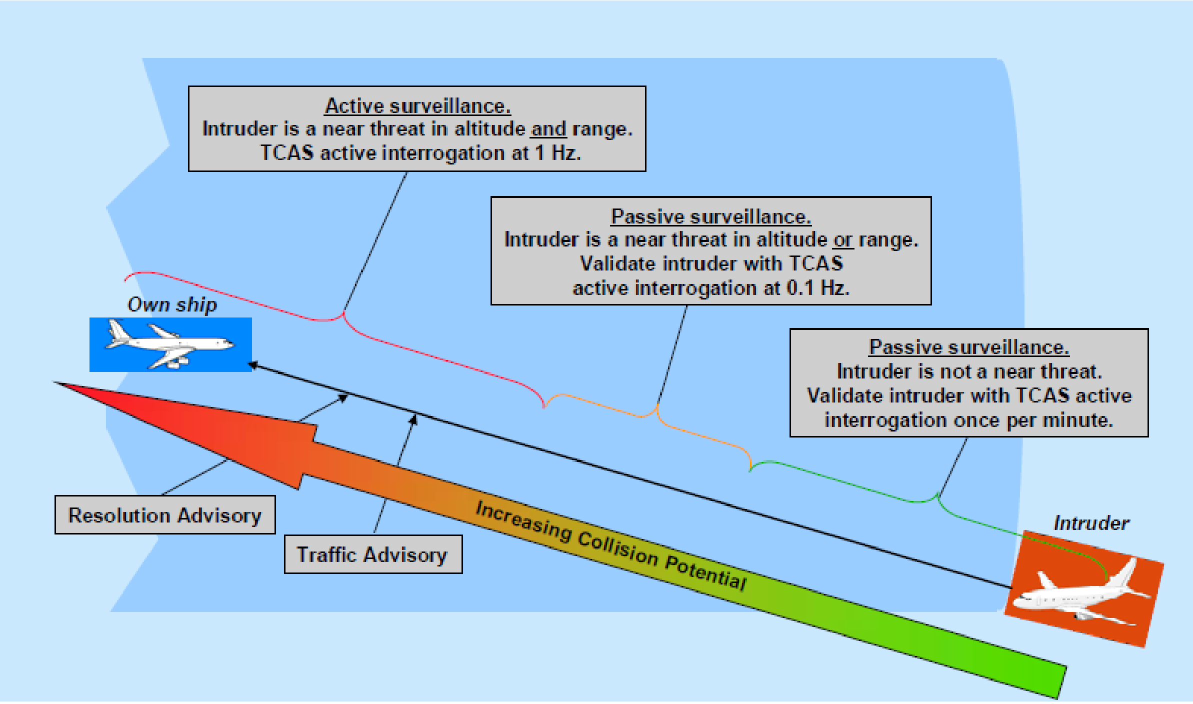


Figure 94 – TCAS Hybrid Surveillance

[Reference: 1090 MHz Spectrum Mitigation Alternatives Analysis – Interim Report, by the FAA, v1.0, August 23, 2012, page 19.]

11.4 ADS-B Concerns, Potential System Improvements, and Cost Effectiveness

ADS-B is an emerging air traffic surveillance technology that enables suitably equipped aircraft and airport ground vehicles to be tracked by: 1) air traffic controllers without the need for conventional radar, and 2) pilots of other aircraft that are equipped with ADS-B receive equipment.

At its core, ADS-B is based on aircraft and airport ground vehicles cooperatively transmitting traffic surveillance information that is updated frequently. The ADS-B surveillance information is typically significantly better than today's traffic surveillance information and, as such, enables a family of ground-based and aircraft-based applications that will improve the safety and operational efficiency of the Air Transportation System.

11.4.1 Concerns with ADS-B System Being Deployed

While ADS-B is being deployed, there are a number of concerns that have been voiced about its implementation, including: 1) frequency congestion on 1090 MHz, 2) poor reception on the airport surface, 3) use of two data link broadcast frequencies, 4) privacy of aircraft operations, 5) security concerns [e.g., the potential disruption of the air transportation system from malicious spoofing, the lack of authentication, open access to information that could be used for malicious purposes], 6) the lack of information that fully supports future air transportation system concepts of operation, and 7) what happens when GNSS is unavailable. Each of these concerns is briefly touched on below.

11.4.1.1 Frequency Congestion on 1090 MHz

The 1090 MHz frequency being used by ADS-B 1090ES is the same frequency that is also used by aircraft transponders for replying to interrogations from both TCAS and secondary surveillance radar systems. With three systems sharing one frequency, there are concerns that in very high traffic density airspace with dense traffic volumes, that it may significantly reduce the usable range for each of these systems. Various mitigations are being explored by the regulatory agencies to address this spectrum congestion issue, including, for example, a next generation of TCAS that will utilize ADS-B surveillance information to reduce the number of interrogations and subsequent replies, known as hybrid surveillance.

11.4.1.2 Poor Reception on the Airport Surface

It is known in the ADS-B community that 1090ES as implemented on aircraft suffers from poor reception between aircraft on the airport surface. Various means to address this problem are being investigated including the required use of both top and bottom mounted antennas, multiple frequencies, different waveforms, etc.

11.4.1.3 Current Use of Two Broadcast Frequencies Necessitates ADS-R Service

In the United States, the FAA allows the use of either 1090ES or UAT (978 MHz) in some airspace. This decision benefits aircraft operators who already have suitable antennas installed on their aircraft; however, not all ADS-B traffic will be visible without the additional cost for implementing the ADS-Rebroadcast (ADS-R) service or requiring the reception of both links. Furthermore, while there are two data links useable for ADS-B, there is no real benefit from having two systems (i.e., potential redundancy benefits of availability, continuity, integrity, and capacity are not being realized).

11.4.1.4 Privacy of Aircraft Operations

In the area of privacy, concerns have been voiced about the potential to track aircraft movements and use that information in ways that were not intended. This might include for example, tracking the movements of special aircraft, or aircraft owned by Very Important People (VIPs) such as celebrities or corporate executives. The ADS-B standards have been developed with a means to mitigate such privacy concerns through the use of anonymous aircraft identifiers.

11.4.1.5 Security Concerns

Security concerns have been voice regarding ADS-B in the areas of insufficient data integrity, lack of authentication, and lack of confidentiality (i.e., open access to information). Various mitigations to address a subset of the security concern are being deployed to confirm ADS-B surveillance information using alternate sources of air traffic surveillance, including for example, multilateration and radar.

11.4.1.6 Lack on Growth Capacity on 1090ES

Because of capacity concerns in high traffic density airspace on 1090 MHz, adding significantly more information to the ADS-B Out broadcasts is likely to be constrained, unless other mitigations are put in place (e.g., hybrid surveillance, which can be applied not only to TCAS, but also SSR).

11.4.1.7 Surveillance Position Source Availability

Another concern often expressed is what happens to ADS-B when the GNSS source used to determine the own ship position and velocity information is not available due to, for example, GNSS outages, interference, or intentional jamming. Various backup strategies are being considered, which include: 1) retaining a backup surveillance system of primary and secondary surveillance radars to maintain Air Traffic Control surveillance in the situation where ADS-B surveillance information becomes unavailable, 2) using surveillance determined from multilateration systems to track aircraft positions when ADS-B surveillance information is not available, and 3) equipping aircraft with one or more alternative sources of position and velocity information suitable to support ADS-B OUT [the latter of which is commonly referred to as Alternative Position, Navigation, and Timing or APNT].

11.4.2 Potential Ways to Improve ADS-B

There are a number of improvements that should be considered and vetted as to the cost/ benefit of various potential improvements for ADS-B to support aircraft operations over the study time horizon. Such potential improvements include:

- Improve ADS-B to better function on the airport surface environment (e.g., fades, nulls, multipath). Potential strategies including changes to the waveform, choice of a different frequency (VHF or UHF), use of multiple frequencies, and use of multiple antennas (e.g., use of both aircraft top and bottom mounted antennas).
- Incorporate communication protocols that support multiple levels of access to information
- Incorporate authentication and other information security protocols
- Improve information integrity (e.g., add data encoding checks) rather than relying on consistency of track information
- Information content: Add additional information (as needed) to support future operations
    - Candidate additional information to support advanced operations includes: aircraft intent information, real time estimates of the aircraft climb/descent performance (to support future ACAS-X separation and collision avoidance functions), continuity information, a characterization of the ADS-B Transmit Quality Level (TQL as defined in RTCA/DO-289), aircraft Application Capability Level (ACL as defined in RTCA/DO-289), other application specific data, vertical position integrity, and velocity integrity information

- Reduce frequency congestion:
    - Use frequency that is not already allocated to other functions, including TCAS and SSR transponders.
    - Consider utilizing whisper/shout mode(s) of operation to support better long range reception while maintaining higher update rates for close traffic
    - Consider changing the transmit update interval based upon intended operations/phase of flight
    - Consider changing from a multiple access technique of random access to a self-organizing TDMA to allow significantly reducing the transmit rate
    - Consider a “smarter” ADS-B network that dynamically adapts to conditions (e.g., to the link loading and the required surveillance performance for the intended operations)
- Transmit ADS-B surveillance information on multiple links: Provides information redundancy, continuity, reduces threat of unintentional interference causing a disruption, and reduces link loading (by distributing the load onto two links rather than one).
- Implement terrestrial and satellite systems such that ADS-B transmissions are received in all airspaces and provided to ATC to support ATM (e.g., use satellites in oceanic, remote, and polar regions to receive ADS-B OUT aircraft transmissions to complement terrestrial ADS-B ground network).

11.4.3 Potential Ways to Make ADS-B More Cost Effective

There are a number of potential ways that should be considered and vetted to make ADS-B even more cost/benefit effective. Such potential improvements include:

- Provide essentially “worldwide” ADS-B coverage through the use of satellites in addition to the ADS-B ground network, such that air traffic separation services can be enhanced with significantly reduced separation minima than today’s procedural separation operations. Within the 50 year modernization time frame, it may become cost effective to support ~5 NM air traffic separation services over oceanic, remote, and polar regions. (Alternatively, it may be more cost effective to have aircraft self-separate in such regions. See autonomous aircraft self-separation concept of operations that is introduced in Section 27.3.)
- Internationally harmonize on one standard for ADS-B. Currently, ADS-B is defined for 1090ES, UAT, and VDL-M4. Having to develop and maintain multiple standards is not cost effective. Needing to install multiple ADS-B systems onboard aircraft that accommodate the transmission and/or reception of multiple ADS-B standards increases costs unnecessarily. This increases not only standardization costs, but also development, certification, installation, training, and maintenance costs.
- Internationally harmonize on one protocol standard and select a frequency (e.g., L-Band) that has the capacity to grow to accommodate the expected traffic increases and growth in communications needed to support future applications. 1090ES is already capacity constrained, and has little growth capability to accommodate future operational needs (e.g., adding significantly more information to the link, including intent information).
- Eliminate the need for the ADS-R service with a single international standard for ADS-B Out. This will reduce ground infrastructure costs.

- ADS-B equipment costs per unit can be driven down by increasing the volume/ number of units sold. Develop ADS-B units that can meet the needs of all aircraft including low end to high end GA aircraft, low end to high end UAVs, helicopters, business/regional/air transport aircraft, special purpose aircraft, space launched vehicles, and the wide range of military aircraft.
- ADS-B equipment costs can be reduced by using waveforms that can re-use COTS chip sets (e.g., cellular radio components).
- Eliminate the random contention media access technique that is currently being used and move toward a self-organizing TDMA structure. This will enable more efficient use of the limited spectrum resource.

11.5 Emerging and Future ADS-B IN Applications

ADS-B IN (see Figure 95) refers to an appropriately equipped aircraft's ability to receive, process, and display information obtained via ADS-B OUT transmissions by other aircraft/vehicles, as well as to receive, process, and display information provided by ground-based surveillance services including Automatic Dependent Surveillance – Rebroadcast (ADS-R), Traffic Information Services – Broadcast (TIS-B), and Flight Information Services – Broadcast (FIS-B). The display of the received surveillance information is processed appropriately for the pilot and is provided on a display commonly referred to as Cockpit Display of Traffic Information (CDTI).

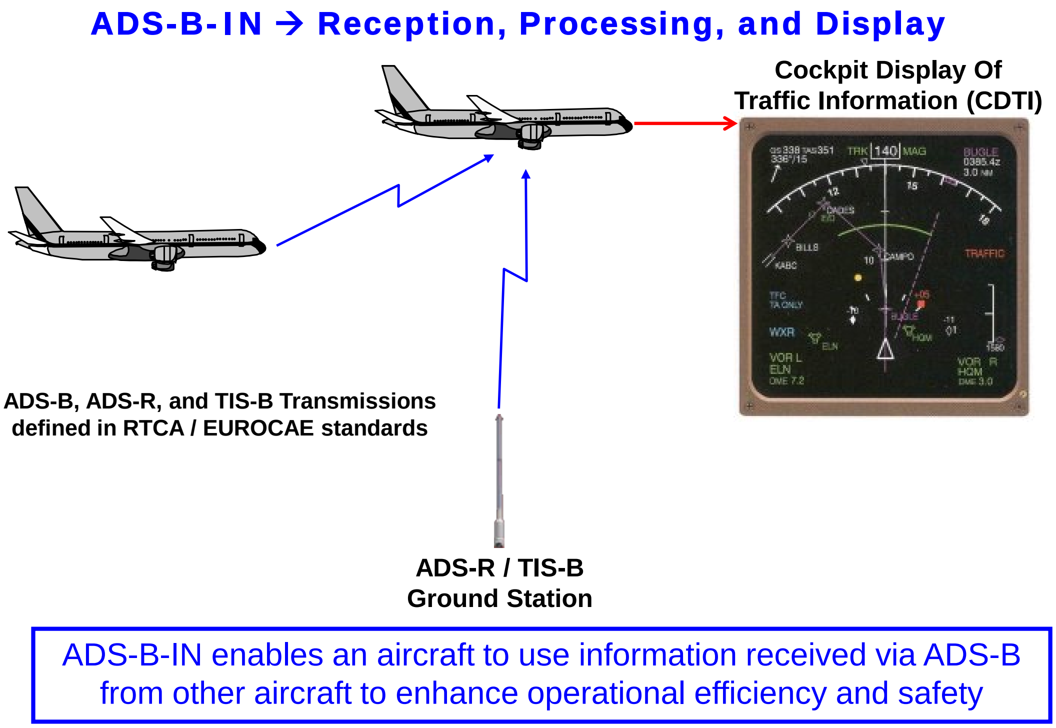


Figure 95 – ADS-B IN On-Aircraft Traffic Applications

Numerous ADS-B IN-enabled traffic applications have been envisioned by the aviation industry to support future NAS operations and are at various stages of development. Some of the traffic applications have been standardized, developed, and have initial fielding, while others are currently being developed and standardized by aviation standards groups including RTCA and EUROCAE. In addition to those that have been already standardized, many more ADS-B IN applications have been proposed. The ADS-B IN applications are being grouped into five broad application categorizes including: 1) Situational Awareness, 2) Extended Situational Awareness, 3) Spacing, 4) Delegated Separation, and 5) Self Separation. A description of each of these five application categories is provided below.

1. **Situational awareness** applications are those that are intended to enhance the pilot's knowledge of surrounding traffic that are in the air as well as those on the airport surface. The improved situational awareness may improve pilot decision making which is expected to result in safer and more efficient flights. There are no changes to the pilot or controller responsibilities for these applications.
2. **Extended situational awareness** applications add provisions to the basic situational awareness applications such as cueing the pilot to traffic conditions through indications and alerts, or providing information that may support a reduced aircraft separation standard during an operational procedure.
3. **Spacing applications** require pilots to achieve and maintain a given longitudinal spacing (or delegated interval) with designated aircraft as specified by ATC instruction. While pilots are given new tasks associated with conducting spacing applications, separation responsibility remains with the controller.
4. **Delegated separation** applications are those where the controller delegates separation responsibility and transfers the corresponding separation task to pilots, who ensure that the applicable separation requirements are met. The separation responsibility delegated to the pilots is limited to designated aircraft within the limitations of the clearance, which is limited in time, space, and scope. Except for the specific limited delegation, separation responsibility for all other aircraft remains the controller's responsibility.
5. **Self-separation** applications are those that require pilots to separate their aircraft from all surrounding traffic in accordance with the applicable separation requirements and flight rules.

Figure 96 identifies a number of example ADS-B IN-enabled applications that have been developed or proposed, including applications from each of the five application categories described above.

Application Category	Name	Acronym	System Require-ments	Avionics Require-ments	Application Description
Situational Awareness	Airborne Situational Awareness	AIRB	DO-319	DO-317	Provides situational awareness of airborne traffic
	Airport Surface Situational Awareness	SURF	DO-322	DO-317	Provides situational awareness of traffic on the airport surface and airborne traffic near the runways
Extended Situational Awareness	Visual Separation on Approach	VSA	DO-314	DO-317	Assist pilots in acquiring and maintaining visual contact with preceding aircraft during visual separation on approach
	Oceanic In-Trail Procedure	ITP	DO-312	DO-317	Assist pilots determine whether the initiation criteria for oceanic climb or descend through are satisfied
	Airport Surface Situational Awareness with Indications and Alerts	SURF IA	DO-323	To be established	Provides situational awareness of traffic on the airport surface and airborne traffic near the runways with indications and alerts
	Traffic Situational Awareness with Alerts	TSAA	DO-338	DO-317	Airborne traffic situational awareness with advisories and alerts to support visual acquisition and avoidance of traffic
Spacing	Flight Deck Interval Management - Spacing (or delegated interval)	FIM-S	DO-328	RTCA MOPS is being developed	Flight Deck based interval management for achieving or maintaining longitudinal spacing from one or more designated aircraft
Delegated Separation	Independent Closely Spaced Parallel Approaches	ICSPA	DO-289	To be established	Airborne application to support conducting independent, simultaneous approaches to closely spaced parallel runways in instrument conditions
	CDTI Enabled Delegated Separation	CEDS	N/A	To be established	Airborne application to support pilots with safely separating from designated aircraft
Self-Separation	Airborne Conflict Management	ACM	DO-289	To be established	Application to prevent loss of separation (Conflict Detection and Resolution) and provide advisory information for trajectories that may cause a conflict (Conflict Prediction)
	Autonomous Flight Rules	AFR	To be established	To be established	Application that enables the flight crew, using on-board systems and procedures, to safely separate from all other aircraft. (See Airborne Self-Separation application described in Section 27.3).

Figure 96 – ADS-B IN Airborne Applications

Note: The most current requirements will be in the latest release of the requirements documents.

12 REQUIRED COMMUNICATIONS PERFORMANCE (RCP) FRAMEWORK

Required Communications Performance (RCP) is intended to characterize the communications capability required to support performance-based Air Traffic Management (ATM) applications without reference to any specific communication technology.

This section of the report documents the RCP framework as it is being developed by ICAO in the context of the broader Required Total System Performance (RTSP) framework, of which RCP is one of the key elements.

12.1 Introduction

The Next Generation Air Transportation System (NextGen) Concept of Operations developed by the Joint Planning and Development Office (JPDO) envisions that the future airspace system will be based upon performance-based operations. The JPDO has identified a number of Operational Improvements (OI's) in its Integrated Work Plan (IWP) for changing the National Airspace for the purposes of realizing capacity, efficiency, safety, and security improvements in NextGen. Many of these OI's depend upon systems and services in NextGen performing their functions at required levels of performance that are yet to be specified.

To realize performance-based operations requires the development of performance-based requirements. ICAO and other industry organizations have begun to conceptualize a hierarchy of performance requirements beginning at the airspace level with Required Air Traffic Management (ATM) Service and Performance (RASP) and flowing down to Required Total System Performance (RTSP), which is the technical performance required to provide the operational functions and performance levels that address the social, political, and business needs of the country from an air transportation system perspective. The purpose of RTSP is to specify the performance of the entire airspace system—aircraft, air navigation service providers, airports, etc. The RTSP requirements then flow down to requirements on the individual components of the total system, including the air-to-ground and air-to-air communications requirements (RCP). It is envisioned that RTSP will mature over the 50 year study period.

12.2 Required Total System Performance (RTSP)

The subsections below provide an overview of the RTSP requirements framework and functional hierarchy of requirements.

12.2.1 Required Total System Performance (RTSP) Framework

Figure 97 is a depiction of the International Civil Aviation Organization (ICAO) concept for how to specify requirements to support performance-based operations. In this concept, high-level needs and desires of government, industry, and society flow down to system performance requirements for the entire air transportation system and then to performance requirements on individual functional components of the system and eventually to specific functional equipment. Performance can be measured at each of the five levels ensuring that the appropriate requirements can be established at each level to achieve the desired goals.

The objective of this model is to specify what is really important to the system performance at each level and ensure that subsequent levels are specified to support the higher level performance needs. Two performance measures are key to the model. The first is the **Required**

ATM Service and Performance (RASP), which was previously known as the "Required Airspace System Performance." RASP deals in numbers of passengers served, acceptable safety margins, efficiency, environmental impact, etc. It defines how the air transportation system as a whole must perform in order to meet the needs of government, industry, and society. The second key performance measure is **Required Total System Performance (RTSP)**, which specifies how well the combined air transportation system, including aircraft, air traffic management, airport services, flight operations services, and other air transportation system services must perform to satisfy the RASP requirements.

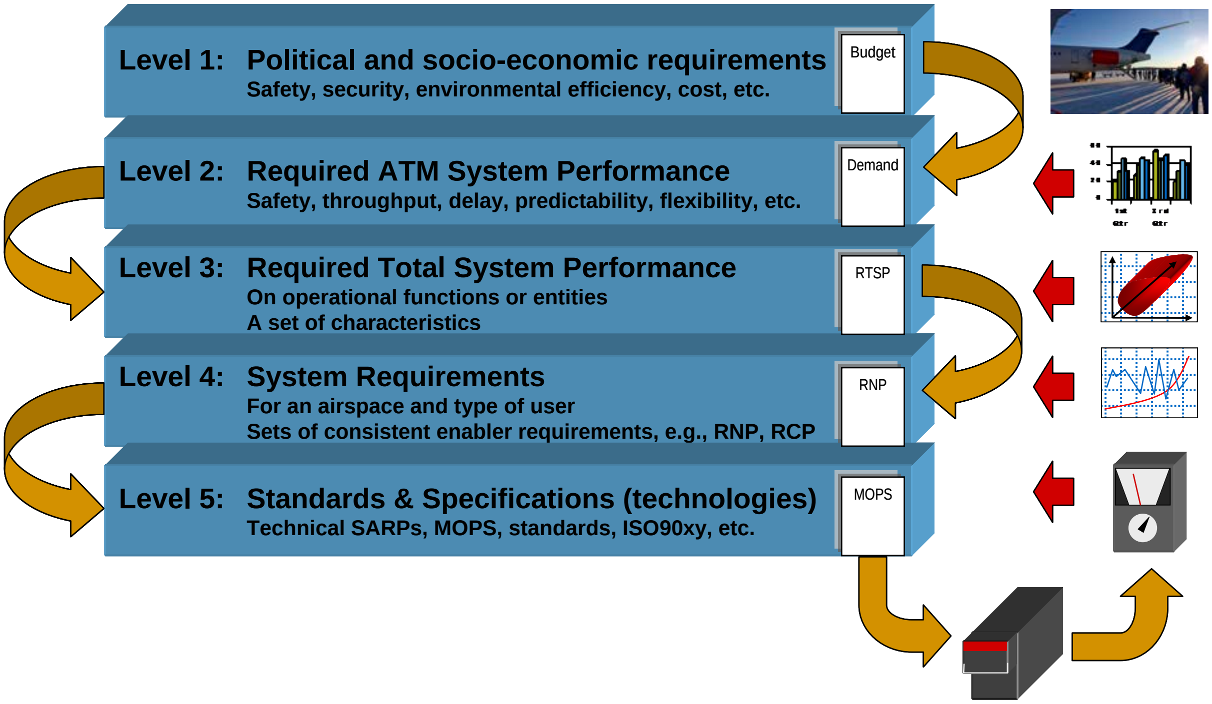


Figure 97 – ICAO Model for Performance-Based Operations

At the highest level, RTSP depends upon information and timing. If every aircraft's 4-dimensional (4D) path were pre-planned to be conflict-free with all other aircraft and constraints (e.g., weather), if each aircraft could always precisely fly its 4D path, and if the exact position and intent of all surrounding aircraft were known by each aircraft, then there would be no need for air traffic control. Every aircraft would have all the information it needed to stay on its flight plan and be confident that no other aircraft was straying into its path. In reality, though, there are many uncertainties and potential failures in the system that necessitate the presence of air traffic control or air traffic monitoring to ensure the safety of those who fly and to expedite traffic flow under adverse conditions. Examples of the uncertainties in the system include uncertainties about the measured position of each aircraft, the measured velocity of each aircraft, the exact time at which a measurement was made, and the delays in communicating and responding. Consequently, RTSP implicitly sets bounds on information accuracy, integrity, latency, continuity, and other lower level performance parameters in order to achieve an acceptable level of operational performance (capacity, separation, sequencing, etc.).

12.2.2 Required Total System Performance (RTSP) Functional Hierarchy

At the time of this study, the RTSP concept (or some equivalent specification) for defining the performance-based airspace requirements has not yet been fully matured. Considerable work must be done to achieve a globally harmonized, standardized set of performance attributes that collectively describe RTSP or its equivalent and all of its various functional decompositions. These functional decompositions would include not only include Required Communication Performance (RCP), Required Navigation Performance (RNP), and Required Surveillance Performance (RSP), but also other dimensions (e.g., required weather detection performance) to meet the required total system performance for supporting the intended airspace operations. This is depicted in Figure 98.

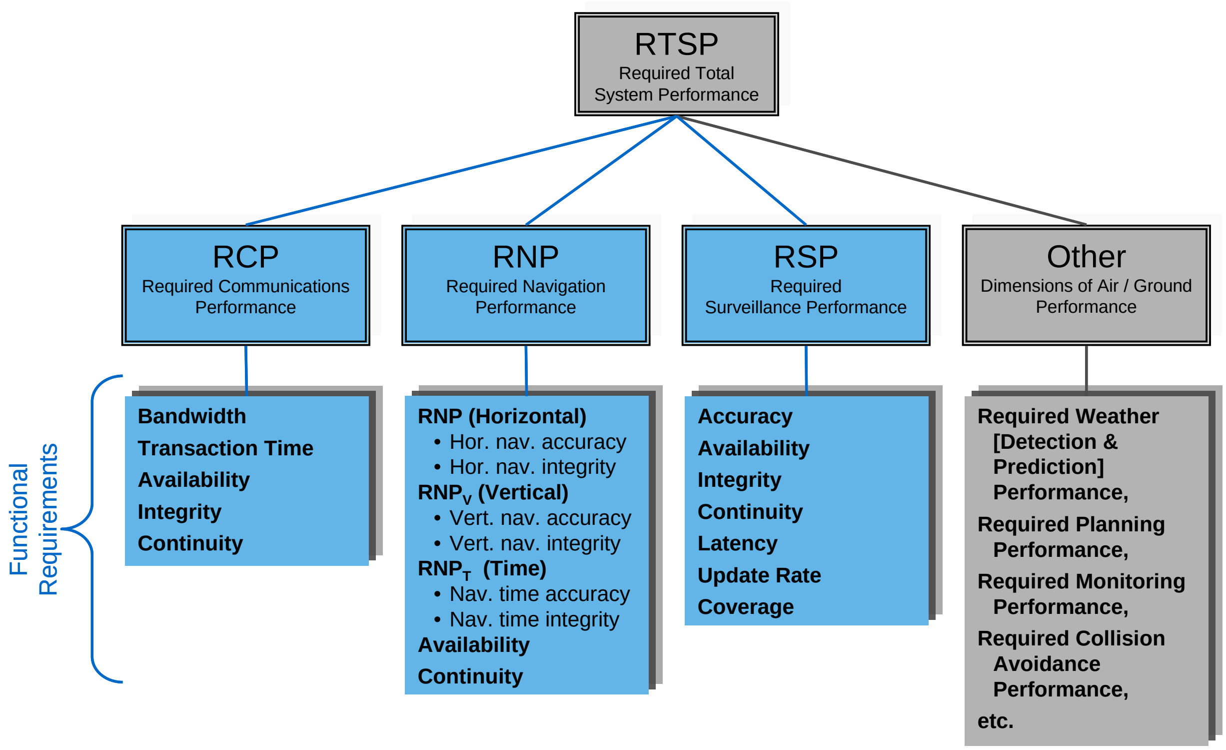


Figure 98 – Required Total System Performance and the Hierarchy of Performance Specifications and Functional Requirements

12.3 Required Communications, Navigation, & Surveillance Requirements Framework

A candidate requirements framework for specifying the Required Communications Performance, Required Navigation Performance, and Requirement Surveillance Performance requirements to support the NextGen and beyond performance-based operations is described in the subsections below.

12.3.1 Required Communications Performance (RCP)

Required Communication Performance, or RCP, is one element of the RTSP. RCP is intended to characterize the communication capability required through a statement of the communication performance (i.e., RCP type) to be achieved in order to support a performance-based ATM function in NextGen and beyond. As defined in the ICAO Manual on Required Communication Performance (RCP)[1], "The RCP concept characterizes the performance required for communication capabilities that support ATM functions without reference to any specific technology." RCP describes the operational communication transactions in the context of an ATM function, taking into account human interactions, decision support tools, procedures, and environmental characteristics.

An Operational Communication Transaction is the process used to send information (e.g., an instruction, a clearance, flight information, a request), and is completed when there is sufficient confidence that the transaction is complete. As depicted in Figure 99, for a typical human-to-human communication transaction, it includes the performance time required by the humans involved to send the initial message, to hear or read and comprehend that message, to respond to the message, and to hear or read the response. It also, of course, includes the communications link delay, the time required for the message and the response to be transmitted between the initiator and the responder.

RCP performance parameters include transaction time, continuity, availability, and integrity, which have been defined by ICAO as follows. The communication **Transaction Time** (in seconds) is the maximum time for the completion of the operational communication transaction after which the initiator should revert to an alternative procedure. **Continuity** (probability/flight hour) is the probability that an operational communication transaction can be completed within the communication transaction time. **Availability** (probability/flight hour) is the probability that an operational communication transaction can be initiated when needed. **Integrity** (acceptable rate per flight hour) is the probability of one or more errors in a completed communication transaction that has not been detected within the communications transaction time.

Various recommended levels of required communication performance have been defined by ICAO and referred to as an RCP type. These RCP types defined by ICAO are identified by the associated transaction time as indicated in Figure 100. In order to assure compliance with RCP type, it may be necessary to monitor that the Actual Communication Performance (ACP) complies with the RCP needed for the intended applications.

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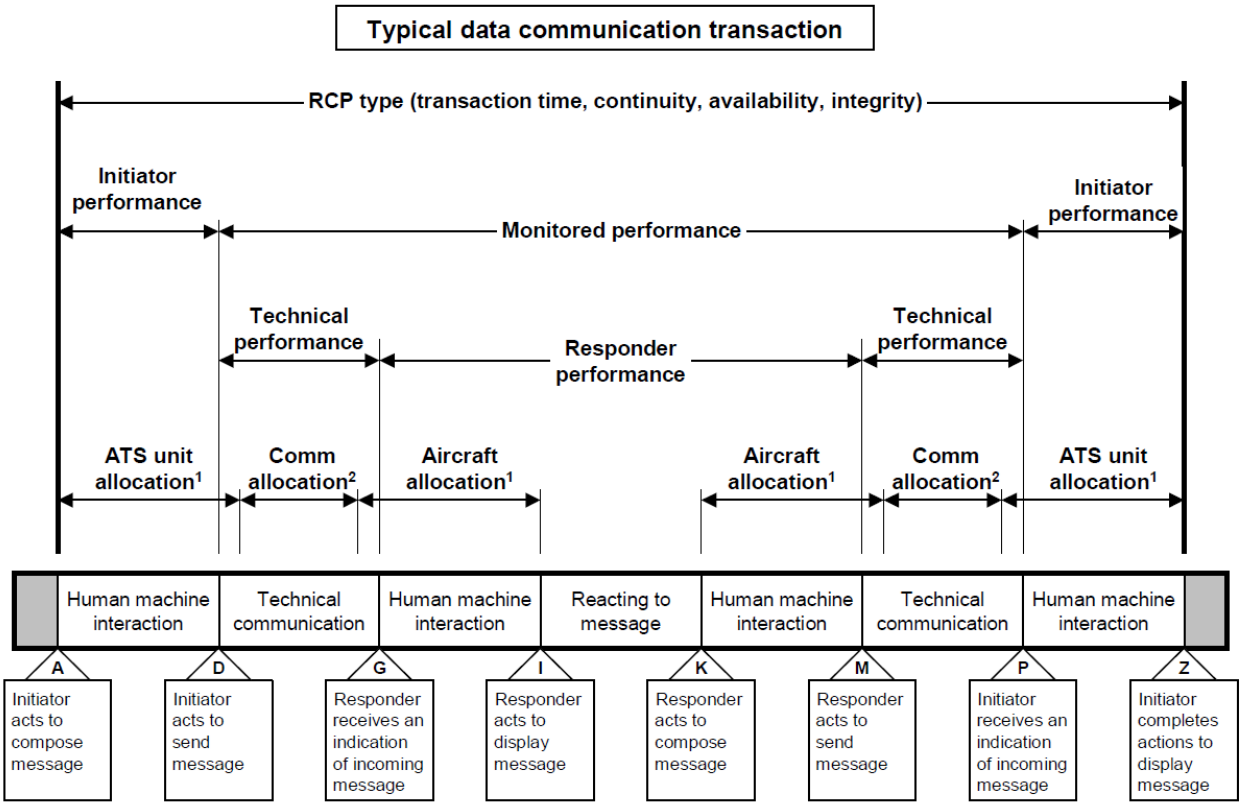
[1] International Civil Aviation Organization (ICAO), Draft ICAO Manual on Required Communication Performance (RCP), First Edition, Doc 9869, (Montreal: ICAO, 2006), p. 6.



Note 1: A controller initiated transaction is shown. ATS unit and Aircraft allocations are transposed for a pilot initiated transaction
Note 2: The aircraft and ATS unit allocations include HMI and a portion of the technical communication to provide a basis for the different types of approvals.

Figure 99 – Structure of an RCP Operational Communication Transaction

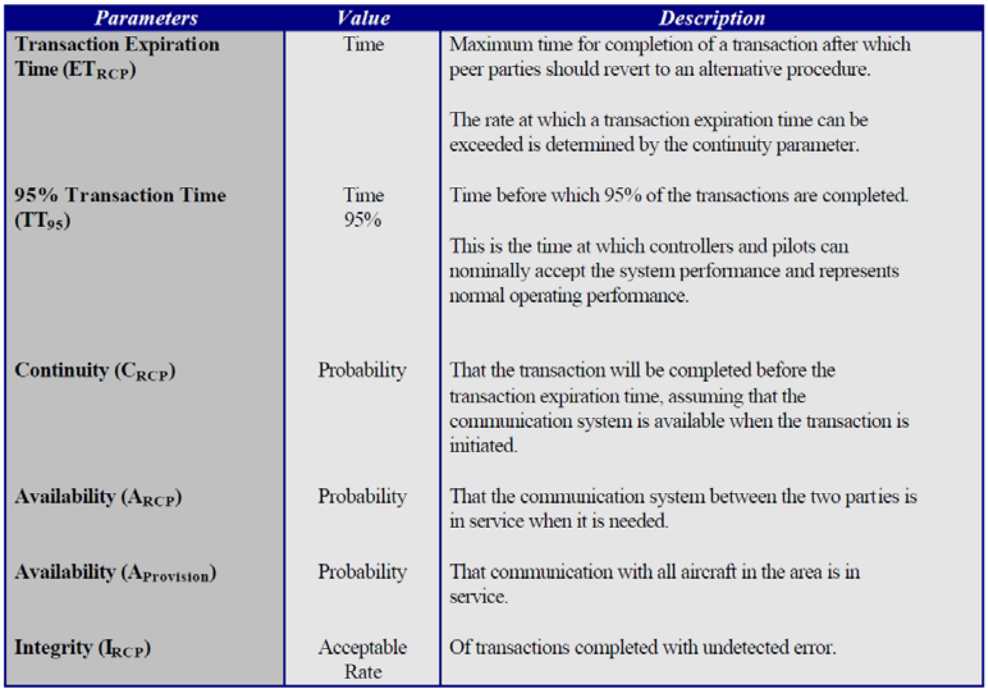
[Reference: Draft ICAO Manual On Required Communications Performance, First Edition, Doc 9869, ICAO, 2006, p. 22.]

RCP type	Transaction time (sec)	Continuity (probability/ flight hour)	Availability (probability/ flight hour)	Integrity (acceptable rate/ flight hour)
RCP 10	10	0.995	0.99998	10^{-5}
RCP 60	60	0.99	0.9995	10^{-5}
RCP 120	120	0.99	0.9995	10^{-5}
RCP 240	240	0.99	0.9995	10^{-5}
RCP 400	400	0.99	0.999	10^{-5}

Figure 100 – ICAO Required Communication Performance Level Definitions

[Reference: Draft ICAO Manual On Required Communications Performance, First Edition, Doc 9869, ICAO, 2006, Table 3-1.]

RTCA SC-189 (reference DO-264 and DO-306) has expanded the definition of RCP and has included additional measures of performance including transaction expiration time (ET_{RCP}), transaction time (TT_{RCP}) for 95% of the transactions, continuity (C_{RCP}), availability of service provision ($A_{Provision}$) for communication with all aircraft in the area, availability of service (A_{RCP}) for communication between the two parties, and the integrity (I_{RCP}) as indicated in Figure 101. RTCA has also further allocated to the RCP to various elements of the communication transaction (TRN) as illustrated in the timing diagram in Figure 102.



Parameters	*Value*	*Description*
Transaction Expiration Time (ET_{RCP})	Time	Maximum time for completion of a transaction after which peer parties should revert to an alternative procedure. The rate at which a transaction expiration time can be exceeded is determined by the continuity parameter.
95% Transaction Time (TT_{95})	Time 95%	Time before which 95% of the transactions are completed. This is the time at which controllers and pilots can nominally accept the system performance and represents normal operating performance.
Continuity (C_{RCP})	Probability	That the transaction will be completed before the transaction expiration time, assuming that the communication system is available when the transaction is initiated.
Availability (A_{RCP})	Probability	That the communication system between the two parties is in service when it is needed.
Availability ($A_{Provision}$)	Probability	That communication with all aircraft in the area is in service.
Integrity (I_{RCP})	Acceptable Rate	Of transactions completed with undetected error.

Figure 101 – RTCA Required Communication Performance Parameters

[Reference: RTCA/DO-264, Guidelines for Approval of the Provision and Use of Air Traffic Services Supported by Data Communications, December 14, 2000, Table 2-1, page 16.]

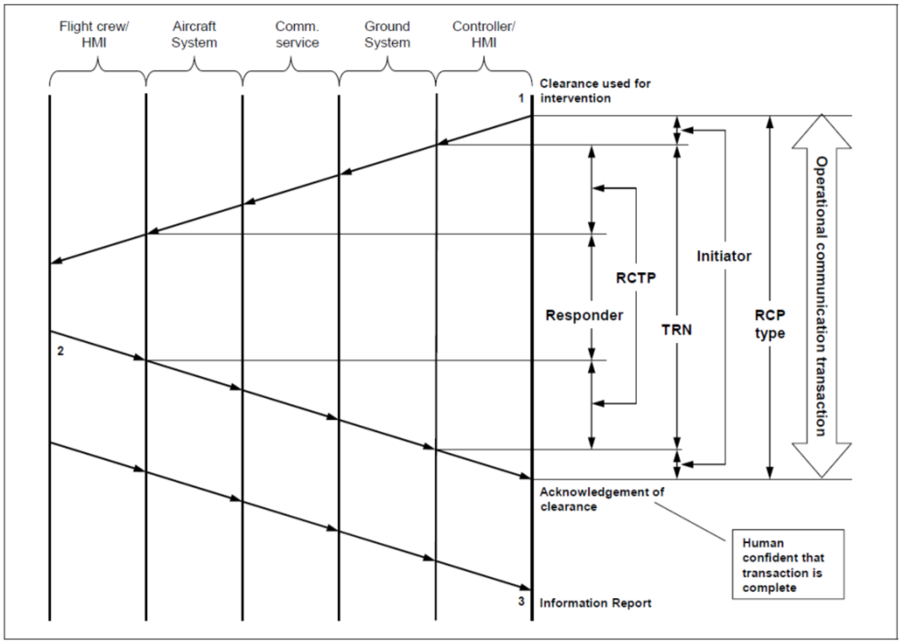
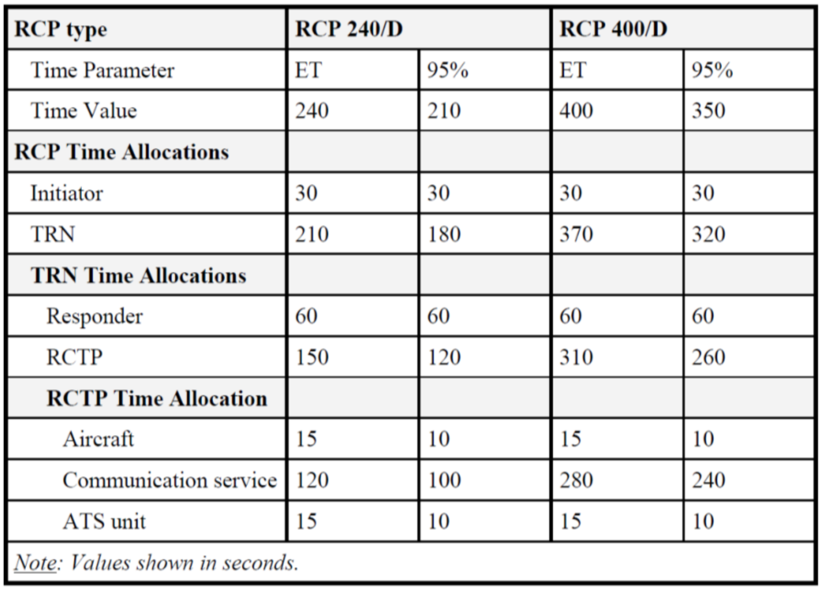


Figure 102 – Relationship of RCP Time Allocations to Time Sequence Diagram

[Reference: RTCA/DO-306, Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace, October 11, 2007, page 112.]

RTCA/DO-306 has allocated the time values for data link communication services to support the ATM application for Oceanic and Remote Air Traffic Separation Services, as indicated in Figure 103 with time allocations per the time sequence diagram in Figure 102.



RCP type	**RCP 240/D**		**RCP 400/D**	
Time Parameter	ET	95%	ET	95%
Time Value	240	210	400	350
RCP Time Allocations				
Initiator	30	30	30	30
TRN	210	180	370	320
TRN Time Allocations				
Responder	60	60	60	60
RCTP	150	120	310	260
RCTP Time Allocation				
Aircraft	15	10	15	10
Communication service	120	100	280	240
ATS unit	15	10	15	10

Note: Values shown in seconds.

Figure 103 – Allocation of Time Values for RCP 240/D and RCP 400/D

[Reference: RTCA/DO-306, Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace, October 11, 2007, page 112.]

12.3.2 Required Navigation Performance (RNP) Concept

Required Navigation Performance (RNP) is defined by ICAO as a statement of the navigation performance necessary for operation within a defined airspace. RNP is a key part of the broader Required Total System Performance (RTSP) concept that is an enabler for performance-based airspace operations. An essential part of the RNP concept is that the performing aircraft must be capable of monitoring its achieved or actual navigation performance (ANP) and must provide an alert in the event that ANP fails to meet the required navigation performance.

The NextGen concept of operations has been defined to allow aircraft to fly negotiated 4D business trajectories. Today's RNP is only defined in the horizontal dimension (2D).

Today's RNP defines a parameter that is also called "RNP" that specifies the required horizontal navigation accuracy. Two times the RNP value defines the required horizontal navigation integrity containment bound. RNP as used in today's airspace is expressed in terms of lateral displacement in nautical miles (NM) [e.g., RNP 4.0 means that the aircraft is expected to stay within 4 NM of a prescribed trajectory or ground track (greater than 95% of the time)]. Two times the RNP value represents the navigation region, that is, an aircraft is not expected to stray outside of twice the RNP (e.g., 8 NM) without annunciation, with a probability of missed detection less than 10^{-5} per hour. Similarly, RNP 0.1 represents one-tenth of a nautical mile, or 607.6 feet, bounds within which the aircraft must stay 95% of the time. In this case, 0.2 NM, or 1215 ft., is the 10^{-5} per hour containment region.

To support the NextGen and beyond vision of 4DT operations, today's horizontal RNP concept must be extended to also include specification of both the vertical dimension and time-of-arrival dimension of navigation performance (Figure 104). 4DT will support safe separation, sequencing, and flow management. With these additions, RNP will have matured from today's 2D navigation operation to enable precision navigation of a 4D trajectory.

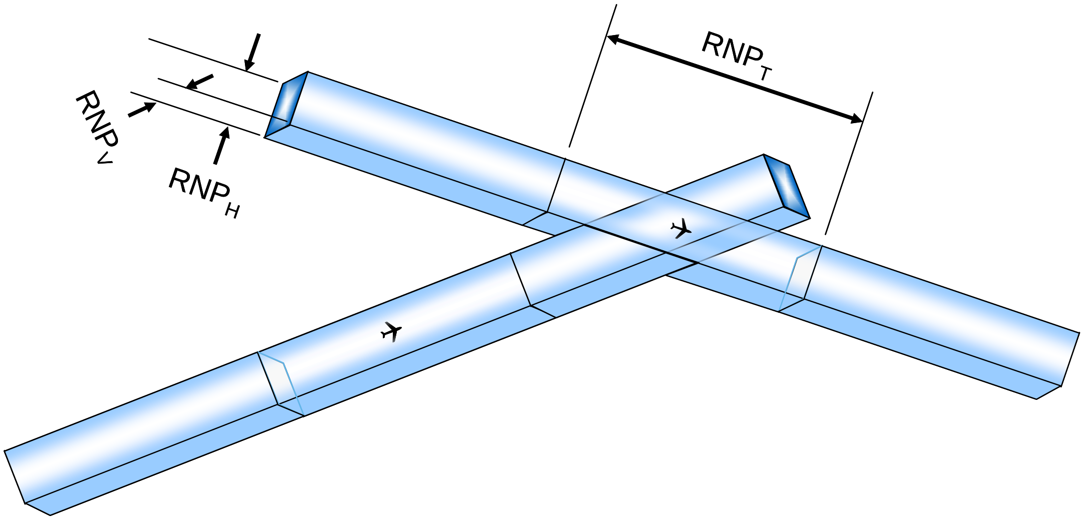


Figure 104 – Possible Future 4D Required Navigation Performance

In order to achieve a definition of RNP that will support 4D operations, today's horizontal-only RNP concept should be expanded to include specification of vertical position and waypoint time-of-arrival control performance, which are abbreviated (respectively) as RNP_V and RNP_T in this document. In order to minimize confusion in this document, the horizontal RNP specification parameter will be denoted as RNP_H and the more general all-encompassing 4D required navigation performance will be abbreviated as RNP.

Thus, 4D RNP can be defined through the specification of the following performance parameters:

1. **RNP_H** : Horizontal RNP (referred to as RNP in today's operations), defines the required horizontal navigation accuracy and integrity containment performance.
2. **RNP_V** : Vertical RNP [referred to as Vertical Navigation (**VNAV**) in RTCA DO-236C (draft)] defines the required vertical (altitude) navigation accuracy and integrity containment performance. Currently, RTCA DO-236C (draft) defines VNAV accuracy as a 99.7% limit. In the far future of the study modernization time period, to enable more advanced 4D TBO operations including, as an example, cruise climb, RNPv may need to be expanded to contain both an accuracy and integrity limit.
3. **RNP_T** : Time RNP [referred to as time of arrival control (**TOAC**) in RTCA DO-236C (draft)] defines the required time accuracy of the navigation system to arrive at a specified trajectory waypoint at the planned time. The overall time-of-arrival control performance that is achieved by the system will depend upon the accuracy and integrity of the input parameters, the control system, aircraft performance, and external factors such as winds.
4. **Continuity**: In the context of RNP, continuity is a performance measure that defines the confidence that the navigation system will continue to satisfy the other navigation performance requirements without unscheduled interruptions during the intended operation. Unscheduled interruption in operation for RNP may result from: 1) total loss of navigation capability (horizontal, vertical, or time); 2) a failure of the system that is annunciated by the system as the loss of RNP capability; or 3) false annunciation of loss of RNP capability while the system is working properly.
5. **Availability**: In the context of RNP, availability is a measure that describes the ability of the navigation system to provide a usable service within the specified coverage volume. It is defined as the fraction of the time period that the system is intended to be used for navigation during which reliable navigation information is present that meets all the requirements necessary to support the intended operation(s).

The performance parameters RNP_H, RNP_V, and RNP_T use the terms accuracy and integrity. Accuracy in the context of the RNP_H, and RNP_V parameters defines the degree of conformance between the desired horizontal and vertical position (respectively) at a given time and the true horizontal and vertical position (respectively). Accuracy for RNP_H and RNP_V is concerned with the accuracy of the positioning source, the accuracy of defining the desired path, and the accuracy of path steering. Accuracy in the context of the RNP_T parameter defines the degree of conformance between the desired time of arrival and the true time of arrival at a given waypoint.

Integrity is defined using two parameters, the "integrity risk" and the "integrity containment bound." The integrity risk is defined as the maximum probability that the navigation error exceeds the integrity containment bound without annunciation, and is specified as 10^{-5} per flight hour. The integrity containment bounds for RNP_H and RNP_V are specified as 2 times the RNP accuracy values.

The CNS/ATM has been using horizontal RNP to require improved lateral performance of aircraft flight paths to fit aircraft horizontally within various operational constraints. Expanding RNP to also cover vertical and time will further define and constrain the flight trajectory to deal with additional ATM constraints enabling more aircraft to utilize a given volume of airspace. The vertical RNP may define flight level/altitude constraints, speed, and/or vertical angles. The time of arrival control expansion of today's RNP will provide an increased certainty of aircraft arriving at a fix within a specified time range.

Airspace Region	**RNP_H** (95% Accuracy, 2*RNP_H is 10^{-5} per flight hour integrity containment)	**RNP_V** (95% Accuracy, 2*RNP_V is 10^{-5} per flight hour integrity containment)	**RNP_T** (95% Accuracy)	**Continuity**	**Availability** (per flight hour)
Oceanic, Remote, and Polar airspace 2:	4.0 NM	200 ft.	45 s	$< 10^{-5}$ per flight hour	99 to 99.999%
Oceanic, Remote, and Polar airspace 2:	2.0 NM	200 ft.	30 s	$< 10^{-5}$ per flight hour	99 to 99.999%
Off-shore (WATRS, Gulf of Mexico):	1.0 NM	200 ft.	20 s	$< 10^{-5}$ per flight hour	99 to 99.999%
En-route 5-mile separation:	1.0 NM	200 ft.	20 s	$< 10^{-5}$ per flight hour	99 to 99.999%
En-route with 3-mile separation:	1.0 NM	150 ft.	15 s	$< 10^{-5}$ per flight hour	99 to 99.999%
En-route with 1.5-mile separation:	0.5 NM	100 ft.	10 s	$< 10^{-5}$ per flight hour	99 to 99.999%
Terminal Area:	0.3 NM	100 ft.	10 s	$< 10^{-5}$ per flight hour	99 to 99.999%
Approach:	0.1 NM	100 ft.	6 s	$< 10^{-7}$ per approach	99 to 99.999%
Surface:	0.05 NM	N/A	10 s	$< 10^{-5}$ per operation	99 to 99.999%

Figure 105 – Notional Long Term 4D Required Navigation Performance Levels

12.3.3 Required Surveillance Performance (RSP)

Analogous to RCP and RNP, RSP is intended to characterize the performance required of the surveillance capability in order to support a performance-based ATM function in NextGen and beyond. RSP includes components similar to those for RCP and RNP but includes some additional criteria because of the nature of the function. Unfortunately, the definition of an internationally standardized RSP concept is lagging behind RCP and RNP and requires further development and maturation.

RSP parameters may include, for instance, accuracy, containment, availability, integrity, latency, update rate, continuity, and coverage. The definitions for these parameters in the context of the surveillance function in this study program are as follows:

The **Accuracy** component includes both accuracy of position measurement and accuracy with which the time of the position measurement is reported. The **Containment** component characterizes the position error integrity containment limit. **Availability** (probability/flight hour) is the probability that a surveillance report will be received when needed. **Integrity** (acceptable rate/flight hour) is the probability of one or more undetected errors in a completed surveillance transaction; however, as it is envisioned that all systems will be operating in a data-rich, network-enabled environment, it is important that network security requirements be addressed to ensure that data integrity is maintained. **Latency** (seconds) is the delay in the surveillance system between making a measurement and using it to support the ATM function. The **Update Interval** (seconds) is the time interval at which the surveillance report is updated. The update interval could be specified at various probabilities including a nominal performance probability (e.g., 95%) as well as a threshold probability (e.g., 99.9% or higher). The **Continuity** (probability/flight hour) is the probability that a surveillance system will continue to satisfy its other performance requirements without unscheduled interruptions during the intended operation. **Coverage** is the volume in space in which reports are received with specified accuracy, availability, latency, update interval, continuity, and integrity. For a ground station, coverage is the volume that it can monitor reliably and for an aircraft it is the volume in which it can expect to be detectable via the surveillance system. In addition, for aircraft-based traffic surveillance applications (e.g., ADS-B IN), coverage also represents the volume in which surveillance reports of specified quality can expect to be received.

ICAO has not yet issued a formal definition of RSP like those that are available for horizontal RNP and RCP. The RSP terminology per the above framework is in the early stages of being applied by RTCA SC-186 to define the requirements for traffic surveillance to support various airspace applications.

The RSP terminology is currently being utilized somewhat differently than the RSP framework defined above by RTCA SC-214 to define the data communications requirements for communication systems to support communicating surveillance information (e.g., ADS-C). Such “RSP” requirements are being defined with performance parameters similar to the RCP (communication) requirements framework and does not include parameters such as position accuracy and position integrity containment.

12.4 Performance-Based Requirements Framework

Performance-based operations are viewed to be as an essential component for many of the operational improvements identified by NextGen and beyond concepts of operation to enhance the capacity, efficiency, safety, and security of our National Air Transportation System.

To realize the vision of performance-based operations, performance-based requirements should be developed that meet the operational, safety, and performance objectives that encompass future airspace applications. The full framework for specifying the performance-based requirements lacks full maturity at the time of this study, but is in the process of being matured by ICAO and other industry standards organizations (e.g., RTCA, EUROCAE).

More work is needed to achieve a vetted and validated set of functional requirements for communications, navigation, and surveillance that meet the operational, safety, and performance objectives that encompass future airspace applications. The RTSP concept, along with its foundational elements of Required Communication Performance (RCP), Required Navigation Performance (RNP), and Required Surveillance Performance (RSP), is a good baseline.

13 AIRSPACE APPLICATIONS AND THEIR COMMUNICATIONS REQUIREMENTS

This section of the report identifies the communications requirements for existing airspace applications, as well as an initial set of communications requirements for future NextGen and beyond anticipated applications. The required communication performance levels provided in this section for future applications should be taken as preliminary, and in need of significantly more operational, performance, safety, and security analyses to confirm that they are appropriate to enable the various intended future applications.

13.1 Airspace Applications and Environment Context

Figure 106 below provides the context for the air traffic services ATM applications, which consist of air traffic control services, flight information services, and alerting services. Also considered in this study are communication applications between the aircraft and AOC.

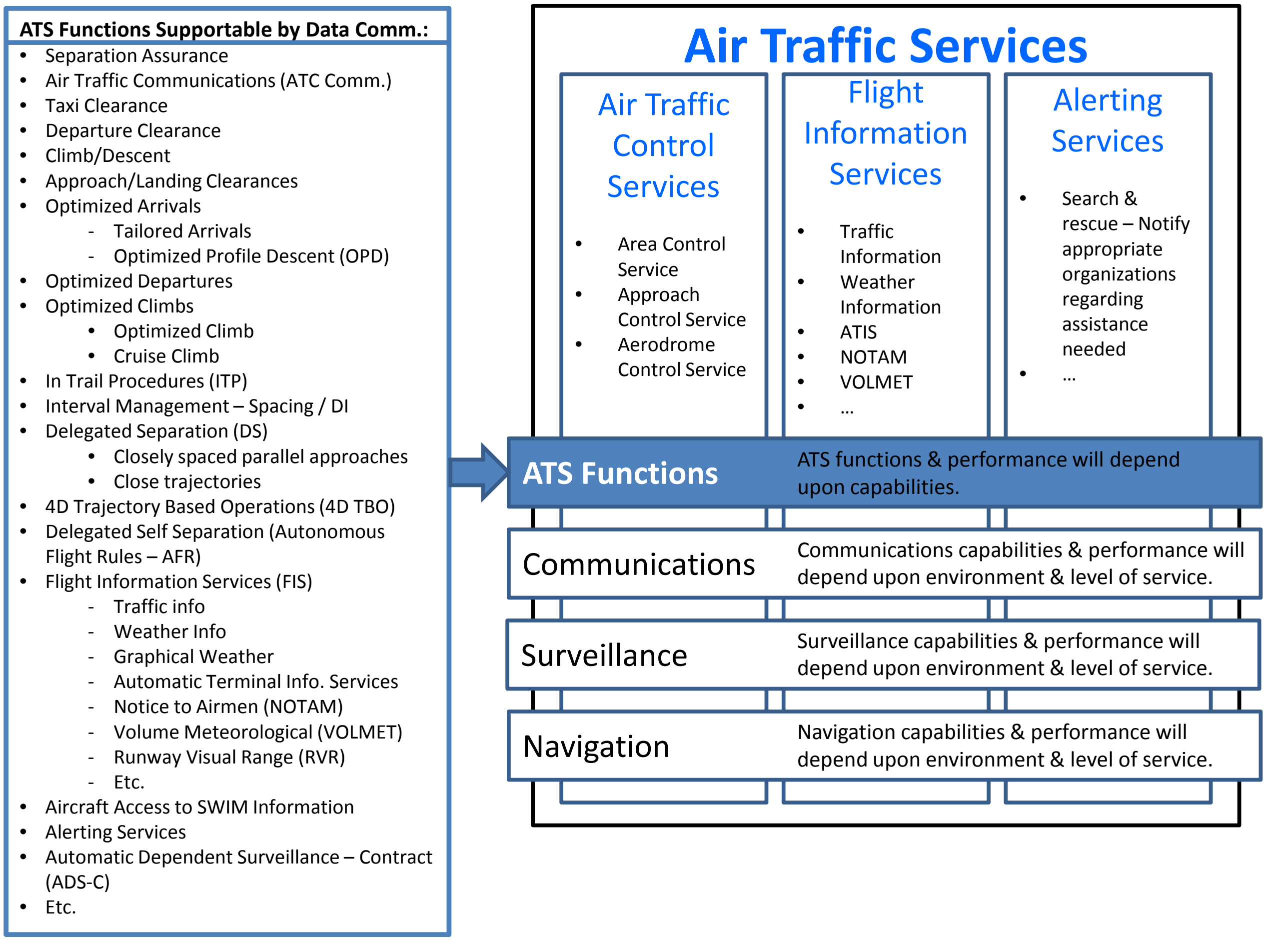


Figure 106 – Relationship of ATS, ATS Functions, CNS Capabilities, & Data Communication Services

[Reference: Diagram based upon RTCA/DO-306, "Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace," Figure 1-2.]

An ATM application may be provided operationally in the airspace when the set of capabilities and required levels of performance are present from the CNS/ATM system. The capabilities and performance associated with the communication, navigation, surveillance, and air traffic management are not independent of one another, but are rather dependent on each other to support a given application.

The airspace environments that applications operate in include the following:

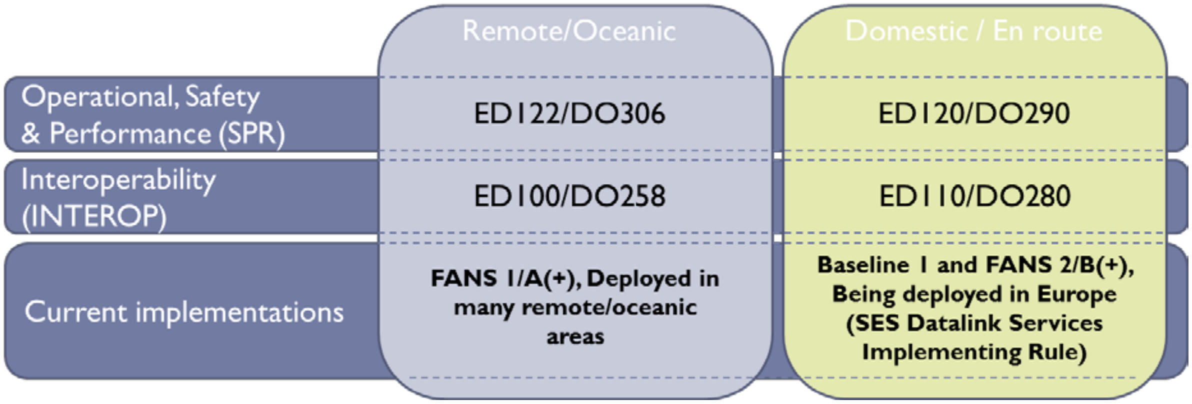
Airport Surface (APT): The APT airspace environment consists of the airport surface, and the immediate vicinity around the airport.

Terminal Area (TMA): The terminal airspace is a volume of controlled airspace set up in the vicinity of one or more major airports to protect traffic climbing out from and descending into the airports. The typical separation minima in this airspace today are 3 NM lateral with appropriate vertical and/or visual separation as required.

ENR-1 (En-route-1): The ENR-1 airspace is a volume of controlled airspace that encloses the flight paths above and between airports where air traffic service in TMA is provided and where ATS has surveillance services. The typical separation minima in this airspace today are 3NM and 5NM laterally with appropriate vertical and/or visual separation.

ENR-2 (En-route-2): The ENR-2 airspace is a volume of controlled airspace that is characterized by the use of procedural control and the lack of ATS surveillance service. The typical separation minima in this airspace today are 100 NM lateral, 100 NM longitudinal, and 1000 feet vertical (RVSM).

The requirements herein have been based upon data communications safety and performance requirements (SPR) documents that have been and are being developed by RTCA Special Committee (SC)-214 and EUROCAE Working Group (WG)-78 (see Figure 107), including documents that are currently in draft form.



	Remote/Oceanic	Domestic / En route
Operational, Safety & Performance (SPR)	ED122/DO306	ED120/DO290
Interoperability (INTEROP)	ED100/DO258	ED110/DO280
Current implementations	**FANS 1/A(+), Deployed in many remote/oceanic areas**	**Baseline 1 and FANS 2/B(+), Being deployed in Europe (SES Datalink Services Implementing Rule)**

Figure 107 – Current Data Link Industry SPR and Interoperability Standards

13.2 Communication Requirements for Existing Airspace Applications

13.2.1 Communication Requirements for Most Existing Airspace Applications

The communication requirements for most of the existing airspace applications are system specific and are not specified using the Required Communications Performance (RCP) framework that was described in Section 12. The exception to this is the RCP requirements specified in RTCA DO-290 / EUROCAE ED-120 (SPR Standard for Air Traffic Data Link Services in Continental Airspace) [see Section 13.2.2 (page 183)] and in RTCA DO-306 / ED-122 (SPR Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace) [see Section 13.2.3 (page 192)].

As such, the communications requirements for most of today's existing applications are identified by the system in the various airspaces. There is on-going effort in ICAO, RTCA, and EUROCAE to mature the performance-based operations framework to support establishing the communications requirements for the future performance-based operations.

Existing airspace ATM applications today all depend on A-G voice communications between air crews and ATC, and thus, direct pilot to ATC (voice) communications is required in all airspaces for all ATM applications today.

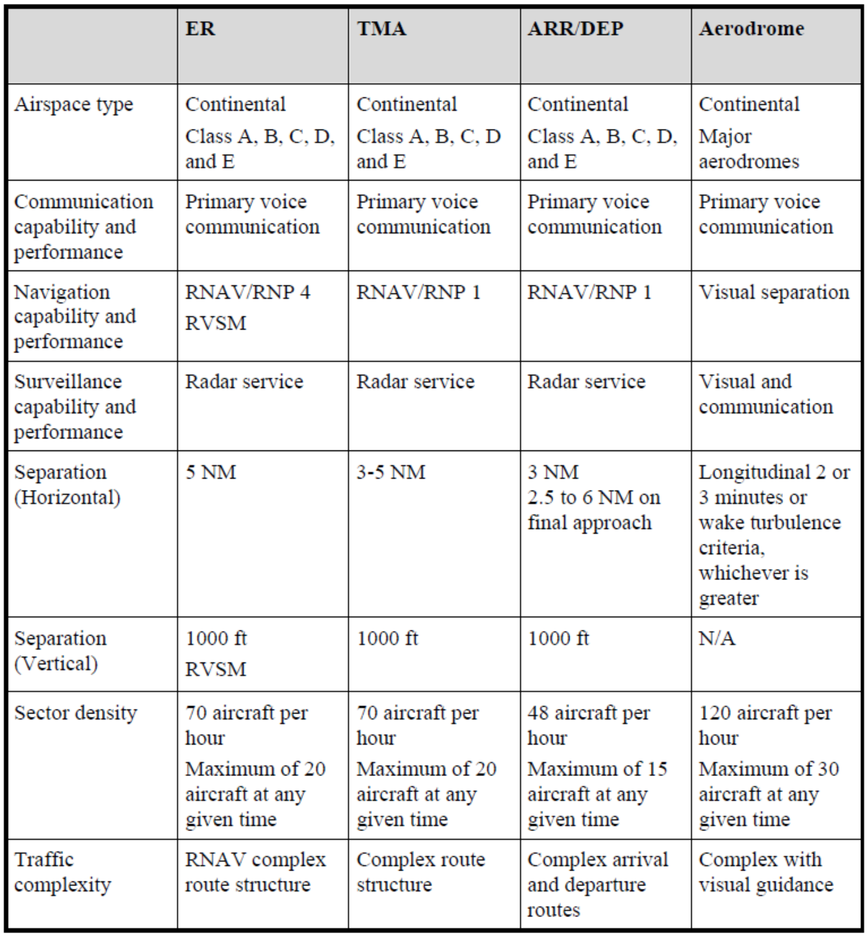
In domestic airspace (which includes airport surface (aerodrome), terminal area, and domestic enroute airspaces), the communications required is VHF voice (See Figure 121).

In oceanic, remote, and polar airspaces, HF voice communications are required for all transoceanic flights and flights under air traffic control into areas that are not covered by VHF air-to-ground voice communications. ATC communications (voice supplemented by data) are supported by HF and SATCOM. FANS is supported with HF data link as well as with data communications services offered by Inmarsat and Iridium (see Section 7.3.3).

VHF, HF, and SATCOM (both voice and data) as described in Section 7 are also the communication systems used for applications that involve A-G communications between the aircraft and AOC.

Most aircraft entering ATC controlled airspace are required to have ATCRBS air-to-ground transponders to support the SSR surveillance. Emerging is the use of ADS-B (and the companion ground services of TIS-B and ADS-R) A-G communications to support the surveillance needs for various (mostly future) ground-based and aircraft-based applications.

Relevant to A-A communications, all aircraft are required to have VHF voice, which is used A-A for the common traffic advisory frequency (CTAF) communications that are used to support operations at non-towered airports. Many aircraft are also required to have TCAS transponders. TCAS II is required to be installed on all commercial turbine-powered transport aircraft having more than 19 passenger seats or having a maximum take-off weight above 5700 kg and either TCAS I or II is required to be installed on aircraft with 10 to 30 seats. Emerging is the use of ADS-B for A-A communications. To date, applications involving ADS-B have been approved primarily only for enhanced situational awareness.



	ER	TMA	ARR/DEP	Aerodrome
Airspace type	Continental Class A, B, C, D, and E	Continental Class A, B, C, D and E	Continental Class A, B, C, D, and E	Continental Major aerodromes
Communication capability and performance	Primary voice communication	Primary voice communication	Primary voice communication	Primary voice communication
Navigation capability and performance	RNAV/RNP 4 RVSM	RNAV/RNP 1	RNAV/RNP 1	Visual separation
Surveillance capability and performance	Radar service	Radar service	Radar service	Visual and communication
Separation (Horizontal)	5 NM	3-5 NM	3 NM 2.5 to 6 NM on final approach	Longitudinal 2 or 3 minutes or wake turbulence criteria, whichever is greater
Separation (Vertical)	1000 ft RVSM	1000 ft	1000 ft	N/A
Sector density	70 aircraft per hour Maximum of 20 aircraft at any given time	70 aircraft per hour Maximum of 20 aircraft at any given time	48 aircraft per hour Maximum of 15 aircraft at any given time	120 aircraft per hour Maximum of 30 aircraft at any given time
Traffic complexity	RNAV complex route structure	Complex route structure	Complex arrival and departure routes	Complex with visual guidance

Figure 108 – Current Domestic Communication Performance Requirements

[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Figure 3-1.]

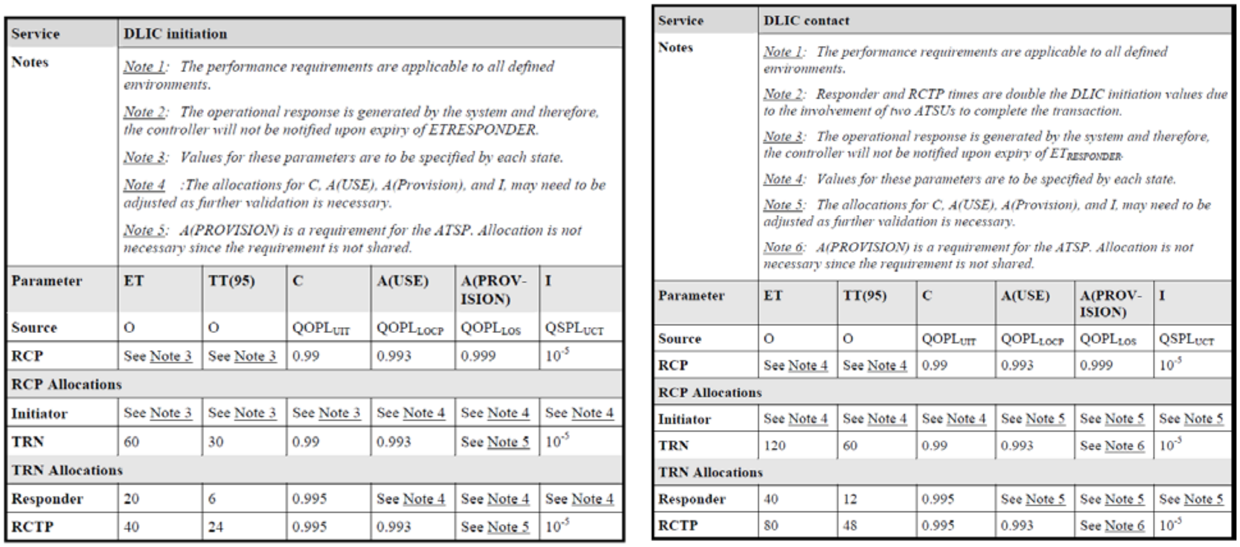
13.2.2 Continental Airspace SPR Standards

DO-290/ED-120 define the required communications performance for data link services applications in continental airspace to support separation assurance, route conformance monitoring, re-route, and weather deviation management taking into consideration the following ATN data link applications:

1) Data Link Initiation Capability (DLIC),
2) Data Link Services for ATC [including a. ATC Communications Management (ACM), b. ATC Clearance (ACL), c. ATC Microphone Check (AMC), d. Departure Clearance Service (DCL), and e. Downstream Clearance (DSC)],
3) Flight Information Services, and
4) Data Link Services for Surveillance.

The RCP as stated in DO-290 for the following data link services are provided in Figure 109 to Figure 117 respectively: a) DLIC initiation and contract performance, b) ATC Communications Management (ACM), c) ATC Clearance – Flight Crew Initiated, d) ATC Clearance – Controller

Initiated, e) Departure Clearance – Flight Crew Initiated, f) Departure Clearance – Controller Initiated, g) Downstream Clearance, h) Digital Automated Terminal Information Service (DATIS), and i) Flight Plan Consistency (FLIPSY) Service.



Service	**DLIC initiation**					
Notes	*Note 1: The performance requirements are applicable to all defined environments.* *Note 2: The operational response is generated by the system and therefore, the controller will not be notified upon expiry of ETRESPONDER.* *Note 3: Values for these parameters are to be specified by each state.* *Note 4 :The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 5: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	O	O	$QOPL_{UIT}$	$QOPL_{LOCP}$	$QOPL_{LOS}$	$QSPL_{UCT}$
RCP	See Note 3	See Note 3	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 3	See Note 3	See Note 3	See Note 4	See Note 4	See Note 4
TRN	60	30	0.99	0.993	See Note 5	10^{-5}
TRN Allocations						
Responder	20	6	0.995	See Note 4	See Note 4	See Note 4
RCTP	40	24	0.995	0.993	See Note 5	10^{-5}

Service	**DLIC contact**					
Notes	*Note 1: The performance requirements are applicable to all defined environments.* *Note 2: Responder and RCTP times are double the DLIC initiation values due to the involvement of two ATSUs to complete the transaction.* *Note 3: The operational response is generated by the system and therefore, the controller will not be notified upon expiry of $ET_{RESPONDER}$.* *Note 4: Values for these parameters are to be specified by each state.* *Note 5: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 6: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	O	O	$QOPL_{UIT}$	$QOPL_{LOCP}$	$QOPL_{LOS}$	$QSPL_{UCT}$
RCP	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 4	See Note 4	See Note 4	See Note 5	See Note 5	See Note 5
TRN	120	60	0.99	0.993	See Note 6	10^{-5}
TRN Allocations						
Responder	40	12	0.995	See Note 5	See Note 5	See Note 5
RCTP	80	48	0.995	0.993	See Note 6	10^{-5}

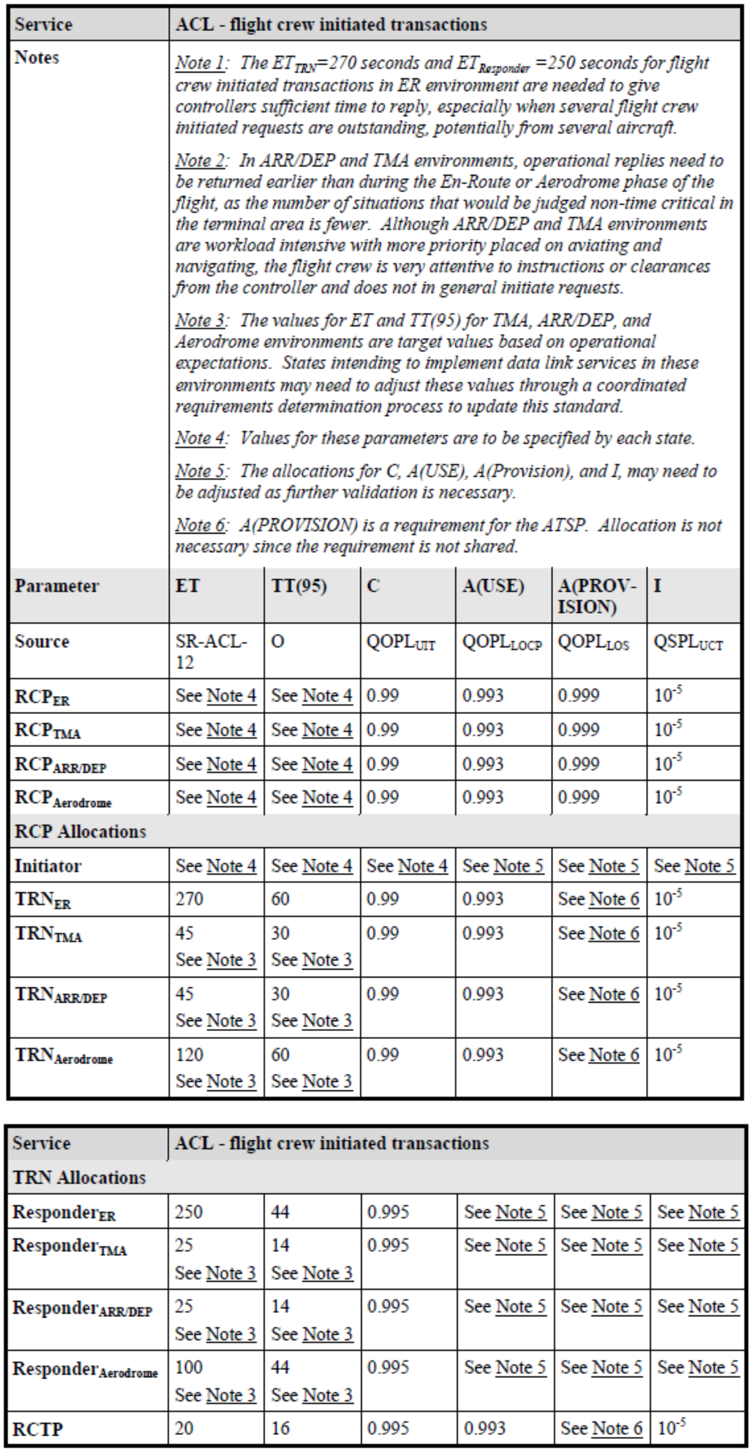
Figure 109 – RCP for Data Link Initiation Capability (DLIC)

[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Tables 4-8 and 4-9.]

Service	**ACM**					
Notes	*Note 1: The performance requirements are applicable to all of the ACM service.* *Note 2: In ARR/DEP and TMA environments, operational replies need to be returned earlier than during the En-Route or Aerodrome phase of the flight, as the number of situations that would be judged non-time critical in the terminal area is fewer. Although Arr/Dep and TMA environments are workload intensive with more priority placed on aviating and navigating, the flight crew is very attentive to instructions or clearances from the controller and does not in general initiate requests.* *Note 3: The values for ET and TT(95) for TMA, ARR/DEP, and Aerodrome environments are target values based on operational expectations. States intending to implement data link services in these environments may need to adjust these values through a coordinated requirements determination process to update this standard.* *Note 4: Values for these parameters are to be specified by each state.* *Note 5: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 6: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	O	O	QOPL$_{UIT}$	QOPL$_{LOCP}$	QOPL$_{LOS}$	QSPL$_{UCT}$
RCP$_{ER}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP$_{TMA}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP$_{ARR/DEP}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP$_{Aerodrome}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 4	See Note 4	See Note 4	See Note 5	See Note 5	See Note 5
TRN$_{ER}$	120	60	0.99	0.993	See Note 6	10^{-5}
TRN$_{TMA}$	45 See Note 3	30 See Note 3	0.99	0.993	See Note 6	10^{-5}
TRN$_{ARR/DEP}$	45 See Note 3	30 See Note 3	0.99	0.993	See Note 6	10^{-5}
TRN$_{Aerodrome}$	120 See Note 3	60 See Note 3	0.99	0.993	See Note 6	10^{-5}
TRN Allocations						
Responder$_{ER}$	100	44	0.995	See Note 5	See Note 5	See Note 5
Responder$_{TMA}$	25 See Note 3	14 See Note 3	0.995	See Note 5	See Note 5	See Note 5
Responder$_{ARR/DEP}$	25 See Note 3	14 See Note 3	0.995	See Note 5	See Note 5	See Note 5
Responder$_{Aerodrome}$	100 See Note 3	44 See Note 3	0.995	See Note 5	See Note 5	See Note 5
RCTP	20	16	0.995	0.993	See Note 5	10^{-5}

Figure 110 – RCP for ATC Communications Management (ACM)

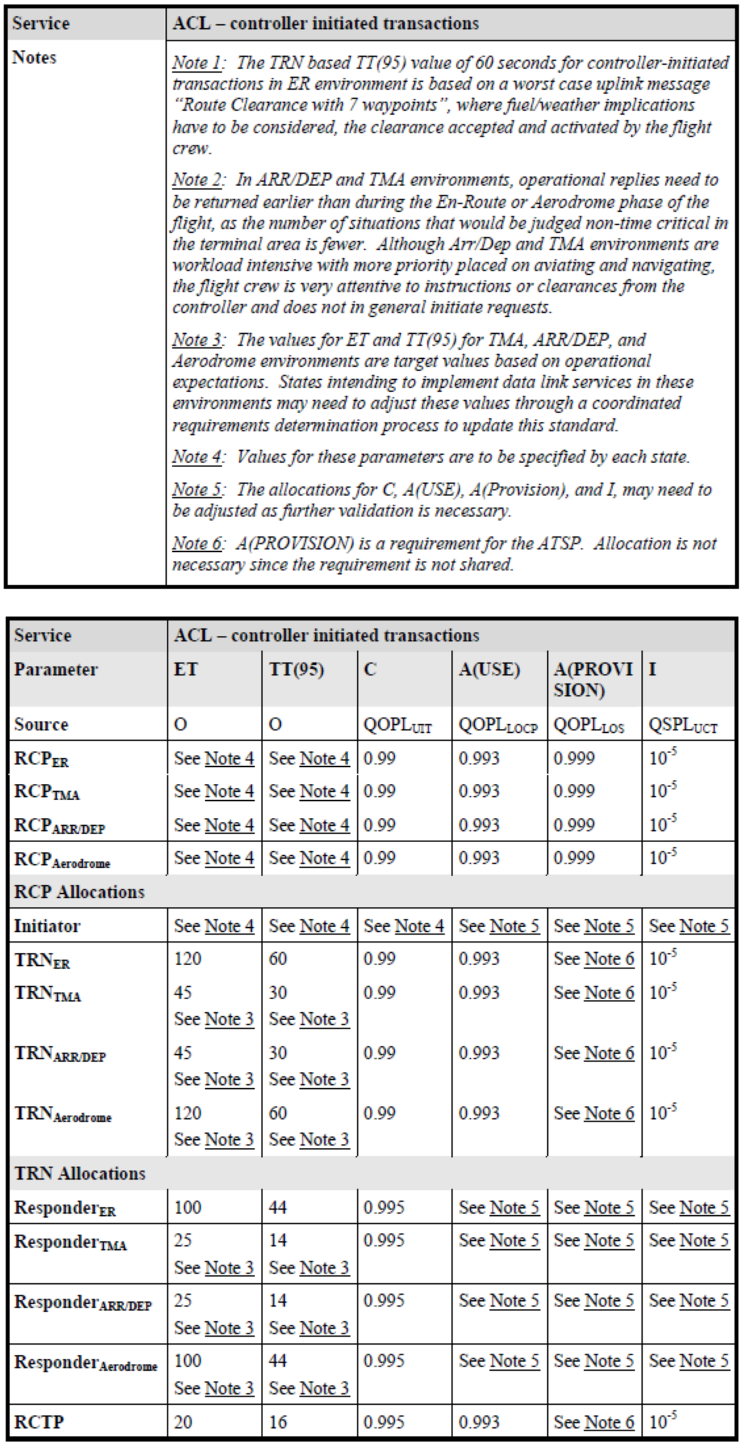
[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Table 5-21.]



Service	**ACL - flight crew initiated transactions**					
Notes	*Note 1: The ET_{TRN}=270 seconds and $ET_{Responder}$ =250 seconds for flight crew initiated transactions in ER environment are needed to give controllers sufficient time to reply, especially when several flight crew initiated requests are outstanding, potentially from several aircraft.* *Note 2: In ARR/DEP and TMA environments, operational replies need to be returned earlier than during the En-Route or Aerodrome phase of the flight, as the number of situations that would be judged non-time critical in the terminal area is fewer. Although ARR/DEP and TMA environments are workload intensive with more priority placed on aviating and navigating, the flight crew is very attentive to instructions or clearances from the controller and does not in general initiate requests.* *Note 3: The values for ET and TT(95) for TMA, ARR/DEP, and Aerodrome environments are target values based on operational expectations. States intending to implement data link services in these environments may need to adjust these values through a coordinated requirements determination process to update this standard.* *Note 4: Values for these parameters are to be specified by each state.* *Note 5: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 6: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	SR-ACL-12	O	$QOPL_{UIT}$	$QOPL_{LOCP}$	$QOPL_{LOS}$	$QSPL_{UCT}$
RCP_{ER}	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP_{TMA}	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
$RCP_{ARR/DEP}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
$RCP_{Aerodrome}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 4	See Note 4	See Note 4	See Note 5	See Note 5	See Note 5
TRN_{ER}	270	60	0.99	0.993	See Note 6	10^{-5}
TRN_{TMA}	45 See Note 3	30 See Note 3	0.99	0.993	See Note 6	10^{-5}
$TRN_{ARR/DEP}$	45 See Note 3	30 See Note 3	0.99	0.993	See Note 6	10^{-5}
$TRN_{Aerodrome}$	120 See Note 3	60 See Note 3	0.99	0.993	See Note 6	10^{-5}
TRN Allocations						
$Responder_{ER}$	250	44	0.995	See Note 5	See Note 5	See Note 5
$Responder_{TMA}$	25 See Note 3	14 See Note 3	0.995	See Note 5	See Note 5	See Note 5
$Responder_{ARR/DEP}$	25 See Note 3	14 See Note 3	0.995	See Note 5	See Note 5	See Note 5
$Responder_{Aerodrome}$	100 See Note 3	44 See Note 3	0.995	See Note 5	See Note 5	See Note 5
RCTP	20	16	0.995	0.993	See Note 6	10^{-5}

Figure 111 – RCP for ATC Clearance (ACL) – Flight Crew Initiated Transaction

[Reference: RTCA/DO-290, “Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace,” April 29, 2004, Table 5-31.]

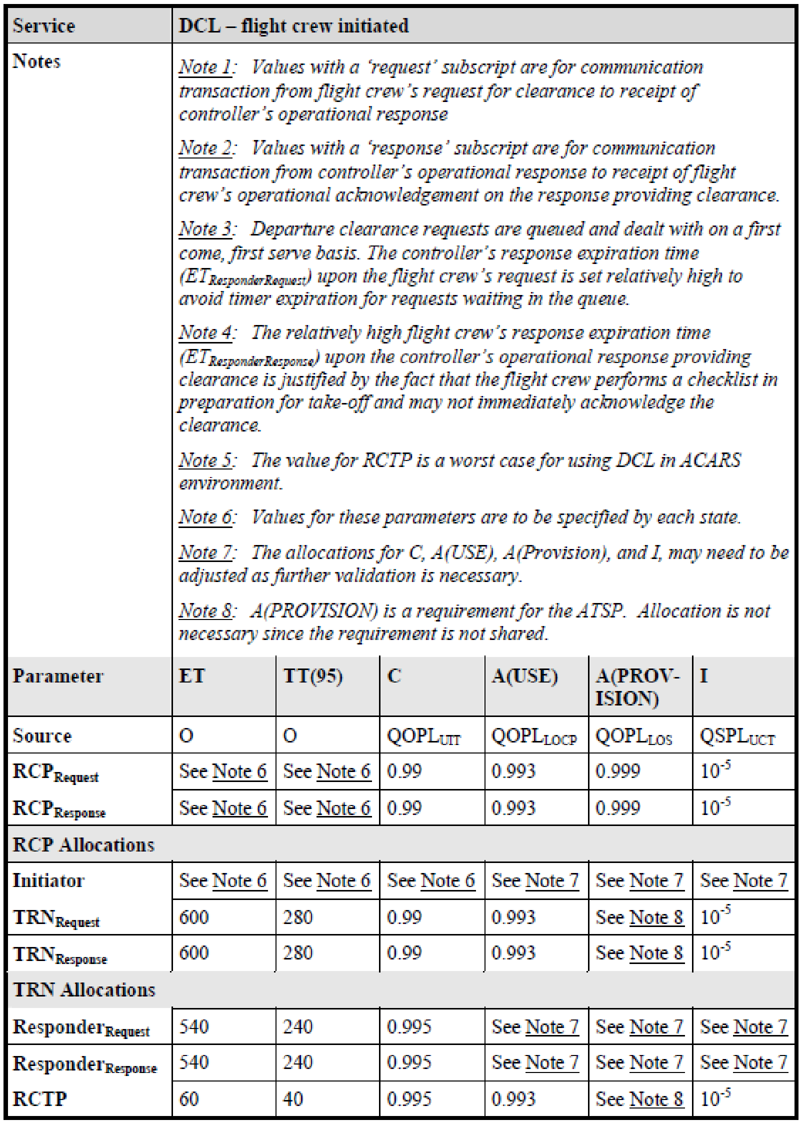


Service	**ACL – controller initiated transactions**
Notes	*Note 1: The TRN based TT(95) value of 60 seconds for controller-initiated transactions in ER environment is based on a worst case uplink message "Route Clearance with 7 waypoints", where fuel/weather implications have to be considered, the clearance accepted and activated by the flight crew.* *Note 2: In ARR/DEP and TMA environments, operational replies need to be returned earlier than during the En-Route or Aerodrome phase of the flight, as the number of situations that would be judged non-time critical in the terminal area is fewer. Although Arr/Dep and TMA environments are workload intensive with more priority placed on aviating and navigating, the flight crew is very attentive to instructions or clearances from the controller and does not in general initiate requests.* *Note 3: The values for ET and TT(95) for TMA, ARR/DEP, and Aerodrome environments are target values based on operational expectations. States intending to implement data link services in these environments may need to adjust these values through a coordinated requirements determination process to update this standard.* *Note 4: Values for these parameters are to be specified by each state.* *Note 5: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 6: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*

Service	**ACL – controller initiated transactions**					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROVISION)**	**I**
Source	O	O	QOPL$_{UIT}$	QOPL$_{LOCP}$	QOPL$_{LOS}$	QSPL$_{UCT}$
RCP$_{ER}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP$_{TMA}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP$_{ARR/DEP}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP$_{Aerodrome}$	See Note 4	See Note 4	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 4	See Note 4	See Note 4	See Note 5	See Note 5	See Note 5
TRN$_{ER}$	120	60	0.99	0.993	See Note 6	10^{-5}
TRN$_{TMA}$	45 See Note 3	30 See Note 3	0.99	0.993	See Note 6	10^{-5}
TRN$_{ARR/DEP}$	45 See Note 3	30 See Note 3	0.99	0.993	See Note 6	10^{-5}
TRN$_{Aerodrome}$	120 See Note 3	60 See Note 3	0.99	0.993	See Note 6	10^{-5}
TRN Allocations						
Responder$_{ER}$	100	44	0.995	See Note 5	See Note 5	See Note 5
Responder$_{TMA}$	25 See Note 3	14 See Note 3	0.995	See Note 5	See Note 5	See Note 5
Responder$_{ARR/DEP}$	25 See Note 3	14 See Note 3	0.995	See Note 5	See Note 5	See Note 5
Responder$_{Aerodrome}$	100 See Note 3	44 See Note 3	0.995	See Note 5	See Note 5	See Note 5
RCTP	20	16	0.995	0.993	See Note 6	10^{-5}

Figure 112 – RCP for ATC Clearance (ACL) – Controller Initiated Transaction

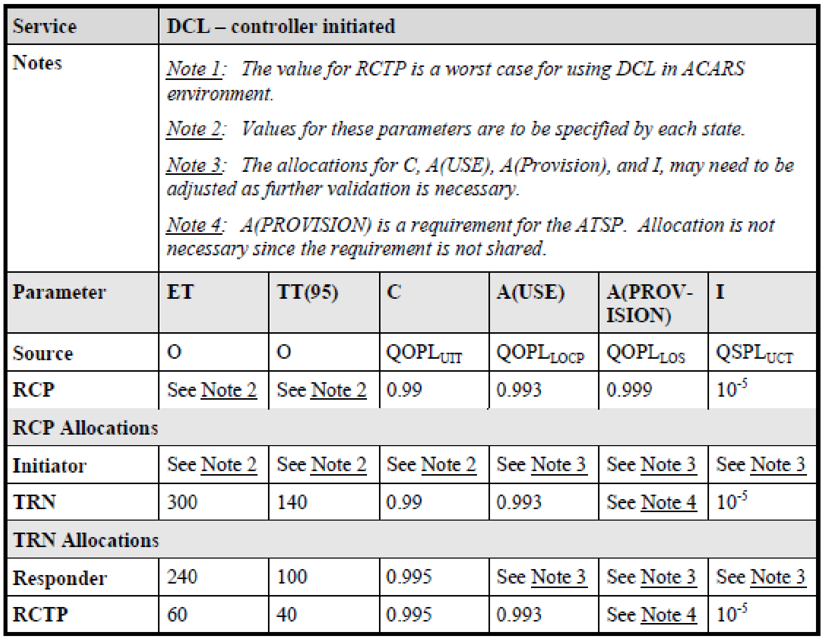
[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Table 5-32.]



Service	**DCL – flight crew initiated**					
Notes	*Note 1: Values with a 'request' subscript are for communication transaction from flight crew's request for clearance to receipt of controller's operational response* *Note 2: Values with a 'response' subscript are for communication transaction from controller's operational response to receipt of flight crew's operational acknowledgement on the response providing clearance.* *Note 3: Departure clearance requests are queued and dealt with on a first come, first serve basis. The controller's response expiration time ($ET_{ResponderRequest}$) upon the flight crew's request is set relatively high to avoid timer expiration for requests waiting in the queue.* *Note 4: The relatively high flight crew's response expiration time ($ET_{ResponderResponse}$) upon the controller's operational response providing clearance is justified by the fact that the flight crew performs a checklist in preparation for take-off and may not immediately acknowledge the clearance.* *Note 5: The value for RCTP is a worst case for using DCL in ACARS environment.* *Note 6: Values for these parameters are to be specified by each state.* *Note 7: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 8: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	O	O	$QOPL_{UIT}$	$QOPL_{LOCP}$	$QOPL_{LOS}$	$QSPL_{UCT}$
$RCP_{Request}$	See Note 6	See Note 6	0.99	0.993	0.999	10^{-5}
$RCP_{Response}$	See Note 6	See Note 6	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 6	See Note 6	See Note 6	See Note 7	See Note 7	See Note 7
$TRN_{Request}$	600	280	0.99	0.993	See Note 8	10^{-5}
$TRN_{Response}$	600	280	0.99	0.993	See Note 8	10^{-5}
TRN Allocations						
$Responder_{Request}$	540	240	0.995	See Note 7	See Note 7	See Note 7
$Responder_{Response}$	540	240	0.995	See Note 7	See Note 7	See Note 7
RCTP	60	40	0.995	0.993	See Note 8	10^{-5}

Figure 113 – RCP for Departure Clearance (DCL) – Flight Crew Initiated Transaction

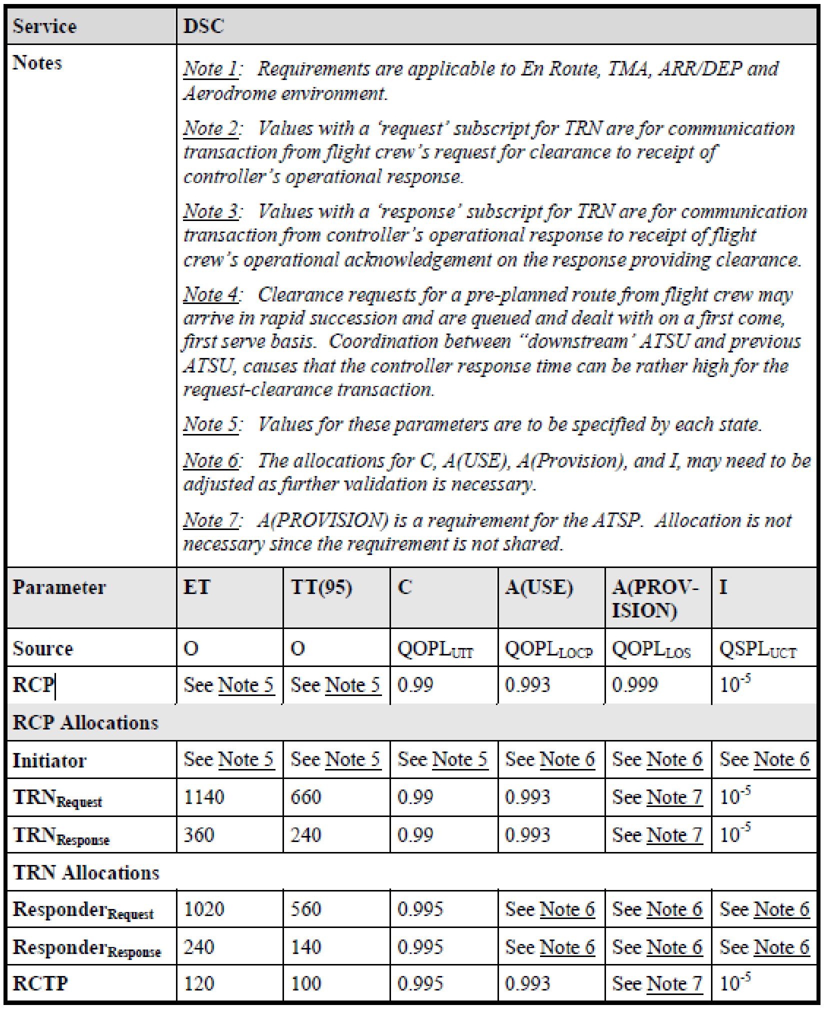
[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Table 5-45.]



Service	**DCL – controller initiated**					
Notes	*Note 1: The value for RCTP is a worst case for using DCL in ACARS environment.* *Note 2: Values for these parameters are to be specified by each state.* *Note 3: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 4: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	O	O	$QOPL_{UIT}$	$QOPL_{LOCP}$	$QOPL_{LOS}$	$QSPL_{UCT}$
RCP	See Note 2	See Note 2	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 2	See Note 2	See Note 2	See Note 3	See Note 3	See Note 3
TRN	300	140	0.99	0.993	See Note 4	10^{-5}
TRN Allocations						
Responder	240	100	0.995	See Note 3	See Note 3	See Note 3
RCTP	60	40	0.995	0.993	See Note 4	10^{-5}

Figure 114 – RCP for Departure Clearance (DCL) – Controller Initiated Transaction

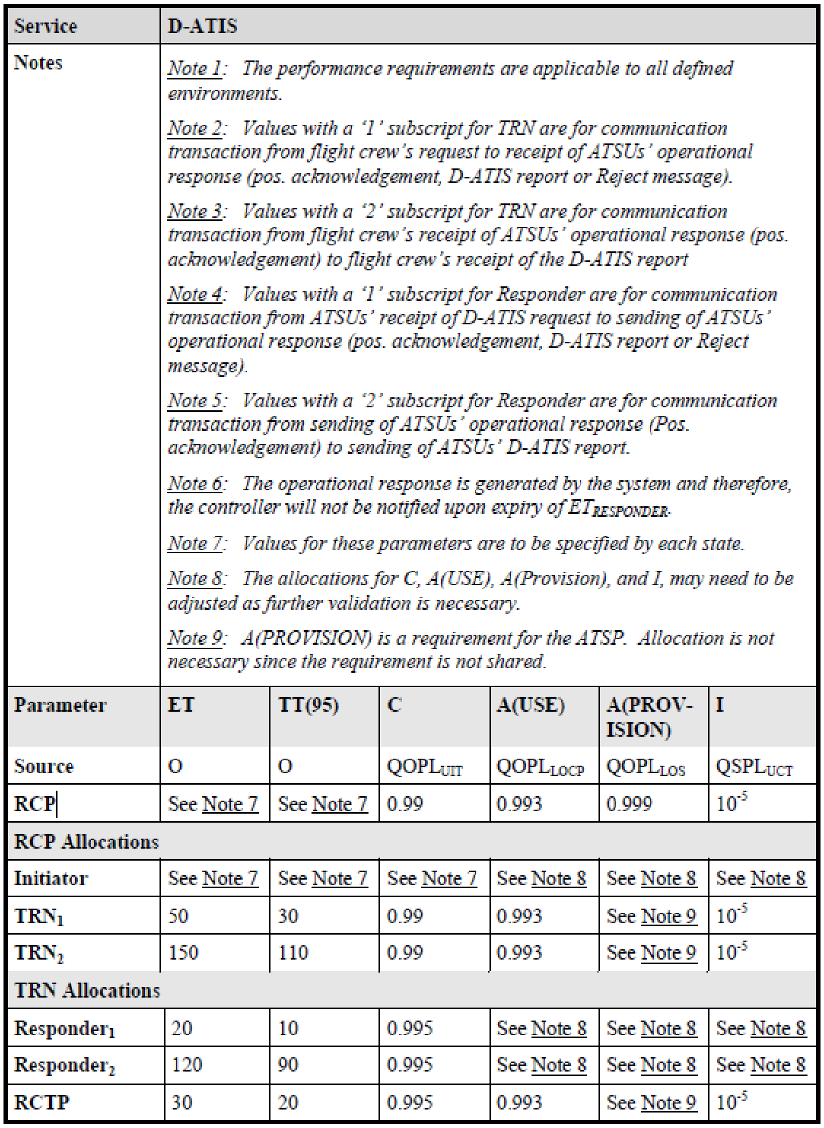
[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Table 5-46.]



Service	**DSC**					
Notes	*Note 1: Requirements are applicable to En Route, TMA, ARR/DEP and Aerodrome environment.* *Note 2: Values with a 'request' subscript for TRN are for communication transaction from flight crew's request for clearance to receipt of controller's operational response.* *Note 3: Values with a 'response' subscript for TRN are for communication transaction from controller's operational response to receipt of flight crew's operational acknowledgement on the response providing clearance.* *Note 4: Clearance requests for a pre-planned route from flight crew may arrive in rapid succession and are queued and dealt with on a first come, first serve basis. Coordination between "downstream' ATSU and previous ATSU, causes that the controller response time can be rather high for the request-clearance transaction.* *Note 5: Values for these parameters are to be specified by each state.* *Note 6: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 7: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	O	O	QOPL$_{UTT}$	QOPL$_{LOCP}$	QOPL$_{LOS}$	QSPL$_{UCT}$
RCP	See Note 5	See Note 5	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 5	See Note 5	See Note 5	See Note 6	See Note 6	See Note 6
TRN$_{Request}$	1140	660	0.99	0.993	See Note 7	10^{-5}
TRN$_{Response}$	360	240	0.99	0.993	See Note 7	10^{-5}
TRN Allocations						
Responder$_{Request}$	1020	560	0.995	See Note 6	See Note 6	See Note 6
Responder$_{Response}$	240	140	0.995	See Note 6	See Note 6	See Note 6
RCTP	120	100	0.995	0.993	See Note 7	10^{-5}

Figure 115 – RCP for Downstream Clearance (DSC)

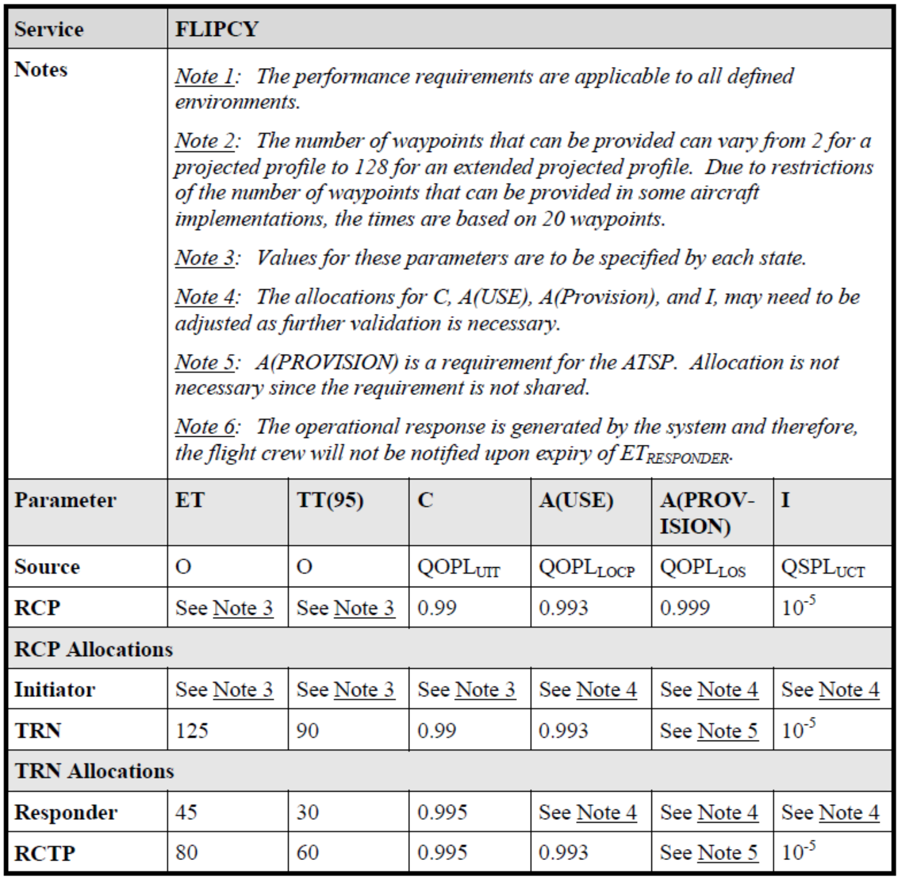
[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Table 5-53.]



Service	**D-ATIS**					
Notes	*Note 1: The performance requirements are applicable to all defined environments.* *Note 2: Values with a '1' subscript for TRN are for communication transaction from flight crew's request to receipt of ATSUs' operational response (pos. acknowledgement, D-ATIS report or Reject message).* *Note 3: Values with a '2' subscript for TRN are for communication transaction from flight crew's receipt of ATSUs' operational response (pos. acknowledgement) to flight crew's receipt of the D-ATIS report* *Note 4: Values with a '1' subscript for Responder are for communication transaction from ATSUs' receipt of D-ATIS request to sending of ATSUs' operational response (pos. acknowledgement, D-ATIS report or Reject message).* *Note 5: Values with a '2' subscript for Responder are for communication transaction from sending of ATSUs' operational response (Pos. acknowledgement) to sending of ATSUs' D-ATIS report.* *Note 6: The operational response is generated by the system and therefore, the controller will not be notified upon expiry of ET$_{RESPONDER}$.* *Note 7: Values for these parameters are to be specified by each state.* *Note 8: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 9: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.*					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROV-ISION)**	**I**
Source	O	O	QOPL$_{UIT}$	QOPL$_{LOCP}$	QOPL$_{LOS}$	QSPL$_{UCT}$
RCP	See Note 7	See Note 7	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 7	See Note 7	See Note 7	See Note 8	See Note 8	See Note 8
TRN$_1$	50	30	0.99	0.993	See Note 9	10^{-5}
TRN$_2$	150	110	0.99	0.993	See Note 9	10^{-5}
TRN Allocations						
Responder$_1$	20	10	0.995	See Note 8	See Note 8	See Note 8
Responder$_2$	120	90	0.995	See Note 8	See Note 8	See Note 8
RCTP	30	20	0.995	0.993	See Note 9	10^{-5}

Figure 116 – RCP Digital Automated Terminal Information Service (DATIS)

[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Table 6-9.]



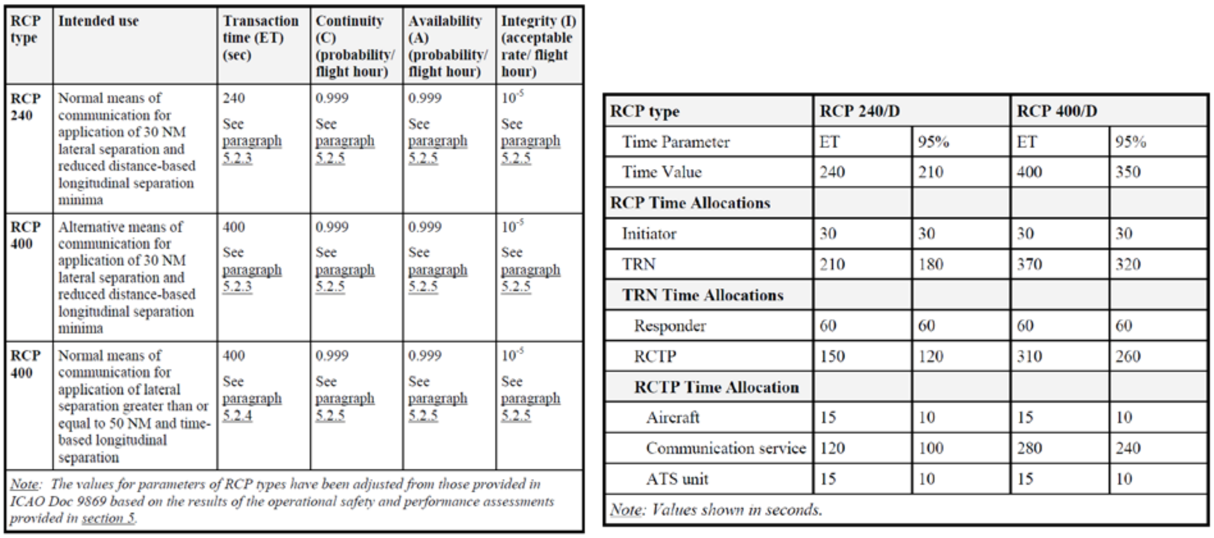
Service	**FLIPCY**					
Notes	*Note 1: The performance requirements are applicable to all defined environments.* *Note 2: The number of waypoints that can be provided can vary from 2 for a projected profile to 128 for an extended projected profile. Due to restrictions of the number of waypoints that can be provided in some aircraft implementations, the times are based on 20 waypoints.* *Note 3: Values for these parameters are to be specified by each state.* *Note 4: The allocations for C, A(USE), A(Provision), and I, may need to be adjusted as further validation is necessary.* *Note 5: A(PROVISION) is a requirement for the ATSP. Allocation is not necessary since the requirement is not shared.* *Note 6: The operational response is generated by the system and therefore, the flight crew will not be notified upon expiry of* $ET_{RESPONDER}$.					
Parameter	**ET**	**TT(95)**	**C**	**A(USE)**	**A(PROVISION)**	**I**
Source	O	O	$QOPL_{UIT}$	$QOPL_{LOCP}$	$QOPL_{LOS}$	$QSPL_{UCT}$
RCP	See Note 3	See Note 3	0.99	0.993	0.999	10^{-5}
RCP Allocations						
Initiator	See Note 3	See Note 3	See Note 3	See Note 4	See Note 4	See Note 4
TRN	125	90	0.99	0.993	See Note 5	10^{-5}
TRN Allocations						
Responder	45	30	0.995	See Note 4	See Note 4	See Note 4
RCTP	80	60	0.995	0.993	See Note 5	10^{-5}

Figure 117 – RCP for Flight Plan Consistency (FLIPSY) Service

[Reference: RTCA/DO-290, "Safety and Performance Standard for Air Traffic Data Link Services in Continental Airspace," April 29, 2004, Table 7-8.]

13.2.3 Oceanic/Remote Airspace SPR Standards

DO-308/ED-122 define the required communications performance for data link services applications in oceanic and remote airspaces to support separation assurance, route conformance monitoring, re-route, and weather deviation management taking into consideration the following FANS 1/A data link applications: 1) ATS Facilities Notification, 2) Controller Pilot Data Link Communications (CPDLC), and 3) Automatic Dependent Surveillance – Contract (ADS-C). The RCP as stated in DO-308 for these oceanic/remote services are provided in Figure 118.



RCP type	Intended use	Transaction time (ET) (sec)	Continuity (C) (probability/ flight hour)	Availability (A) (probability/ flight hour)	Integrity (I) (acceptable rate/ flight hour)
RCP 240	Normal means of communication for application of 30 NM lateral separation and reduced distance-based longitudinal separation minima	240 See paragraph 5.2.3	0.999 See paragraph 5.2.5	0.999 See paragraph 5.2.5	10^{-5} See paragraph 5.2.5
RCP 400	Alternative means of communication for application of 30 NM lateral separation and reduced distance-based longitudinal separation minima	400 See paragraph 5.2.3	0.999 See paragraph 5.2.5	0.999 See paragraph 5.2.5	10^{-5} See paragraph 5.2.5
RCP 400	Normal means of communication for application of lateral separation greater than or equal to 50 NM and time-based longitudinal separation	400 See paragraph 5.2.4	0.999 See paragraph 5.2.5	0.999 See paragraph 5.2.5	10^{-5} See paragraph 5.2.5

Note: The values for parameters of RCP types have been adjusted from those provided in ICAO Doc 9869 based on the results of the operational safety and performance assessments provided in section 5.

RCP type	**RCP 240/D**		**RCP 400/D**	
Time Parameter	ET	95%	ET	95%
Time Value	240	210	400	350
RCP Time Allocations				
Initiator	30	30	30	30
TRN	210	180	370	320
TRN Time Allocations				
Responder	60	60	60	60
RCTP	150	120	310	260
RCTP Time Allocation				
Aircraft	15	10	15	10
Communication service	120	100	280	240
ATS unit	15	10	15	10

Note: Values shown in seconds.

Figure 118 – RCP for Data Link Services in Remote and Oceanic Airspace

[Reference: RTCA/DO-306, "Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace," October 11, 2007, Tables 5-6 and 5-10.]

13.3 Communication Requirements and Rationale for Future Applications

This section of the report identifies initial notional communication requirements for future applications in the future airspace. Note that some of the requirements for applications in this section have been proposed to be more stringent than the requirements for existing applications in the existing airspace provided in 13.2.

13.3.1 Future Airspace Applications

It is envisioned that over time, there will be paradigm changes in the way that air traffic is managed. Figure 119 below highlights a number of the expected operational changes.

In the future, it is envisioned that information will flow via appropriate communication paths to enable decisions to be made with a much better awareness of the system-wide implications. Communications of information is key to improving operational efficiencies (enabling aircraft to fly their preferred business case trajectories), while reducing human workload and enhancing safety & security.

Current	Future
First come, first served	Best equipped, best served
Direct control of aircraft	Management by exception
Ground-centric Air Traffic Control	Distributed decision making with aircraft as an integrated element
Limited information sharing	**Network-enabled, information rich environment**
Rigid rules, daily Ops Plan with periodic updates	Flexibility to support dynamically changing conditions, timely info.
Rigorous roles and responsibilities	Distributed roles between flight deck and ground control
Equipment based	Performance based
Limited automation	Wide use of ground and aircraft decision support tools
Human-centric information exchange	Human-in-the-loop decision making, machine-to-machine dialog

Figure 119 – Possible Future ATM Operational Paradigm Changes

Aligned with the expected operational paradigm changes, anticipated future airspace applications have been identified in each of the flight phases as indicated below.

13.3.1.1 Future Airport Surface Applications

A representative set of anticipated future airport surface applications have been identified ranging from routine airport surface applications [including providing taxi and departure clearances] to supporting more advanced applications [including simultaneous runway operations, “4D” TBO (really 3D horizontal position and time)]. Also considered are near zero visibility airport surface movement taxi, ground based runway incursion alerting, as well as aircraft access to SWIM, Flight & Weather Information Services, and communications with AOC. See Figure 120.

13.3.1.2 Future Terminal Area Applications

A representative set of anticipated future airport terminal area applications have been identified ranging from standard arrival / departure / approach applications in use today [including Standard Arrival Route (STAR), Standard Instrument Departures (SID), Category I/II/III ILS approach operations] to supporting more advanced applications [including Closely Spaced Parallel runway Operations (CSPO), Optimized Profile Descent, Interval Management – Delegated Interval, Delegated Separation, 4D TBO]. Many additional terminal area applications have been considered including airspace separation (at today’s 3 NM, and potentially reduced to 2 and 1 NM in the future), additional approach applications (including converging and intersecting runway applications, GBAS Cat. I/II/III precision approach, and simultaneous runway operations), and advanced arrival/departure operations (including tailored arrivals and departures, wake turbulence mitigation for arrivals/departures), as well as Airborne Access to SWIM, Flight & Weather Information Services, and communications with AOC. Applications that involve the airborne exchange of sensed information (e.g., WxR information) were also considered. See Figure 120.

13.3.1.3 Future Domestic Enroute Applications

A representative set of anticipated future domestic enroute airspace applications have been identified ranging from standard ATC separation services in use today [including 5 NM separation] to supporting more advanced applications [including In-Trail Procedure (ITP), advanced climb/descent procedures, interval management – delegated interval, delegated separation, 4D TBO, reduced separation, cruise climb/descent, Autonomous Flight Rules/self-separation. Many additional Domestic Enroute applications have been identified as indicated in Figure 120.

13.3.1.4 Future Remote / Oceanic / Polar Applications

A representative set of anticipated future applications for remote / oceanic / polar airspaces have been identified ranging from standard ATC separation services in use today [including greater than 50 NM lateral and 10 minutes longitudinal separation] to supporting more advanced applications [including In-Trail Procedure (ITP), advanced oceanic/remote climb/descent procedures, interval management – delegated interval, delegated separation, 4D TBO, significantly reduced separation (enabled with the advent of satellite-based ADS-B surveillance), cruise climb/descent, Autonomous Flight Rules/self-separation. Many additional applications for remote / oceanic / polar airspaces have been identified as indicated in Figure 120.

Airspace	Future Airspace Applications
Surface / APT	Air Traffic Control Communications
	Surface Traffic Management:
	Departure Clearance
	Taxi Clearance
	Ground-Based Runway Incursion Alerting
	Simultaneous Runway Operations
	Near Zero Visibility Taxi Operations
	Surface Situational Awareness (SURF)
	SURF with Indications and Alerts (SURF IA)
	4D Trajectory Based Operations (TBO)
	Airborne Access to SWIM (AAtS)
	Airborne Exchange of Sensed Information
	Flight & Weather Information Services (FIS)
	AOC Communications
Terminal Area	Air Traffic Control Communications
	Airspace Separation:
	1 NM / 2 NM / 3 NM
	Approach Applications:
	Non-Precision Approach (NPA)
	LPV Operations
	ILS Cat. I/II/III Precision Approach
	GPS/LAAS Cat. I/II/III Precision Approach
	Closely Spaced Parallel RW Operations (CSPO)
	Converging & Intersecting RW Operations
	Simultaneous Runway Operations
	Arrival /Departure Applications:
	Standard Arrival Route (STAR) Procedures
	Standard Instrument Departure (SID)
	Tailored Arrivals or Departure
	Optimized Profile Descent (OPD)
	Optimized Departure Climb
	Ground-Based Interval Management - Spacing
	Flight Deck IM - Spacing / Delegated Interval
	Delegated Separation
	Wake Turbulance Mitigation for Arrivals / Departures
	RNP Operations
	4D Trajectory Based Operations (TBO)
	Airborne Access to SWIM (AAtS)
	Airborne Exchange of Sensed Information
	Flight and Weather Information Services
	AOC Communications
Enroute Domestic	Air Traffic Control Communications
	Separation Assurance:
	2 NM / 3 NM / 5 NM
	In-Trail Procedure (ITP)
	Climb/Descent Procedure (CDP)
	Cruise Climb / Descent
	Ground Interval Management
	Flight Deck IM - Spacing / Delegated Interval
	Delegated Separation (DS)
	4D Trajectory Based Operations (TBO)
	Airborne Access to SWIM (AAtS)
	Airborne Exchange of Sensed Information
	Flight and Weather Information Services
	AOC Communications
	Autonomous Flight Rules (AFR)
Enroute Oceanic / Remote / Polar	Air Traffic Control Communications
	Separation Assurance:
	5 NM / 10 NM / 30 NM
	Greater than 30 NM lat. & 5 minutes long.
	Greater than 50 NM lat. & 10 minutes long.
	In-Trail Procedure
	Climb/Descent Procedure (CDP)
	Cruise Climb / Descent
	Flight Deck IM / Delegated Interval
	Delegated Separation (DS)
	Trajectory Based Operations (TBO)
	Airborne Access to SWIM (AAtS)
	Airborne Exchange of Sensed Information
	Flight and Weather Information Services
	AOC Communications
	Autonomous Flight Rules (AFR)

Figure 120 – Future Applications

13.3.2 Required Comm. Performance & Rationale for Future Applications

13.3.2.1 Required Communications Performance for Future Applications

To operationally enable the applications identified and envisioned for NextGen and beyond, it has been postulated by our study team that a limited number of RCP types as identified in Figure 121 may be sufficient to begin to realize that vision. These RCP type values are provided to stimulate discussion and thought on RCP for different airspaces and provide a starting point for further analysis, validation, and vetting with all stakeholders. The rationale for the RCP values are based upon our initial evaluations of the communications transactions expected to be necessary to support the initial set of future applications that have been identified. These evaluations have leveraged information available in industry guidance documents including, for example, RTCA, EUROCAE, and ICAO. <u>The required communication performance values identified for future applications are very preliminary and need additional operational, performance, safety, and security analyses to confirm that they are appropriate to enable the various intended applications.</u>

While there has been considerable work within the industry on RCP, there is little consensus as to what RCP types will be required to enable a wide range future applications. It is expected that as the future applications are being developed, the RCP definition will be revised over time and may eventually include other measures of communications performance.

The aircraft applications that can be conducted in the various airspaces are dependent upon the performance of the communication, navigation, and surveillance systems, as well as other elements to ensure system safety. Communication requirements are enabling requirements and not sufficient requirements without the other necessary elements of the applications which are identified as part of the Operational Services and Environmental Definition (OSED) for each application.

Figure 122 provides an initial allocation of each RCP level to the Required Communication Transaction Performance (RCTP) envisioned for the communication system to meet the NAS operational demands for the NextGen and beyond airspace applications identified.

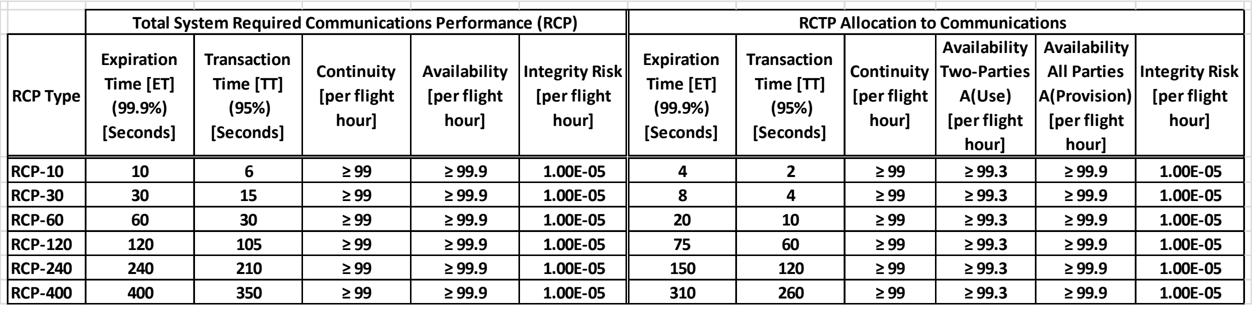
Figure 123 provides an initial allocation of the required future Required Surveillance Performance (RSP) allocation to the communication link for supporting the ADS-B function. Notice that several allocations are provided, including for the allocation aligned with the FAA's ADS-B Out Rule and for expected future RSP requirements envisioned to be needed to support future applications. Notice that the communication requirements allocations associated with the transaction expiration time (ET) and 95% transaction time (TT) are dependent upon the range between the transmitter and the receiver.

Figure 124 provides an initial allocation of the required future required performance allocation to the communication link for supporting the GPS/Local Area Augmentation System (LAAS) VHF Data Broadcast (VDB) function. Notice that three allocations are provided, which are intended to support Category I / II / III precision approach operations, respectively. Notice in this table, the communication requirements allocations associated with the transaction expiration time (ET) specifically identify the more stringent probability of exceeding the transaction time, rather than using the 99.9% probability that has been used to specify RCP, because of the more critical nature of the loss of the LAAS-based precision approach guidance when the ET is exceeded.

RCP Type	Expiration Time [ET] (99.9%)	Transaction Time [TT] (95%)	Conti-nuity	Availability	Integrity Risk (per flight hour)	Airspace Mapping	General Types of Applications Supported by this RCP Type
			(probability/ flight hour)				
RCP 10	10 s	6 s	≥ 99 [Typically ≥ 99.9]	≥ 99.9 [Typically ≥ 99.998]	1.00E-05	Critical / timely domestic communications (RCP 10 or better)	RCP 10 may be applied to controller intervention capability supporting ATM applications in surface, terminal area, and enroute domestic airspaces.
RCP 30	30 s	15 s	≥ 99 [Typically ≥ 99.9]	≥ 99.9 [Typically ≥ 99.99]	1.00E-05	Essential domestic for busy terminal areas (RCP 30 or better)	RCP 30 may be applied to routine ATM relevant communications supporting applications in busy terminal areas.
RCP 60	60 s	30 s	≥ 99 [Typically ≥ 99.9]	≥ 99.9 [Typically ≥ 99.99]	1.00E-05	Essential domestic enroute (RCP 60 or better)	RCP 60 may be applied to routine ATM relevant communications supporting applications in surface, terminal area, and enroute domestic airspaces. In the future, RCP 60 (with appropriate surveillance) may be applied to enable oceanic separations with 10 NM separations.
RCP 120	120 s	105 s	≥ 99 [Typically ≥ 99.9]	≥ 99.9 [Typically ≥ 99.99]	1.00E-05	Advisory domestic, Critical oceanic (RCP 120 or better)	RCP 120 may be applied to advisory communications in domestic airspace, and for controller intervention capability supporting separation assurance in oceanic/remote airspaces with smaller separation environment.
RCP 240	240 s	210 s	≥ 99 [Typically ≥ 99.9]	≥ 99.9 [Typically ≥ 99.99]	1.00E-05	Essential oceanic (RCP 240 or better)	RCP 240 may be a basis for controller intervention capability supporting separation assurance in oceanic/remote airspaces with greater than or equal 30 NM lateral or greater than 5 minutes longitudinal separation.
RCP 400	400 s	350 s	≥ 99 [Typically ≥ 99.9]	≥ 99.9	1.00E-05	Advisory Oceanic (RCP 400 or better)	RCP 400 may be used for controller intervention capability supporting separation assurance in current environments where separations are greater than 50 NM lateral or greater than 10 minutes longitudinal.

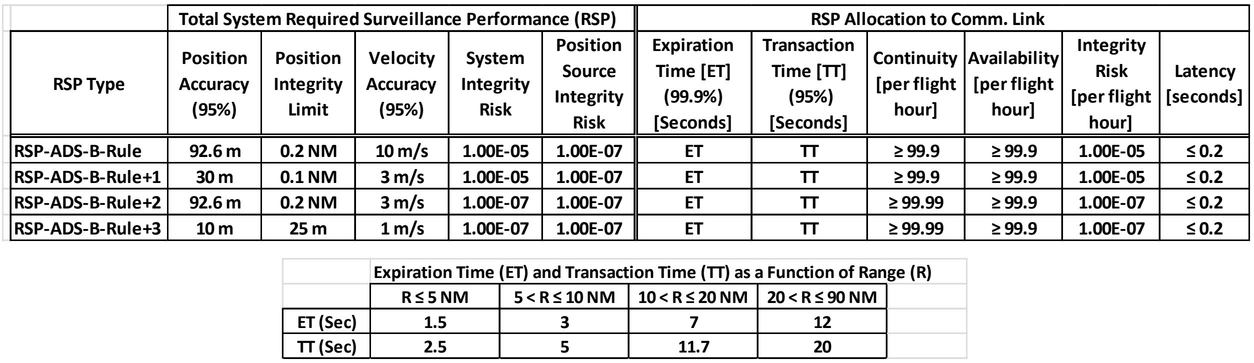
Note: RCP levels based upon ICAO Manual on Required Communication Performance (RCP), First Edition, 2006, Doc 9869. (Section 3.2 RCP Types – General Application, page 3-1).

Figure 121 – Straw Man Future Required Communication Performance Levels



	Total System Required Communications Performance (RCP)					RCTP Allocation to Communications					
RCP Type	Expiration Time [ET] (99.9%) [Seconds]	Transaction Time [TT] (95%) [Seconds]	Continuity [per flight hour]	Availability [per flight hour]	Integrity Risk [per flight hour]	Expiration Time [ET] (99.9%) [Seconds]	Transaction Time [TT] (95%) [Seconds]	Continuity [per flight hour]	Availability Two-Parties A(Use) [per flight hour]	Availability All Parties A(Provision) [per flight hour]	Integrity Risk [per flight hour]
RCP-10	10	6	≥ 99	≥ 99.9	1.00E-05	4	2	≥ 99	≥ 99.3	≥ 99.9	1.00E-05
RCP-30	30	15	≥ 99	≥ 99.9	1.00E-05	8	4	≥ 99	≥ 99.3	≥ 99.9	1.00E-05
RCP-60	60	30	≥ 99	≥ 99.9	1.00E-05	20	10	≥ 99	≥ 99.3	≥ 99.9	1.00E-05
RCP-120	120	105	≥ 99	≥ 99.9	1.00E-05	75	60	≥ 99	≥ 99.3	≥ 99.9	1.00E-05
RCP-240	240	210	≥ 99	≥ 99.9	1.00E-05	150	120	≥ 99	≥ 99.3	≥ 99.9	1.00E-05
RCP-400	400	350	≥ 99	≥ 99.9	1.00E-05	310	260	≥ 99	≥ 99.3	≥ 99.9	1.00E-05

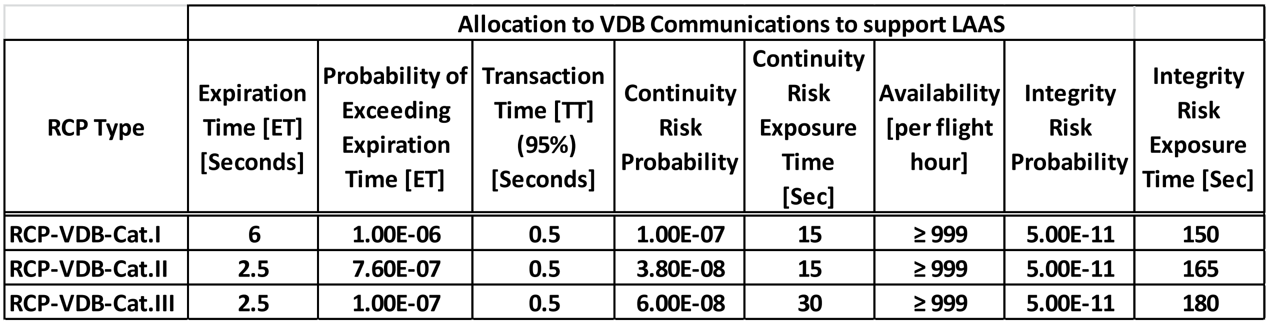
Figure 122 – Straw Man Future Required Communications Transaction Performance (RCTP) for Each RCP Level



	Total System Required Surveillance Performance (RSP)					RSP Allocation to Comm. Link					
RSP Type	Position Accuracy (95%)	Position Integrity Limit	Velocity Accuracy (95%)	System Integrity Risk	Position Source Integrity Risk	Expiration Time [ET] (99.9%) [Seconds]	Transaction Time [TT] (95%) [Seconds]	Continuity [per flight hour]	Availability [per flight hour]	Integrity Risk [per flight hour]	Latency [seconds]
RSP-ADS-B-Rule	92.6 m	0.2 NM	10 m/s	1.00E-05	1.00E-07	ET	TT	≥ 99.9	≥ 99.9	1.00E-05	≤ 0.2
RSP-ADS-B-Rule+1	30 m	0.1 NM	3 m/s	1.00E-05	1.00E-07	ET	TT	≥ 99.9	≥ 99.9	1.00E-05	≤ 0.2
RSP-ADS-B-Rule+2	92.6 m	0.2 NM	3 m/s	1.00E-07	1.00E-07	ET	TT	≥ 99.99	≥ 99.9	1.00E-07	≤ 0.2
RSP-ADS-B-Rule+3	10 m	25 m	1 m/s	1.00E-07	1.00E-07	ET	TT	≥ 99.99	≥ 99.9	1.00E-07	≤ 0.2

	Expiration Time (ET) and Transaction Time (TT) as a Function of Range (R)			
	R ≤ 5 NM	5 < R ≤ 10 NM	10 < R ≤ 20 NM	20 < R ≤ 90 NM
ET (Sec)	1.5	3	7	12
TT (Sec)	2.5	5	11.7	20

Figure 123 – Straw Man Future Required Surveillance Performance Allocation to the Communication Link for ADS-B Surveillance



	Allocation to VDB Communications to support LAAS							
RCP Type	Expiration Time [ET] [Seconds]	Probability of Exceeding Expiration Time [ET]	Transaction Time [TT] (95%) [Seconds]	Continuity Risk Probability	Continuity Risk Exposure Time [Sec]	Availability [per flight hour]	Integrity Risk Probability	Integrity Risk Exposure Time [Sec]
RCP-VDB-Cat.I	6	1.00E-06	0.5	1.00E-07	15	≥ 999	5.00E-11	150
RCP-VDB-Cat.II	2.5	7.60E-07	0.5	3.80E-08	15	≥ 999	5.00E-11	165
RCP-VDB-Cat.III	2.5	1.00E-07	0.5	6.00E-08	30	≥ 999	5.00E-11	180

Figure 124 – Straw Man Future Required Navigation Performance Allocation to the GPS/LAAS VHF Data Broadcast (VDB) Function

[Rationale: Allocation is based upon RTCA DO-245A, "Minimum Aviation System Performance Standards for GPS/Local Area Augmentation System (LAAS)," Appendix D.]

		Air-to-Air		Air-to-Ground		
Airspace	**Future Airspace Applications**	**RCP**	**Required Com. To Support Surv. [Note 1]**	**RCP**	**Required Com. To Support Surv. [Note 2]**	**Required Com. To Support Nav.**
Surface / APT	Air Traffic Control Communications	---	---	RCP-30	---	---
	Surface Traffic Management:	-	-	-	-	-
	Departure Clearance	---	---	RCP-30	---	---
	Taxi Clearance	---	---	RCP-30	---	---
	Ground-Based Runway Incursion Alerting	---	---	RCP-10	RSP-ADS-B-Rule+1 or other Ground Surveillance	---
	Simultaneous Runway Operations	---	RSP-ADS-B-Rule	RCP-10	RSP-ADS-B-Rule+1	---
	Near Zero Visibility Taxi Operations	---	RSP-ADS-B-Rule+3	RCP-10	RSP-ADS-B-Rule+3	RCP-VDB
	Surface Situational Awareness (SURF)	---	RSP-ADS-B-Rule	---	---	---
	SURF with Indications and Alerts (SURF IA)	---	RSP-ADS-B-Rule+1	---	---	---
	4D Trajectory Based Operations (TBO)	---	---	RCP-60	RSP-ADS-B-Rule+1	---
	Airborne Access to SWIM (AAtS)	---	---	RCP-120	---	---
	Airborne Exchange of Sensed Information	RCP-120	---	---	---	---
	Flight & Weather Information Services (FIS)	---	---	RCP-120	---	---
	AOC Communications	---	---	RCP-120	---	---
Terminal Area	Air Traffic Control Communications	---	---	RCP-60	---	---
	Airspace Separation:	-	-	-	-	-
	1 NM	---	---	RCP-10	RSP-ADS-B-Rule+2	---
	2 NM	---	---	RCP-10	RSP-ADS-B-Rule+2	---
	3 NM	---	---	RCP-10	RSP-ADS-B-Rule	---
	Approach Applications:	-	-	-	-	-
	Non-Precision Approach (NPA)	---	---	RCP-10	RSP-ADS-B-Rule	---
	LPV Operations	---	---	RCP-10	RSP-ADS-B-Rule	---
	ILS Cat. I/II/III Precision Approach	---	---	RCP-10	RSP-ADS-B-Rule	---
	GPS/LAAS Cat. I/II/III Precision Approach	---	---	RCP-10	RSP-ADS-B-Rule	RCP-VDB
	Closely Spaced Parallel RW Operations (CSPO)	---	RSP-ADS-B-Rule	RCP-10	RSP-ADS-B-Rule	---
	Converging & Intersecting RW Operations	---	RSP-ADS-B-Rule+1	RCP-10	RSP-ADS-B-Rule	---
	Simultaneous Runway Operations	---	RSP-ADS-B-Rule+1	RCP-10	RSP-ADS-B-Rule+1	---
	Arrival /Departure Applications:	-	-	-	-	-
	Standard Arrival Route (STAR) Procedures	---	---	RCP-10	RSP-ADS-B-Rule	---
	Standard Instrument Departure (SID)	---	---	RCP-10	RSP-ADS-B-Rule	---
	Tailored Arrivals or Departure	---	---	RCP-10	RSP-ADS-B-Rule	---
	Optimized Profile Descent (OPD)	---	---	RCP-10	RSP-ADS-B-Rule	---
	Optimized Departure Climb	---	---	RCP-10	RSP-ADS-B-Rule	---
	Ground-Based Interval Management - Spacing	---	---	RCP-60	RSP-ADS-B-Rule	---
	Flight Deck IM - Spacing / Delegated Interval	---	RSP-ADS-B-Rule	RCP-30	RSP-ADS-B-Rule	---
	Delegated Separation	---	RSP-ADS-B-Rule	RCP-30	RSP-ADS-B-Rule	---
	Wake Turbulance Mitigation for Arrivals / Departures	---	---	RCP-30	RSP-ADS-B-Rule	---
	RNP Operations	---	---	RCP-30	---	---
	4D Trajectory Based Operations (TBO)	---	---	RCP-30	RSP-ADS-B-Rule	---
	Airborne Access to SWIM (AAtS)	---	---	RCP-120	---	---
	Airborne Exchange of Sensed Information	RCP-120	---	---	---	---
	Flight and Weather Information Services	---	---	RCP-120	---	---
	AOC Communications	---	---	RCP-120	---	---

Figure 125 – Straw Man RCP for Future Applications in the Surface and Terminal Area Airspaces

Notes: 1) TCAS air-to-air communications required by most aircraft per today's requirements (see Section 13.2.1).

2) ATCRBS air-to-ground communications required by most aircraft in ATC controlled airspace (see Section 13.2.1).

		Air-to-Air		Air-to-Ground		
Airspace	**Future Airspace Applications**	**RCP**	**Required Com. To Support Surv. [Note 1]**	**RCP**	**Required Com. To Support Surv. [Note 2]**	**Required Com. To Support Nav.**
Enroute Domestic	Air Traffic Control Communications	---	---	RSP-120	---	---
	Separation Assurance:	-	-	-	-	-
	2 NM	---	---	RCP-30	RSP-ADS-B-Rule+2	---
	3 NM	---	---	RCP-60	RSP-ADS-B-Rule	---
	5 NM	---	---	RCP-60	RSP-ADS-B-Rule	---
	In-Trail Procedure (ITP)	---	RSP-ADS-B-Rule	RCP-120	RSP-ADS-B-Rule	---
	Climb/Descent Procedure (CDP)	---	RSP-ADS-B-Rule	RCP-120	RSP-ADS-B-Rule	---
	Cruise Climb / Descent	---	RSP-ADS-B-Rule	RCP-120	RSP-ADS-B-Rule	---
	Ground Interval Management	---	RSP-ADS-B-Rule	RCP-120	RSP-ADS-B-Rule	---
	Flight Deck IM - Spacing / Delegated Interval	---	RSP-ADS-B-Rule	RCP-120	RSP-ADS-B-Rule	---
	Delegated Separation (DS)	---	RSP-ADS-B-Rule	RCP-60	RSP-ADS-B-Rule	---
	4D Trajectory Based Operations (TBO)	---	---	RCP-120	RSP-ADS-B-Rule	---
	Airborne Access to SWIM (AAtS)	---	---	RCP-240	---	---
	Airborne Exchange of Sensed Information	RCP-120	---	---	---	---
	Flight and Weather Information Services	---	---	RCP-120	---	---
	AOC Communications	---	---	RCP-120	---	---
	Autonomous Flight Rules (AFR)	---	RSP-ADS-B-Rule+2	RCP-60	RSP-ADS-B-Rule+2	---
Enroute Oceanic / Remote / Polar	Air Traffic Control Communications	---	---	RCP-400	---	---
	Separation Assurance:	-	-	-	-	-
	5 NM	---	RSP-ADS-B-Rule	RCP-30	ADS-C at RCP-30	---
	10 NM	---	RSP-ADS-B-Rule	RCP-60	ADS-C at RCP-60	---
	30 NM	---	---	RCP-120	ADS-C at RCP-120	---
	Greater than 30 NM lat. & 5 minutes long.	---	---	RCP-240	ADS-C at RCP-240	---
	Greater than 50 NM lat. & 10 minutes long.	---	---	RCP-400	ADS-C at RCP-400	---
	In-Trail Procedure	---	RSP-ADS-B-Rule	RCP-240	ADS-C at RCP-400	---
	Climb/Descent Procedure (CDP)	---	RSP-ADS-B-Rule	RCP-240	ADS-C at RCP-120	---
	Cruise Climb / Descent	---	RSP-ADS-B-Rule	RCP-240	ADS-C at RCP-120	---
	Flight Deck IM / Delegated Interval	---	RSP-ADS-B-Rule	RCP-240	ADS-C at RCP-240	---
	Delegated Separation (DS)	---	RSP-ADS-B-Rule	RCP-120	ADS-C at RCP-240	---
	Trajectory Based Operations (TBO)	---	RSP-ADS-B-Rule	RCP-240	ADS-C at RCP-400	---
	Airborne Access to SWIM (AAtS)	---	---	---	---	---
	Airborne Exchange of Sensed Information	RCP-400	---	---	---	---
	Flight and Weather Information Services	---	---	RCP-400	---	---
	AOC Communications	---	---	RCP-400	---	---
	Autonomous Flight Rules (AFR)	---	RSP-ADS-B-Rule+2	RCP-120	ADS-C at RCP-240	---

Figure 126 – Straw Man RCP for Future Applications in the Enroute Domestic and Remote / Oceanic / Polar Airspaces

Notes: 1) TCAS air-to-air communications required by most aircraft per today's requirements (see Section 13.2.1).

2) ATCRBS air-to-ground communications required by most aircraft in ATC controlled airspace (see Section 13.2.1).

13.3.2.2 Rationale for RCP Levels and RCTP Allocations to Address Future Applications

RCP performance requirements for airspace applications are heavily dependent upon the intended function(s) being supported. Applications for which the communicated information is of importance and will need to be utilized in a timely manner for operational utility or safety of flight tend to drive the required performance for communications transaction times to be better (i.e., smaller) than for applications for which the timeliness of acting on the information is of lesser importance from operational utility and/or safety.

Applications where the communicated information is more critical to the safety of flight will tend to have higher performance integrity requirements than applications where the communicated information does not impact the safety of flight. Applications where the loss of information during an application is potentially hazardous or causes significant operational consequences will tend to have higher performance continuity requirements than applications where the loss of information causes minimal to no operational effects.

Applications that are very important to the airspace operations will tend to drive the required performance for communications to support them to higher levels of availability than for applications that have minimal impact if they are not operational.

Communication system designs are highly dependent upon peak loading requirements and geographic dispersion of the communicating parties. In supporting future NAS operations, it is envisioned that surface/terminal area operations will be the most demanding from a communications loading perspective. The need to communicate with many aircraft on the ground and in the air within the same geographic location requires considerable communications bandwidth.

Remote and oceanic regions are the most demanding from a communications technology perspective. Beyond line-of-sight communications are typically more difficult to implement and manage. Terminal area and oceanic/remote operations are envisioned to be the primary performance drivers for the RCP types needed to support NextGen and beyond applications.

In the surface/terminal area, ATM applications where the information communicated may result in altering the flight path of an aircraft moving in close proximity in space or time to one another aircraft or to some hazard (e.g., weather) tend to require shorter transaction times than applications where aircraft are farther apart (e.g., in oceanic and remote airspaces). This tends to be the case for both the 95% nominal and the 99.9% bound on the transaction times.

The transaction times (both the 95% nominal and the 99.9% limit) also affect the operational usability and utility, as well as potentially the safety of the applications that are intending to use the information.

The intended use of the communication as well as the potential hazards that may occur during the application from the loss of information or the use of incorrect information, affect the required continuity and integrity, respectively. The availability of the communication function to support application(s) primarily affects the cost/benefit of the communication service.

As transaction times needed to support an RCP type within a given airspace become more demanding, the human machine interface performance will become the gating function on the RCP type. Optimum communications latency can be managed through performance monitoring and communications load balancing. Human machine interactions are much more difficult to manage from a latency perspective than the communication systems latencies.

The rationale for the values RCP-240 and RCP-400 are based upon the requirements in RTCA/DO-306 (EUROCAE ED-122), which have been defined to support today’s oceanic and remote airspace applications. In the future, taking advantage of better Communication / Navigation / Surveillance systems and the corresponding better required CNS performance will enable applications in such airspaces that will significantly improve the operational efficiency by, for example, reducing the aircraft separation standards.

All of these factors have been considered as part of the rationale for the initial communication requirements identified for future applications.

14 MAPPING OF COMMUNICATION CANDIDATES TO APPLICATIONS

This section maps the communications technology candidates to the airspace applications based upon their ability to support ATM applications. The mapping has been done generically by the ability to support any ATM applications in the airspace (Section 14.1) and then by specific applications in each of the airspaces (Section 14.2).

14.1 Communication Technology Candidates by Airspace

The communication technology candidates for A-A and A-G communications have been identified in Section 10. Figure 127 below summarizes the A-A communication technology candidates by their ability to provide a quality of service commensurate with satisfying future ATM applications identified in Section 13.3.1 as a function of the airspace environment. Similarly, Figure 128 summarizes the A-G candidates mapping to airspace. These airspace mapping figures are notional simplifications. Some candidates can support some ATM applications in other airspace (e.g., MEO SATCOM can also support communications in surface and terminal airspace environments).

		Airspace				
#	**Communications Candidates**	**Surface**	**Terminal**	**En Route**	**Oceanic/Remote**	**Polar**
A-A	**Air-to-Air (A-A) Communications Candidates**					
1	**VHF A-A**	X	X	X	X	X
2	**UHF A-A**	X	X	X	X	X
3	**L-Band A-A**	X	X	X	X	X
4	**S-Band A-A**	X	X	X	X	X
5	**C-Band A-A**	X	X	X	X	X
6	**X-Band A-A**	X	X	X	X	X
7	**Optical A-A**	X	X	X	X	X
8	**Hybrid RF/Optical A-A**	X	X	X	X	X
9	**LEO SATCOM A-A (One Hop through Satellite)**	X	X	X	X	X
10	**GEO SATCOM A-A (One Hop through Satellite)**	X	X	X	X	
11	**MEO SATCOM A-A (One Hop through Satellite)**	X	X	X	X	X
12	**GEO + HEO SATCOM A-A (One Hop through Sat.)**	X	X	X	X	X

Figure 127 – Notional Airspace Mapping of Air-to-Air Communications Candidates

		Airspace				
#	Communications Candidates	Surface	Terminal	En Route	Oceanic/Remote	Polar
A-G	Air-to-Ground (A-G) Communication Candidates					
1	HF A-G				X	X
2	VHF A-G	X	X	X		
3	UHF A-G	X	X	X		
4	L-Band A-G	X	X	X		
5	S-Band A-G	X	X	X		
6	C-Band A-G	X	X	X		
7	Optical A-G	X	X			
8	Hybrid RF/Optical A-G	X	X	X		
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)	X	X	X		
10	DTV VHF/UHF Network	X	X	X		
11	Cellular Network (e.g., Aircell)	X	X	X		
12	LEO SATCOM Network (e.g., Iridium Next+)	X	X	X	X	X
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)			X	X	
14	MEO SATCOM Network (e.g. GlobalStar+)			X	X	X
15	VHF A-A Hopping for long range A-G Com.				X	X
16	UHF A-A Hopping for long range A-G Com.				X	X
17	L-Band A-A Hopping for long range A-G Com.				X	X
18	X-Band A-G	X	X			
19	GEO + HEO SATCOM Network	X	X	X	X	X

Figure 128 – Notional Airspace Mapping of Air-to-Ground Comm. Candidates

14.2 Communication Technology Candidates by Application

Section 13 identifies the required communication performance necessary to support a wide range of current and future airspace applications. This subsection provides a mapping of the A-A and A-G candidates based upon their capability [i.e., Actual Communications Performance (ACP)] to satisfy the required communications performance necessary to support applications. Figure 129 provides the mapping for applications in the surface and terminal area airspaces, and Figure 130 provides the mapping for applications in the enroute, oceanic/remote, and polar airspaces.

As can be seen by the mappings, there are a number of technology candidates that are capable of meeting the required communications performance for all applications.

		Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	**Future Airspace Applications**	**RCP**	**Required Com. To Support Surv. [Note 1]**	**RCP**	**Required Com. To Support Surv. [Note 2]**	**Required Com. To Support Nav.**
Surface / APT	Air Traffic Control Communications	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	Surface Traffic Management:	-	-	-	-	-
	Departure Clearance	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	Taxi Clearance	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	Ground-Based Runway Incursion Alerting	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	Simultaneous Runway Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	Near Zero Visibility Taxi Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	2, 3, 4, 5, 6, 18
	Surface Situational Awareness (SURF)	---	1, 2, 3, 4, 5, 6	---	---	---
	SURF with Indications and Alerts (SURF IA)	---	1, 2, 3, 4, 5, 6	---	---	---
	4D Trajectory Based Operations (TBO)	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 18, 19	---	---
	Airborne Exchange of Sensed Information	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	Flight & Weather Information Services (FIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	AOC Communications	---	---	2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 18, 19	---	---
Terminal Area	Air Traffic Control Communications	---	---	2, 3, 4, 5, 6, 7, 8, 18	---	---
	Airspace Separation:	-	-	-	-	-
	1 NM	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	2 NM	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	3 NM	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Approach Applications:	-	-	-	-	-
	Non-Precision Approach (NPA)	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	LPV Operations	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	ILS Cat. I/II/III Precision Approach	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	GPS/LAAS Cat. I/II/III Precision Approach	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	2, 3, 4, 5, 6, 18
	Closely Spaced Parallel RW Operations (CSPO)	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Converging & Intersecting RW Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Simultaneous Runway Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Arrival /Departure Applications:	-	-	-	-	-
	Standard Arrival Route (STAR) Procedures	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Standard Instrument Departure (SID)	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Tailored Arrivals or Departure	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Optimized Profile Descent (OPD)	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Optimized Departure Climb	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	Ground-Based Interval Management - Spacing	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	Flight Deck IM - Spacing / Delegated Interval	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	Delegated Separation	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	Wake Turbulence Mitigation for Arrivals / Departures	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	RNP Operations	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	4D Trajectory Based Operations (TBO)	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	Airborne Exchange of Sensed Information	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	Flight and Weather Information Services	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	AOC Communications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---

Figure 129 – Mapping of A-A and A-G Technology Candidates to Applications in the Surface and Terminal Area Airspaces

Table Notes: 1) TCAS aircraft-to-aircraft communications required by many aircraft per today's requirements.

2) ATCRBS aircraft-to-ground communications required by most aircraft in ATC controlled airspace.

		Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	**Future Airspace Applications**	**RCP**	**Required Com. To Support Surv. [Note 1]**	**RCP**	**Required Com. To Support Surv. [Note 2]**	**Required Com. To Support Nav.**
Enroute Domestic	Air Traffic Control Communications	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	Separation Assurance:	-	-	-	-	-
	2 NM	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	3 NM	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	5 NM	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	In-Trail Procedure (ITP)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	Climb/Descent Procedure (CDP)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	Cruise Climb / Descent	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	Ground Interval Management	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	Flight Deck IM - Spacing / Delegated Interval	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	Delegated Separation (DS)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	4D Trajectory Based Operations (TBO)	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	Airborne Exchange of Sensed Information	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	Flight and Weather Information Services	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	AOC Communications	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	Autonomous Flight Rules (AFR)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
Enroute Oceanic / Remote	Air Traffic Control Communications	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	Separation Assurance:	-	-	-	-	-
	5 NM	---	1, 2, 3	12, 13, 14, 15, 16, 17, 19	12, 13, 14, 15, 16, 17, 19	---
	10 NM	---	1, 2, 3	12, 13, 14, 15, 16, 17, 19	12, 13, 14, 15, 16, 17, 19	---
	30 NM	---	---	12, 13, 14, 15, 16, 17, 19	12, 13, 14, 15, 16, 17, 19	---
	Greater than 30 NM lat. & 5 minutes long.	---	---	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	Greater than 50 NM lat. & 10 minutes long.	---	---	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	In-Trail Procedure	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	Climb/Descent Procedure (CDP)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	12, 13, 14, 15, 16, 17, 19	---
	Cruise Climb / Descent	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	12, 13, 14, 15, 16, 17, 19	---
	Flight Deck IM / Delegated Interval	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	Delegated Separation (DS)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	Trajectory Based Operations (TBO)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	Airborne Access to SWIM (AAtS)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	Airborne Exchange of Sensed Information	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	Flight and Weather Information Services	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	AOC Communications	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	Autonomous Flight Rules (AFR)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
Polar	Air Traffic Control Communications	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	Separation Assurance:	-	-	-	-	-
	5 NM	---	1, 2, 3	12, 14, 15, 16, 17, 19	12, 14, 15, 16, 17, 19	---
	10 NM	---	1, 2, 3	12, 14, 15, 16, 17, 19	12, 14, 15, 16, 17, 19	---
	30 NM	---	---	12, 14, 15, 16, 17, 19	12, 14, 15, 16, 17, 19	---
	Greater than 30 NM lat. & 5 minutes long.	---	---	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	Greater than 50 NM lat. & 10 minutes long.	---	---	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	In-Trail Procedure	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	Climb/Descent Procedure (CDP)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	12, 14, 15, 16, 17, 19	---
	Cruise Climb / Descent	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	12, 14, 15, 16, 17, 19	---
	Flight Deck IM / Delegated Interval	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	Delegated Separation (DS)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	Trajectory Based Operations (TBO)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	Airborne Access to SWIM (AAtS)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	Airborne Exchange of Sensed Information	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12	---	---	---	---
	Flight and Weather Information Services	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	AOC Communications	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	Autonomous Flight Rules (AFR)	---	1, 2, 3	12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---

Figure 130 – Mapping of A-A and A-G Technology Candidates to Applications in Enroute Domestic, Remote / Oceanic, and Polar Airspaces

Table Notes: 1) TCAS aircraft-to-aircraft communications required by many aircraft per today's requirements.

2) ATCRBS aircraft-to-ground communications required by most aircraft in ATC controlled airspace.

15 PHASE 1 INTERIM STUDY FINDINGS

The section of the report summarizes the interim study findings and provides a conclusion to the first phase of the study.

15.1 Summary of Phase 1 Interim Study Findings

1. The future NAS will require significantly more A-A and A-G communications to support the envisioned NAS NextGen and beyond operations as envisioned in the JPDO Concept of Operations.
2. Current A-A and A-G NAS communications links are insufficient to meet the anticipated future needs of the NAS.
3. Traffic is expected to increase 3X to 10X of today's NAS traffic levels over the 50 year study time horizon, assuming a yearly nominal growth rate between 2.2% and 4.7%.
4. Current spectrum efficiency of today's NAS A-A and A-G communications is inefficient by today's state of the practice for wireless communications.
5. The current state of the art for wireless communications achieves ~60% of Shannon's channel capacity limit. 60% to 70% of Shannon's channel capacity limit will likely become the state of the practice for wireless communications systems during the modernization time horizon.
6. Wireless communications technologies are advancing in a number of areas that will lead to significant increases in the spectral efficiency (e.g., bits/Hz).
7. Spectrum is a very limited resource. Allocation of it among all those who desire to use the spectrum is becoming increasingly more difficult. Many existing users of the spectrum (including aviation) will over time need to modernize their systems to improve their spectral efficiency to enable the spectrum to meet the future demands.
8. Obtaining significantly more spectrum allocations dedicated to support NAS A-A and/or A-G communications will become increasingly challenging.
9. It is envisioned that commercial broadband communication networks will expand beyond what is offered today to further support ATM communications (primarily A-G, but also A-A).
10. Technology will advance over the study modernization time horizon that will enable:
    a. the use of spectrum in the K, V, W, and G bands (up to ~200 GHz not including around 60 GHz) for SATCOM and/or airport surface/terminal area communications
    b. the use of free space optical communications for ground to satellite, satellite to aircraft, aircraft-to-ground, and aircraft-to-aircraft communications
    c. Future SATCOM communication systems that are capable of allocating communication bandwidth (BW) and quality of service (QOS) on demand to support a wide range of applications, including those in civil aviation.
11. Future Aviation CNS needs will evolve during the 50 year NAS study time horizon. NAS data communications can potentially reuse aviation spectrum that is decommissioned by other NAS services. The primary opportunities identified over the study period include:
    a. the MLS band (C-band), [already being planned with use for airport surface data link (AeroMACS) and UAS Control Non-payload Communications (CNPC) data link]

    - Currently the MLS (C-band) spectrum is not being used in the NAS.

  b. portions of the VHF VOR/ILS Localizer bands (including at least 112 to 118 MHz and possibly part of 108 to 112 MHz band)
    - VOR is expected to be decommissioned over the study period.
    - ILS is expected to be retained in a reduced service configuration as a backup to GNSS-based approach and landing systems.

  c. portions of the DME (L-band)
    - The DME spectrum is predicted over the long term to transition to support a highly capable Alternative Position / Navigation / Timing (APNT) terrestrial-based navigation aid in a small percentage of the existing DME allocated spectrum (e.g., ~10%), and remainder could be allocated to support NAS A-A and A-G communications.

12. Five fundamental strategic approaches have been identified for addressing the long term NAS communication needs including:
    a. Reducing the need for communications bandwidth (e.g., using techniques such as advanced data compression and data acceleration)
    b. More efficiently using existing aviation communications spectrum (e.g., using higher order modulations)
    c. Leveraging commercial communications networks to support NAS communications needs
    d. Identifying and reusing "aviation" spectrum to support NAS communications [e.g., MLS (C-Band) and DME (L-band)]
    e. Identifying and obtaining new spectrum allocations for NAS communications
13. Future air-to-air and air-to-ground communication systems should be architected to much more easily incorporate new technologies to meet the evolving future NAS needs.
14. No one single communications data link technology can meet all the expected future A-A and A-G communications requirements for the NAS. A combination of various communication technologies will be needed to address the diverse aeronautical communications requirements across all the operational flight domains.
15. The emerging and the predicted future communication technologies are envisioned to be able to meet the NextGen and beyond NAS air-to-air and air-to-ground communication needs.

15.2 Interim Study Conclusion

This concludes Phase 1 of the study (presented in Sections 5 to 15 of this report) which was originally documented in the first in a series of five interim reports that were completed during the execution of this study to identify and evaluate air-to-air and air-to-ground candidates for meeting the long-term evolving needs of the National Airspace System during the modernization time horizon of 50 years. Subsequent sections of this document describe the results from phases 2 through 5 of the study.

Phase 2 of the study is documented in Sections 16 to 20. These sections describe the results from the investigations of identifying and evaluating the architecture needs, interfaces, infrastructure elements, vulnerabilities, and threats to the communication candidates.

Phase 3 of the study is documented in Sections 21 to 24. These sections describe a comparative cost analysis of the implementation, operation, and maintenance costs for the communications candidates.

Phase 4 of the study is documented in Sections 25 to 28. These sections: a) identify, describe, and prioritize a set of long-term ATM applications including identifying which applications could be supported by the communications candidates, and b) provide use case analyses for three of the highest priority applications including Delegated Interval / Interval Management, Delegated Separations, and Airborne Self-Separation.

Phase 5 of the study is documented in Sections 29 to 32. These sections identify criteria for prioritizing the communication candidates and describe the use of the criteria to prioritize the candidates from most promising to least promising.

16 CURRENT NAS INFRASTRUCTURE ELEMENTS AND THEIR ARCHITECTURES

The “NAS infrastructure” is defined to include the basic physical and organizational structures needed for the operation of the National Air Transportation System, and includes Air Traffic Control; communication, navigation, and surveillance equipment; airports; aircraft; Airline / Aeronautical Operational Control (AOC) centers; etc.

“NAS architecture” is defined to include the basic structural form of the physical and organizational infrastructure elements.

Thus, as an example of the terminology difference between “infrastructure” and “architecture” as used in this document, consider “Air Traffic Control” as an infrastructure element of the NAS. Describing the “architecture” of Air Traffic Control would include a description the way that ATC is structured to include the ATC Command Center, Air Route Traffic Control Centers, airport terminal approach control, airport tower control, airport surface control, and Flight Service Stations that all work together to provide air traffic control services to aircraft operating within controlled airspace.

While the focus of this study is on the long range future A-A and A-G Data Communication technology candidates (including their relevant infrastructure and architectural elements needed to address the NAS communication needs for NextGen and beyond), it is important to also understand and consider the infrastructure and architecture of other functional elements of the NAS such that the overall NAS infrastructure and architecture can be optimized.

According to the latest released version at the time of this writing of the FAA Administrator’s Fact Book (June 2012), the NAS consists of approximately 65,000 operational facilities. A description of all of this infrastructure and architecture is beyond the scope of this study.

Instead, this section of the report has captured the current infrastructure and architecture of the following elements of the NAS that are viewed as relevant or potentially relevant to the Com50 study:

- Overview of the Entire NAS (Section 16.1)
- Air Traffic Control (Section 16.2)
- Communication (Section 16.3)
- Navigation (Section 16.4)
- Surveillance (Section 16.5)
- Key NAS NextGen Ground and Aircraft Infrastructure [per FAA] (Section 16.6)

A-A and A-G communication candidates need to be able to address the NAS needs for communications in support of ATM, which may also include the data communication aspects of Navigation and Surveillance functions. It is also important to consider: a) any possible decommissioning of navigation and surveillance systems (e.g., VOR, ILS, DME, SSR) as possible future candidates of spectrum resources and ground facilities to support communications, b) the potential for a given spectrum resource to simultaneously support the future needs of more than one CNS element, and c) sharing facilities (e.g., ground stations) that could be expanded and leveraged to also support NAS communications. The latter is important, for example, to reduce the physical number of facilities/infrastructure elements and their associated costs needed to support aviation.

16.1 Today's National Airspace System Infrastructure and Architecture

The National Airspace System of the United States is one of the most complex aviation systems in the world which consists of thousands of people, procedures, facilities, and pieces of equipment that collectively enable safe and expeditious air travel in the United States and over large portions of the world's oceans.

The United States National Airspace System consists of designated U.S. airspace and a complex collection of systems, facilities, equipment, regulations, rules, procedures, information/services, airports, and aircraft that are operated by thousands of people to provide a safe and efficient flying environment. The NAS infrastructure is enormous, and includes for example the following elements *[Reference: FAA Administrator's Fact Book, June 2012]*:

- ~19,782 airports capable of accommodating a wide range of aircraft and aircraft operations, many of which support instrument flight rules (IFR) departures and arrivals
- ~800 Air Traffic Control facilities, supported with associated systems (e.g., CNS) and equipment to provide ATM, consisting of ~20 ARTCCs, ~200 TRACON facilities, and ~500 air traffic control towers, ~20 flight service stations / automated flight service stations
- ~40,000 ground radios
- ~400 radar sites
- ~5,000 navigation aids
- ~18,000 commercial aircraft (18,023 per CY 2011 data)
- ~225,000 general aviation aircraft (223,400 per CY 2010 data)
- ~1 trillion passenger miles flown by Air Carriers (0.815 trillion per CY 2011 data)
- ~47,000 FAA employees who provide air traffic control, flight services, security, field maintenance, certification, systems acquisitions, and a variety of other services
- ~700,000 pilots (687,048 per CY2010 data)
- ~65,000 NAS operational facilities (as of December 1, 2011: NAS Operational facilities numbered 64,937; which includes 19,020 communications facilities; 12,977 navigation facilities; 1,707 surveillance facilities; and 31,233 other facilities)

The National Airspace System is defined in the FAA's Instrument Procedures Handbook as: "The common network of U.S. airspace, air navigation facilities, equipment and services, airports and landing areas, aeronautical charts, information and services, rules, regulations, procedures, technical information, manpower, and material. Included are system components shared jointly with the military." *[Reference: Instrument Procedures Handbook, FAA-H-8261-1A, FAA Flight Procedure Standards Branch, DoT / FAA, 2007.]*

All control towers, control centers, radios, radars and many airports are interconnected to form the NAS operational communications network. This network supports the transfer of voice and data among pilots, controllers, and airline/aircraft operational control centers.

Figure 131 shows conceptually the interworking of the NAS and its major components, including aircraft, airports, air traffic control facilities, flight information services, CNS elements (e.g., terrestrial and satellite communications and navigation equipment, and surveillance radars), airline dispatch, weather sensors, etc.

Of the approximately 20,000 airports in the NAS, Figure 132 (page 213) illustrates the locations of the major airports in the NAS (as indicated with yellow-colored dots).

Figure 133 (page 214) illustrates the communication paths between the major NAS components. This figure indicates (with yellow colored lines) the data communications between the various NAS components. Figure 134 (page 215) provides a second form of the NAS operational connectivity diagram developed by the Enterprise Architects from the FAA Air Traffic Organization.

Figure 135 (page 216) provides a simplified NAS system diagram, showing the major components and relationship between the various NAS elements.

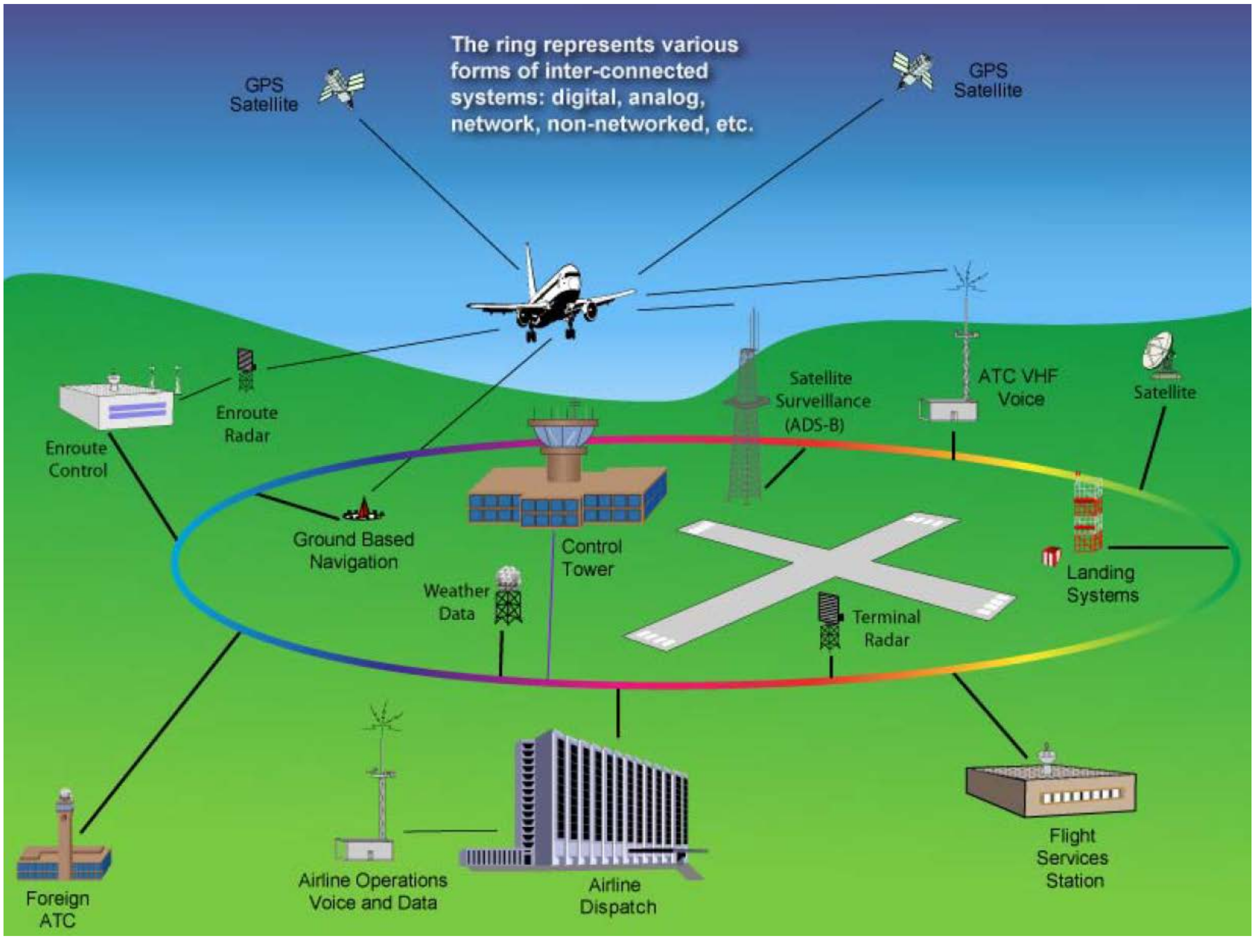


Figure 131 – National Airspace System Major Components

[Reference: "National Airspace System Security Cyber Architecture" report, by James H. Williams (FAA) and T.L. Signore (The MITRE Corporation), page 2.]

Figure 132 – NAS Major Airport Locations / Architecture

[Reference: www.mapsofworld.com.]

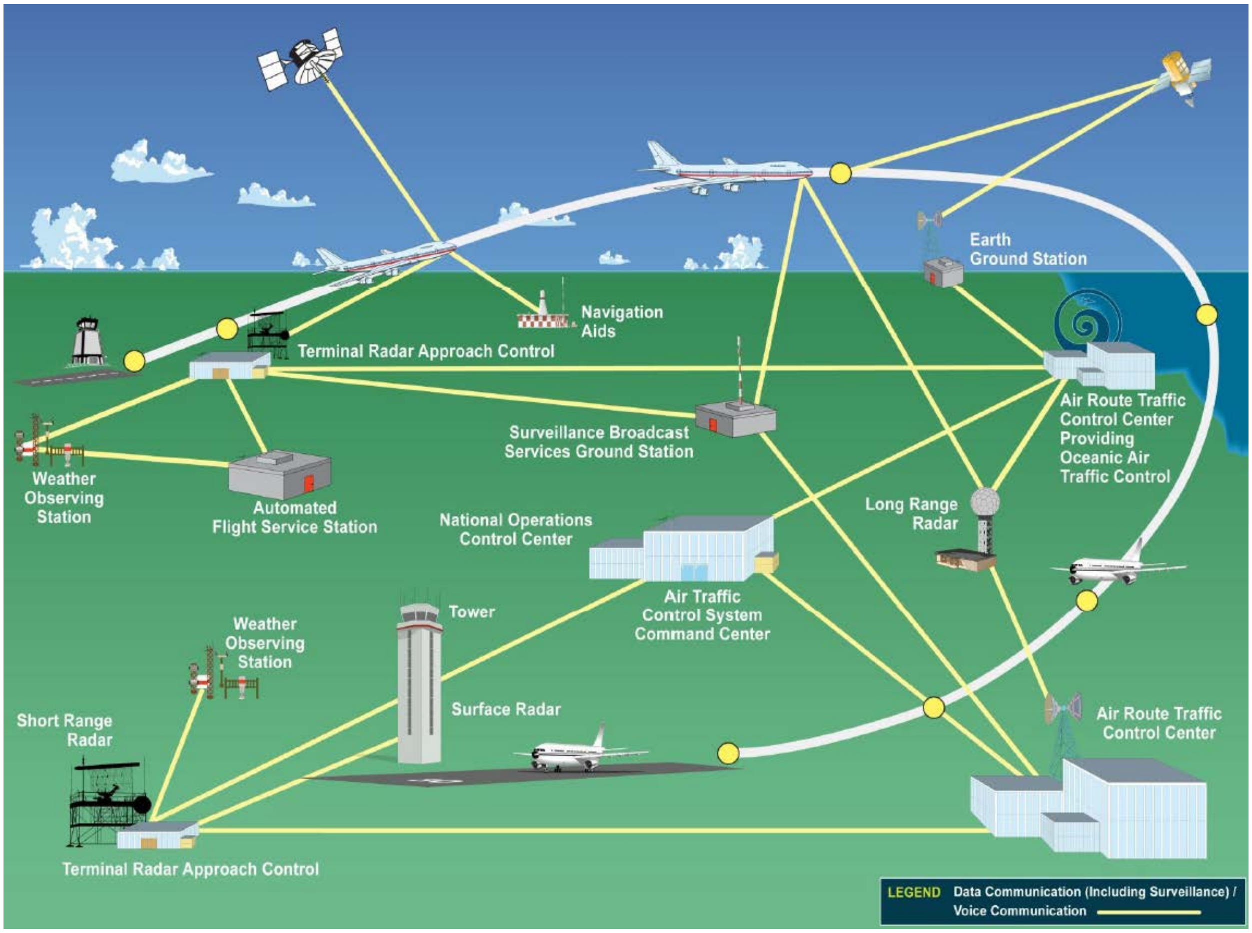


Figure 133 – NAS Enterprise-Level Architecture

[Reference: National Airspace System Enterprise Architecture Framework, FAA Air Traffic Organization, NAS 2011 As-Is Enterprise-Level Architecture High Level Concept Graphic, Version 1.0, September 13, 2011.]

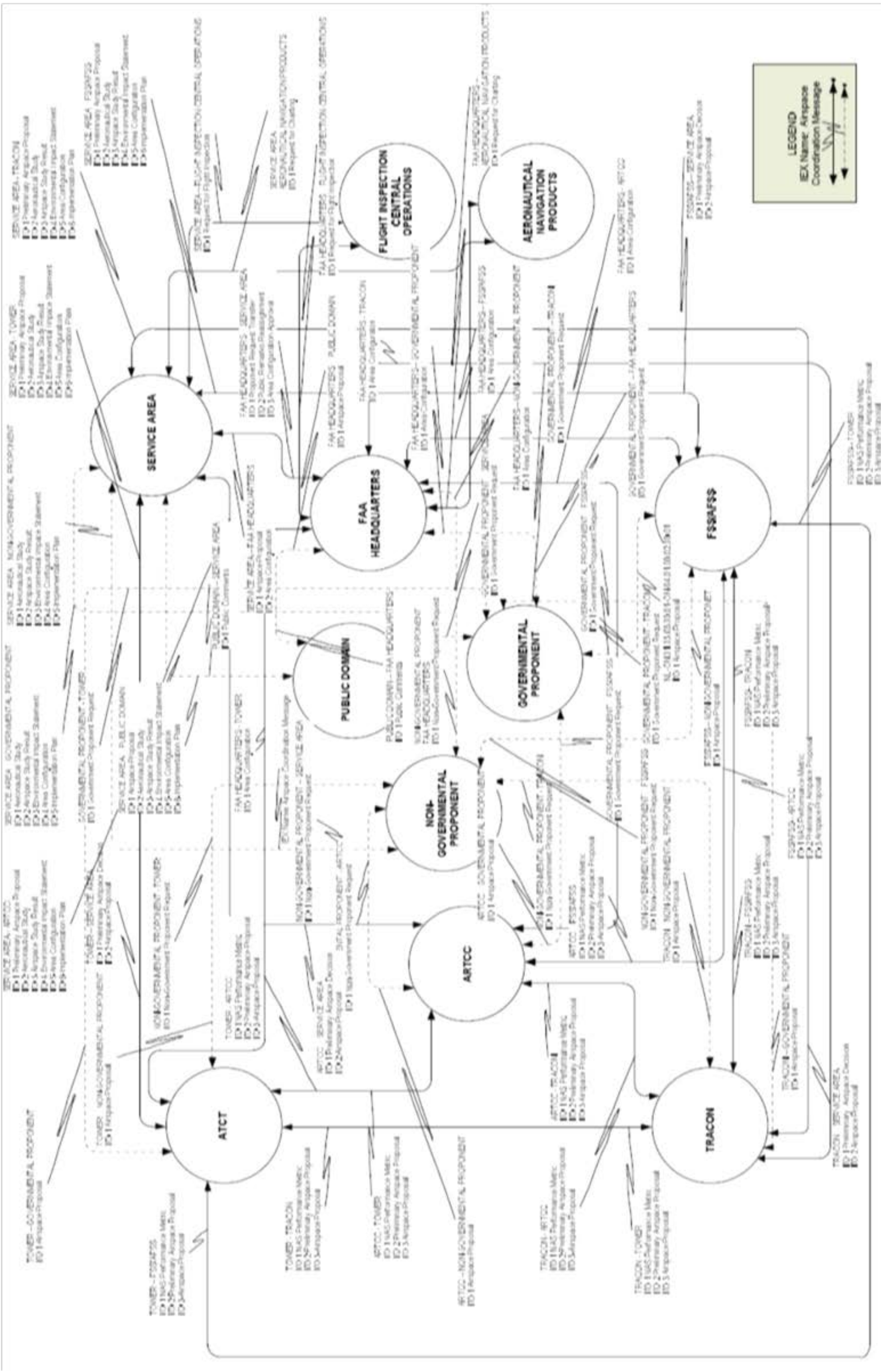


Figure 134 – NAS Operational Connectivity Diagram

[Reference: National Airspace System Enterprise Architecture Framework, FAA Air Traffic Organization, Operational Node Connectivity Diagram, Version 1.0, September 13, 2011.]

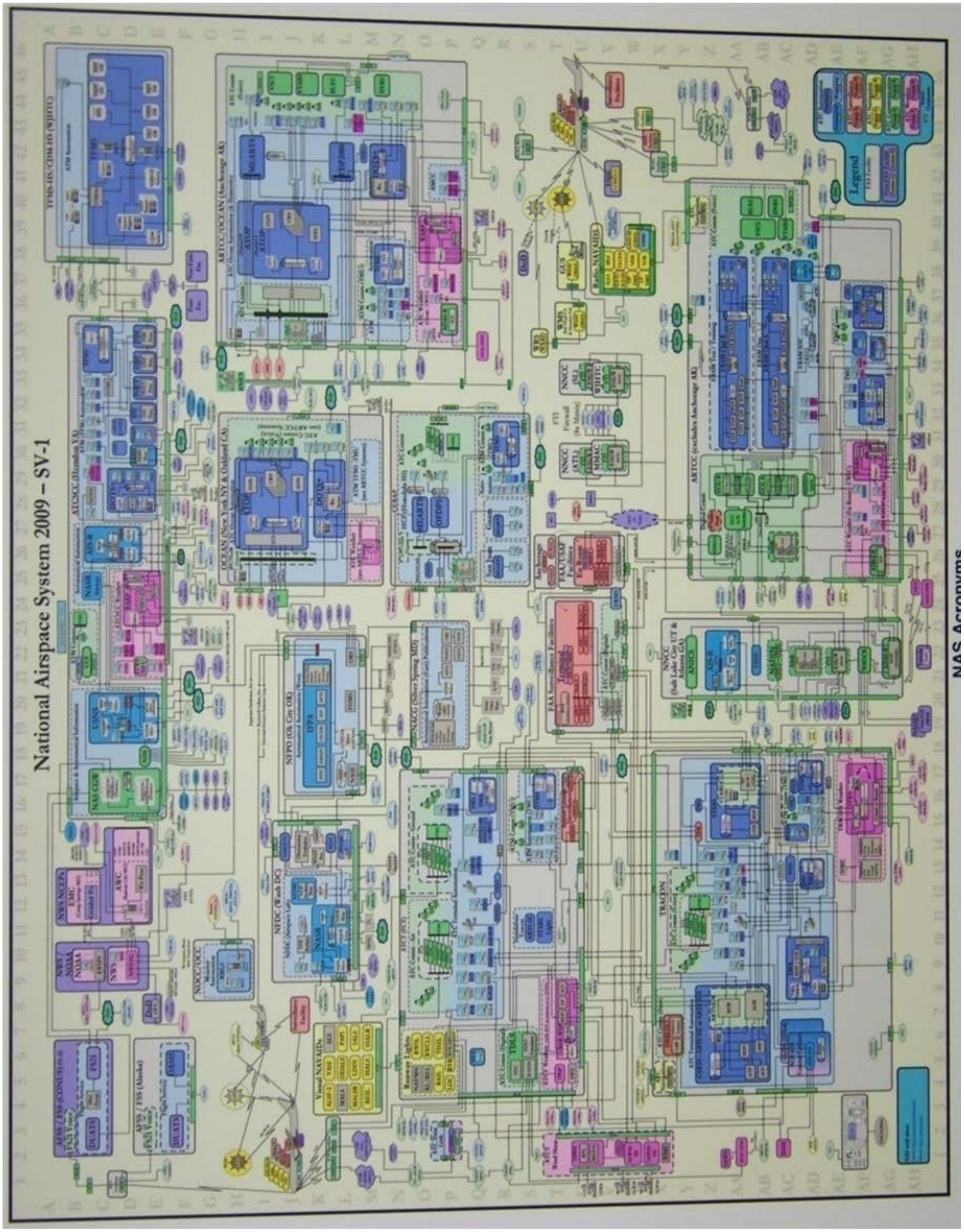


Figure 135 – Simplified National Airspace System Architecture Diagram

[Reference: FAA Air Traffic Organization (ATO), 2009.]

16.2 Air Traffic Control Infrastructure and Architecture

Air Traffic Control is provided by enroute, TRACON, approach, and surface controllers. The enroute control is provided by Air Route Traffic Control Centers (ARTCC), which are facilities established to provide air traffic control service to aircraft operating on IFR flight plans within controlled airspace and principally during the enroute phase of flight. When equipment capabilities and controller workload permit, certain advisory/ assistance services may be provided to VFR aircraft.

Air Traffic Controllers communicate with pilots of instrument flight rules aircraft passing through their controlled airspace. A Center's communication frequencies are published in aeronautical charts and manuals and communicated to pilots by the previous controller during hand-offs. Typically, VHF frequencies (118 MHz to 137 MHz) are used for the communications within VHF ground station coverage areas that include overland and oceanic near land, while HF and SATCOM communications are used to communicate with the pilots of aircraft in overland remote and oceanic airspaces.

In addition to radios to communicate with aircraft, Center controllers have access to communication links with other Centers and TRACONs. In the United States, Centers are electronically linked through the National Airspace System, which allows nationwide coordination of traffic flow to manage congestion. Centers in the United States also have electronic access to nationwide radar data. Controllers today primarily use radar and ADS-C reports to monitor the progress of flights and instruct aircraft to adjust their course as needed to maintain separation from other aircraft. Emerging is the use of ADS-B.

There are approximately 800 Air Traffic Control facilities in the NAS consisting of 1 Command Center, 23 Air Route Traffic Control Centers, ~500 air traffic control towers, ~200 TRACON facilities, and ~20 flight service stations (FSS) / automated FSS.

16.2.1 ATC Command Center

The Air Traffic Control System Command Center (ATCSCC) in Herndon, Virginia monitors traffic flows across the United States and communicates with other air traffic facilities and airline operating centers to minimize congestion and delays due to adverse weather, equipment outages, closed runways, and other capacity-related circumstances.

16.2.2 Air Route Traffic Control Centers (ARTCCs)

ARTCCs control and monitor aircraft in transit over the United States and during approaches to some airports. Each enroute center handles a different region of airspace, passing control from one to another as respective borders are reached until the aircraft reaches TRACON airspace or leaves U.S. airspace. Three centers, including Oakland, New York, and Anchorage, also control aircraft over the ocean. Outside radar range, which extends approximately 175 to 225 miles offshore, controllers currently must rely on periodic radio communication of position reports to determine an aircraft's location.

There are 23 ARTCC centers in the NAS, 20 across the continental US (see Figure 136), plus one in each of the following locations: Alaska, Hawaii, and San Juan Puerto Rico. The 23 ARTCC centers include: Albuquerque, Anchorage, Atlanta, Boston, Chicago, Cleveland, Denver, Fort Worth, Honolulu, Houston, Indianapolis, Jacksonville, Kansas City, Los Angeles, Memphis, Miami, Minneapolis, New York, Oakland, Salt Lake City, San Juan (Puerto Rico), Seattle, and Washington DC.

The centers are designated by a three-letter code that begins with Z; for example, the Los Angeles center is designated ZLA. The size of the airspace managed by a center varies substantially, but typically consists of tens of thousands of square miles extending over several states.

Some Centers have ICAO-designated responsibility for airspace located over an ocean such as the Oakland ARTCC (designated ZOA), the majority of which is international airspace. Because substantial volumes of oceanic airspace lie beyond the range of ground-based radars, oceanic airspace controllers have to estimate the position of an aircraft from pilot reports and computer models (procedural control), rather than observing the position directly (radar control, also known as positive control). Pilots flying over an ocean can determine their own positions accurately (using GPS for instance) and can supply periodic updates to a Center.

Figure 136 – FAA Air Route Traffic Control Centers

[Reference: FAA as posted on Wikipedia.]

16.2.3 ATC Towers

Air Traffic Control Towers at more than ~500 airports control the effective movement of traffic both on the ground and in the air within approximately five nautical miles of the airport and up to an altitude of 3,000 feet. Air traffic controllers direct aircraft departures and approaches, maintain safe distances between aircraft, and communicate weather-related information, clearances, and other instructions to pilots.

16.2.4 TRACON

Approximately 200 Terminal Radar Approach Control (TRACON) facilities sequence and separate aircraft as they approach and depart major metropolitan areas. TRACONs typically control air traffic within a 30 to 80 mile radius of a major airport and at altitudes of less than 15,000 feet, exclusive of airspace controlled by the tower controllers.

16.2.5 Flight Service Stations

A Flight Service Station (FSS) is an air traffic facility that provides information and services to aircraft pilots before, during, and after flights; however, unlike air traffic control, the flight service stations are not responsible for giving instructions or clearances or providing separation services.

The United States FSS service is provided by a network of facilities across the NAS operated by the FAA or FAA contractors. These stations are a part of the FAA air traffic system and are staffed by uniquely trained air traffic control specialists.

The newest site map of the FSS station locations that is posted on the FAA.gov web site at the time of this writing is depicted in Figure 137. As of December 2011, there were 17 Flight Service Stations and 3 Automated Flight Service Stations in the NAS *[Reference: FAA Administrator's Fact Book, June 2012]*.

The primary role of FSS is to provide weather briefings and flight planning services to pilots. FSS specialists also issue and cancel Notices To Airmen (NOTAMs), collect and disseminate pilot reports (PIREPs), monitor and report on the status of navigational aids (NAVAIDS), maintain continuous weather broadcasts, coordinate VFR search and rescue services, provide orientation service to lost aircraft, provide traffic advisories to aircraft on the ground or in flight, and provide assistance in an emergency.

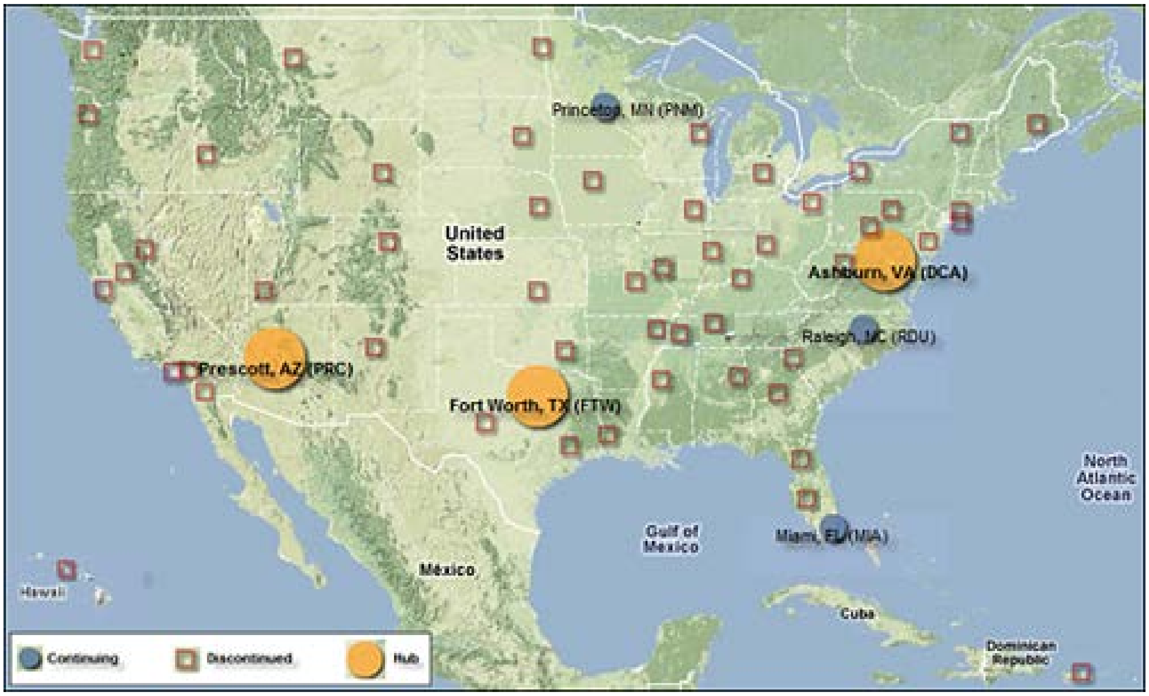


Figure 137 – Flight Service Station Facilities Architecture

[Reference: FAA (effective February 1, 2010) as posted on http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/systemops/fs/.]

16.3 Communications Infrastructure and Architecture

The existing aviation communications infrastructure that supports A-G data communications with aircraft via VHF, HF, and SATCOM is depicted in Figure 138.

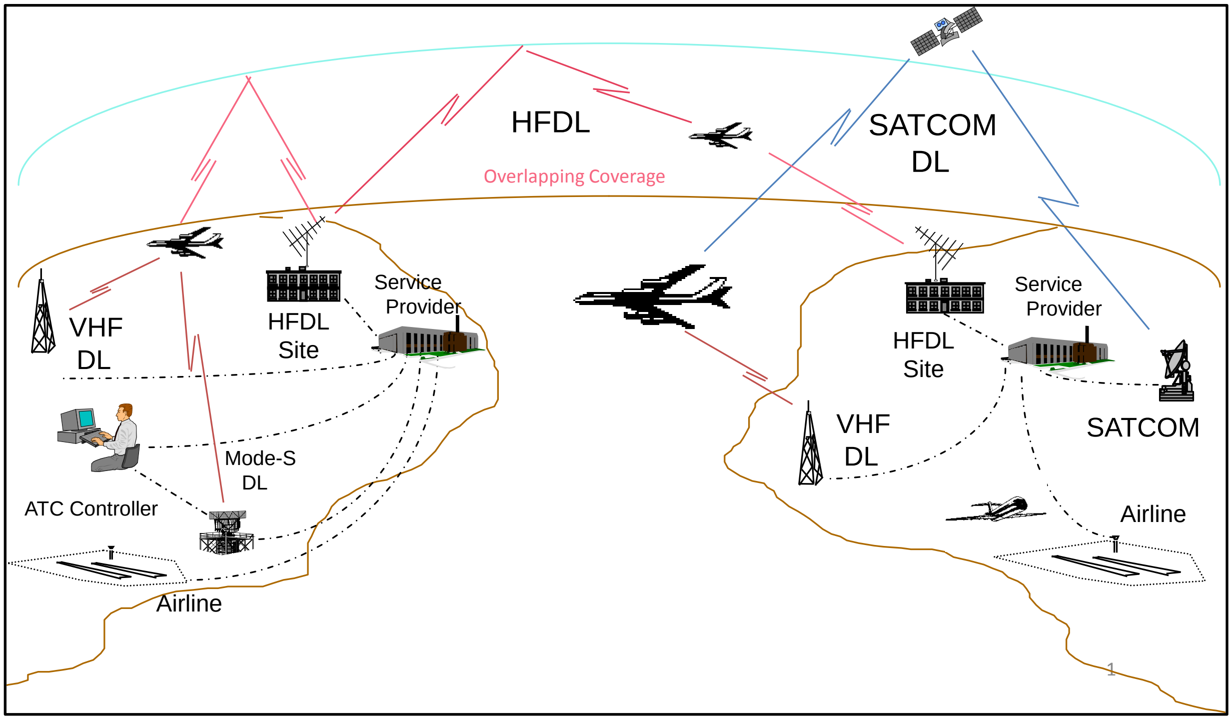


Figure 138 – Air-Ground Communications

Within this overall A-G communication network, ARINC has A-G Global Network for A-G data communications using VHF [including VHF Data Link (VDL) and Plain Old ACARS (POC), the latter of which refers to ACARS protocols prior to VDL Mode 2], HF, and SATCOM as is depicted in Figure 139.

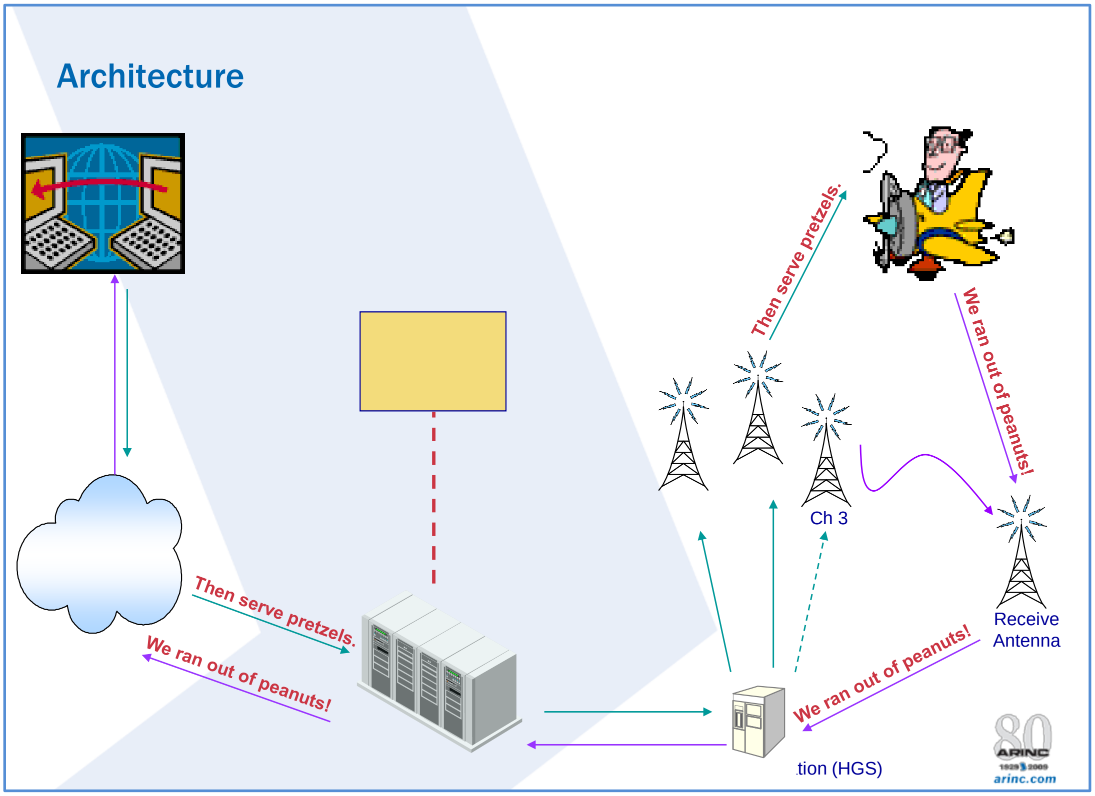


Figure 139 – ARINC Global Network Communications Architecture

[Reference: Personal Communications with Bill Doyen, ARINC, July 23, 2013.]

16.3.1 VHF Communications

The NAS architecture (as of November 2013) for VHF communications includes 2708 ground stations that utilize 6570 channels. Note that VHF communications in the NAS utilizes the 118 to 137 MHz portion of the VHF band and that there are 760 unique channels with 25 kHz channel spacing with the lowest assignable channel frequency at 118.000 MHz and the highest assignable channel frequency at 136.975 MHz. The 6570 channels used in the NAS come about from channel re-use when the appropriate criteria are met.

Enroute coverage: Of the 2708 total number of VHF communications ground stations, 1285 stations are used to provide enroute service with 729 stations (utilizing 1258 channels) that provide the main VHF enroute communications service and 635 stations (utilizing 1016 channels) that provide backup enroute communications (whereby 79 of the 1285 stations support both main and backup enroute communications services).

Terminal area coverage: 1319 VHF ground stations are utilized to provide terminal area VHF communications services utilizing ~3600 channels. Of these 1319 stations, 115 of them also provide enroute coverage.

Emergency: 629 VHF ground stations are fielded to support communication on the emergency 121.5 MHz channel. 219 of these stations are solely dedicated to the emergency channel, while 410 of the ground stations also support enroute or terminal areas services.

The locations of the VHF comm ground stations in the continental United States used for primary enroute, backup enroute, main terminal area, backup terminal area, and emergency frequency stations are plotted in Figure 140 through Figure 144, respectively. Not depicted these figures are the VHF communications station locations in Alaska, Hawaii, and Puerto Rico.

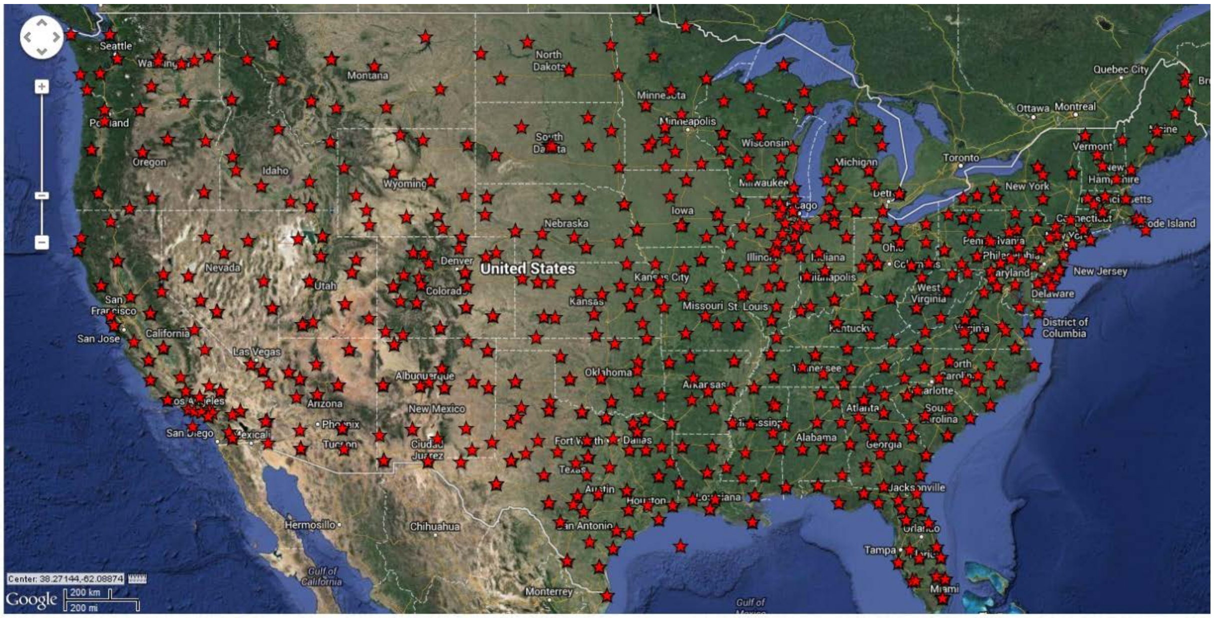


Figure 140 – Enroute Primary VHF Comm. Ground Infrastructure (729 Stations)

[Reference: VHF Ground Station Database, personal communications with Lorena Carvajal (FAA Spectrum Engineering), November 4, 2013. Plotted on Google map using www.gpsvisualizer.com.]

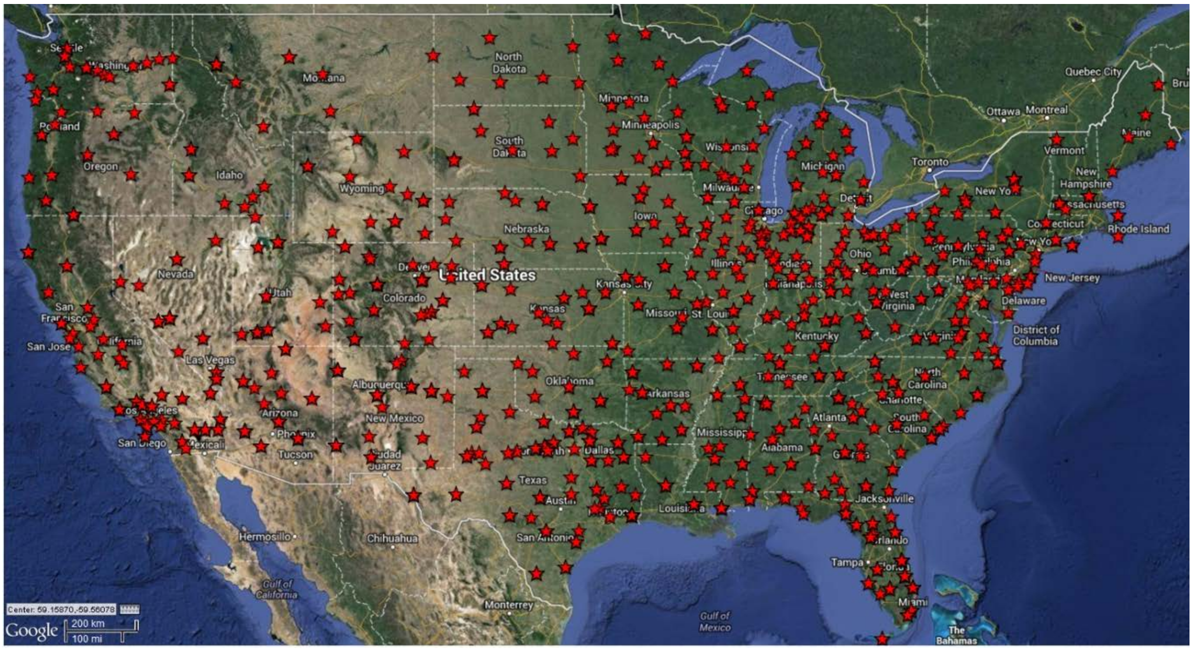


Figure 141 – Enroute Backup VHF Comm. Ground Infrastructure (635 Stations)

[Reference: VHF Ground Station Database, personal communications with Lorena Carvajal (FAA Spectrum Engineering), November 4, 2013. Plotted on Google map using www.gpsvisualizer.com.]

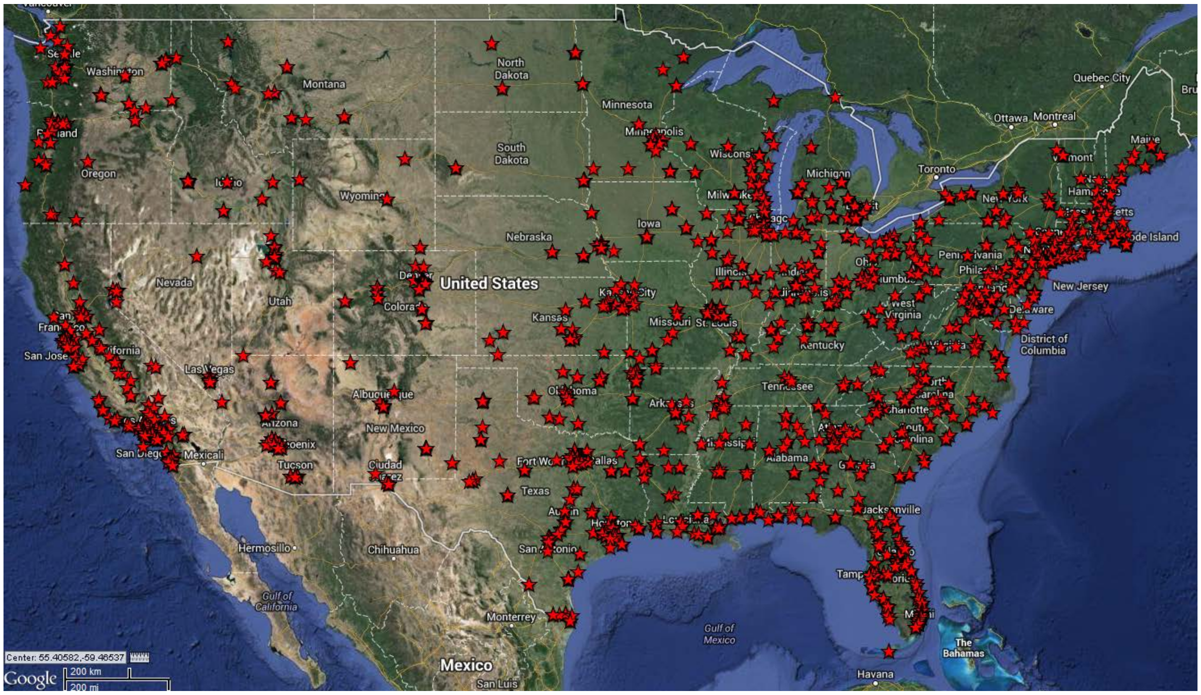


Figure 142 – Terminal Main VHF Comm. Ground Infrastructure (1258 Stations)

[Reference: VHF Ground Station Database, personal communications with Lorena Carvajal (FAA Spectrum Engineering), November 4, 2013. Plotted on Google map using www.gpsvisualizer.com.]

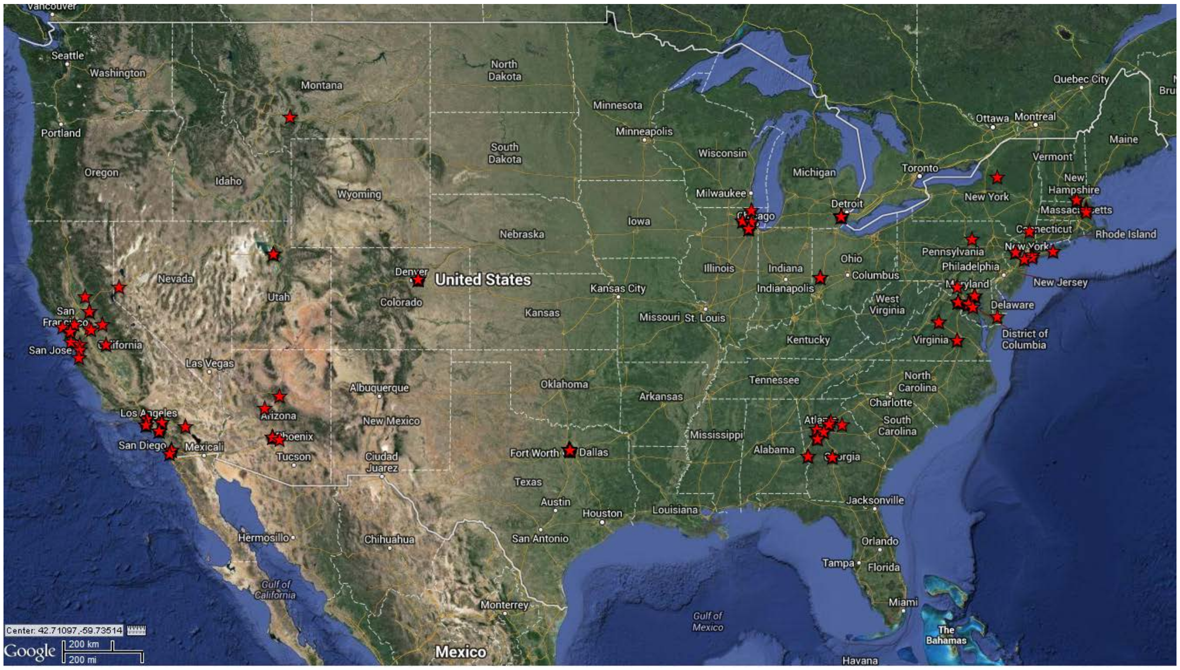


Figure 143 – Terminal Backup VHF Comm. Ground Infrastructure (81 Stations)

[Reference: VHF Ground Station Database, personal communications with Lorena Carvajal (FAA Spectrum Engineering), November 4, 2013. Plotted on Google map using www.gpsvisualizer.com.]

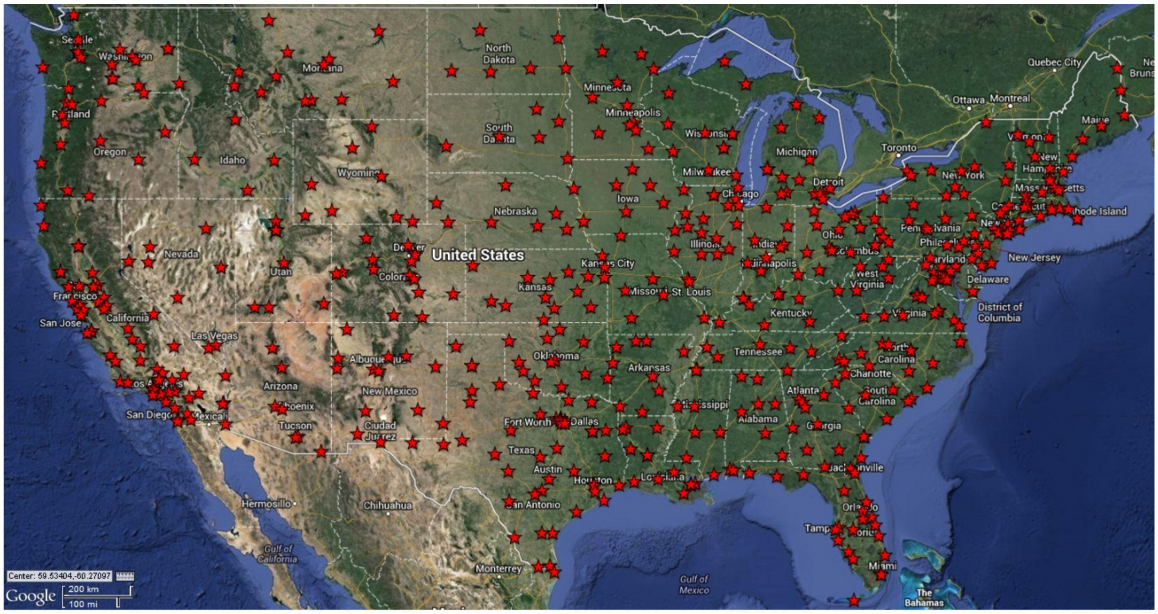


Figure 144 – Emergency (121.5 MHz) VHF Comm. Ground Infrastructure (629 Stations)

[Reference: VHF Ground Station Database, personal communications with Lorena Carvajal (FAA Spectrum Engineering), November 4, 2013. Plotted on Google map using www.gpsvisualizer.com.]

16.3.2 HF Communications

The HF communications architecture has a wide area network interconnecting the HF Data Link (HFDL) Ground Stations (HGS) with ATC and Airline / Aeronautical Operational Control (AOC) as depicted in Figure 145.

ARINC and their partners have a network of fifteen HF Data Link ground stations spread around the world that support civil aircraft HF communications, with stations located in Alaska, Bahrain, Bolivia, California, Canary Islands, Guam, Hawaii, Iceland, Ireland, New York, New Zealand, Panama, Russia, South Africa, and Thailand (see Figure 146). These stations use the ARINC635 waveform with equipment that is compatible per the ARINC753 characteristic. Also shown in Figure 146 is the HF coverage volume whereby coverage areas indicated as “primary” have communications coverage by at least 3 HF ground stations for more highly robust communications and coverage areas indicated as “secondary” have communications coverage with at least two ground stations.

Figure 147 (page 226) and Figure 148 (page 227) provide an illustration of the A-G civil aircraft HFDL communications over the entire world that occurred during the month of December in the year 2011. This plot is depicted by color, whereby the ground station that serviced the HFDL communication is indicated with a colored dot over the earth. Figure 147 depicts location (with a dot) and ground station (per the color legend in the figure) of the worldwide HFDL communications overlaid on a flat earth projection map of the earth. Figure 148 similarly depicts the location (with a dot) and ground station (per the same color legend) of the worldwide HFDL communications overlaid on an invisible earth polar projection. The earth in this figure is “invisible” in that you can see messages depicted with dots on both sides of the earth.

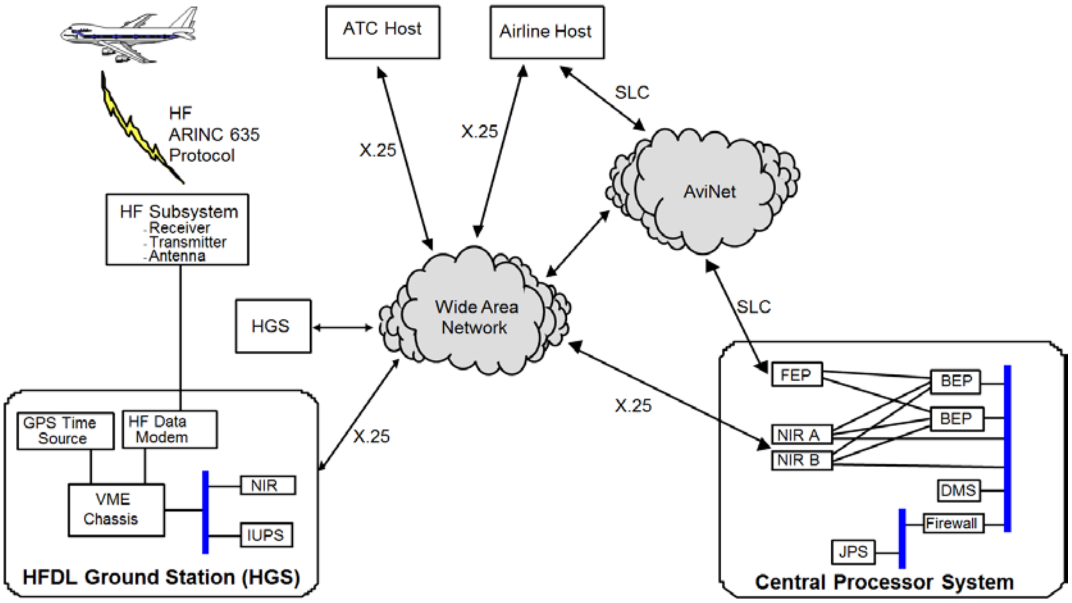
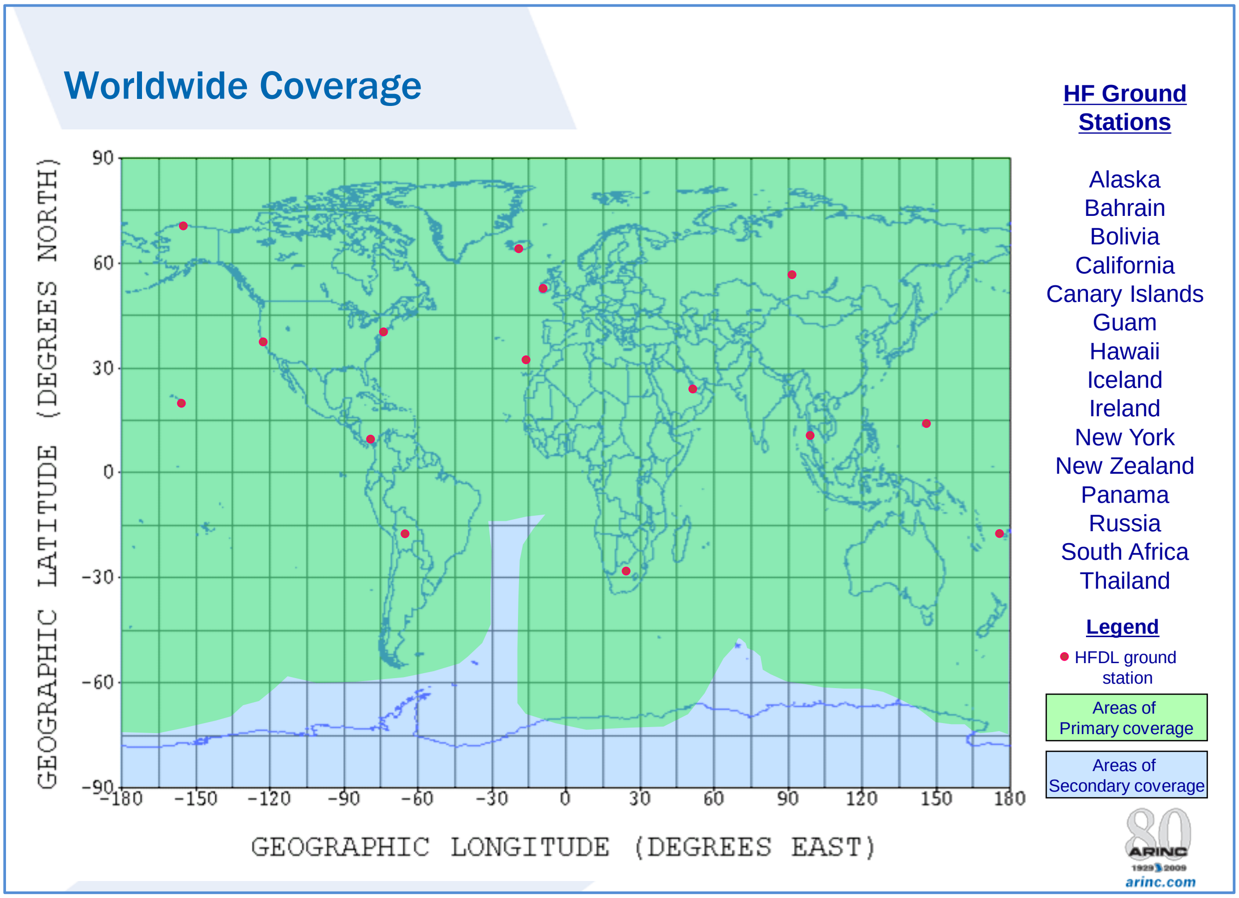


Figure 145 – Current HF Communications System Architecture


Worldwide Coverage

HF Ground Stations

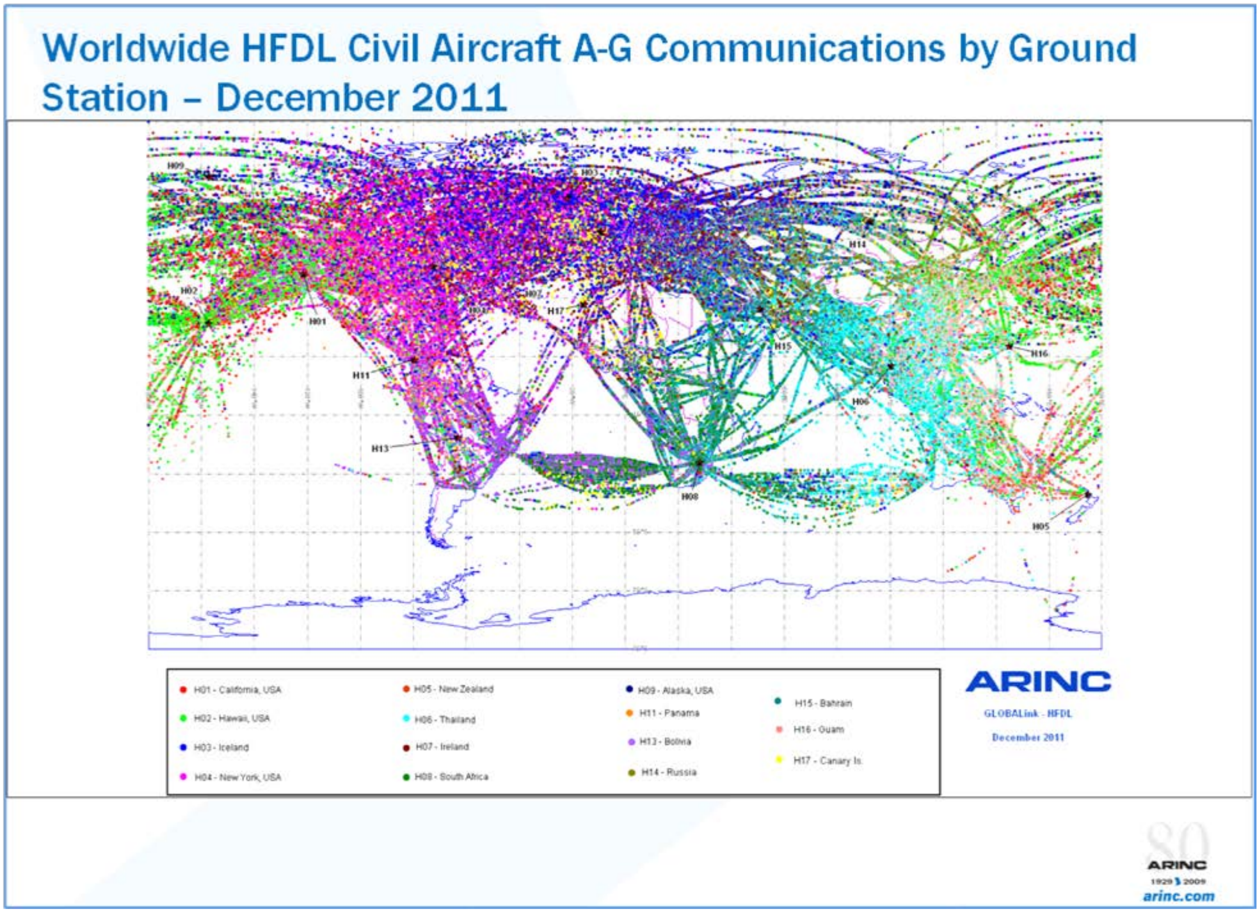
Alaska
Bahrain
Bolivia
California
Canary Islands
Guam
Hawaii
Iceland
Ireland
New York
New Zealand
Panama
Russia
South Africa
Thailand

Legend

● HFDL ground station
🟩 Areas of Primary coverage
🟦 Areas of Secondary coverage

Figure 146 – HF Comm. Ground Station Locations and Worldwide Coverage

[Reference: Personal Communications with Bill Doyen, ARINC, July 23, 2013.]



Worldwide HFDL Civil Aircraft A-G Communications by Ground Station – December 2011

Figure 147 – HFDL Comm. (Dec. 2011) Overlaid on Flat Earth Projection Map

[Reference: Personal Communications with Bill Doyen, ARINC, July 23, 2013.]

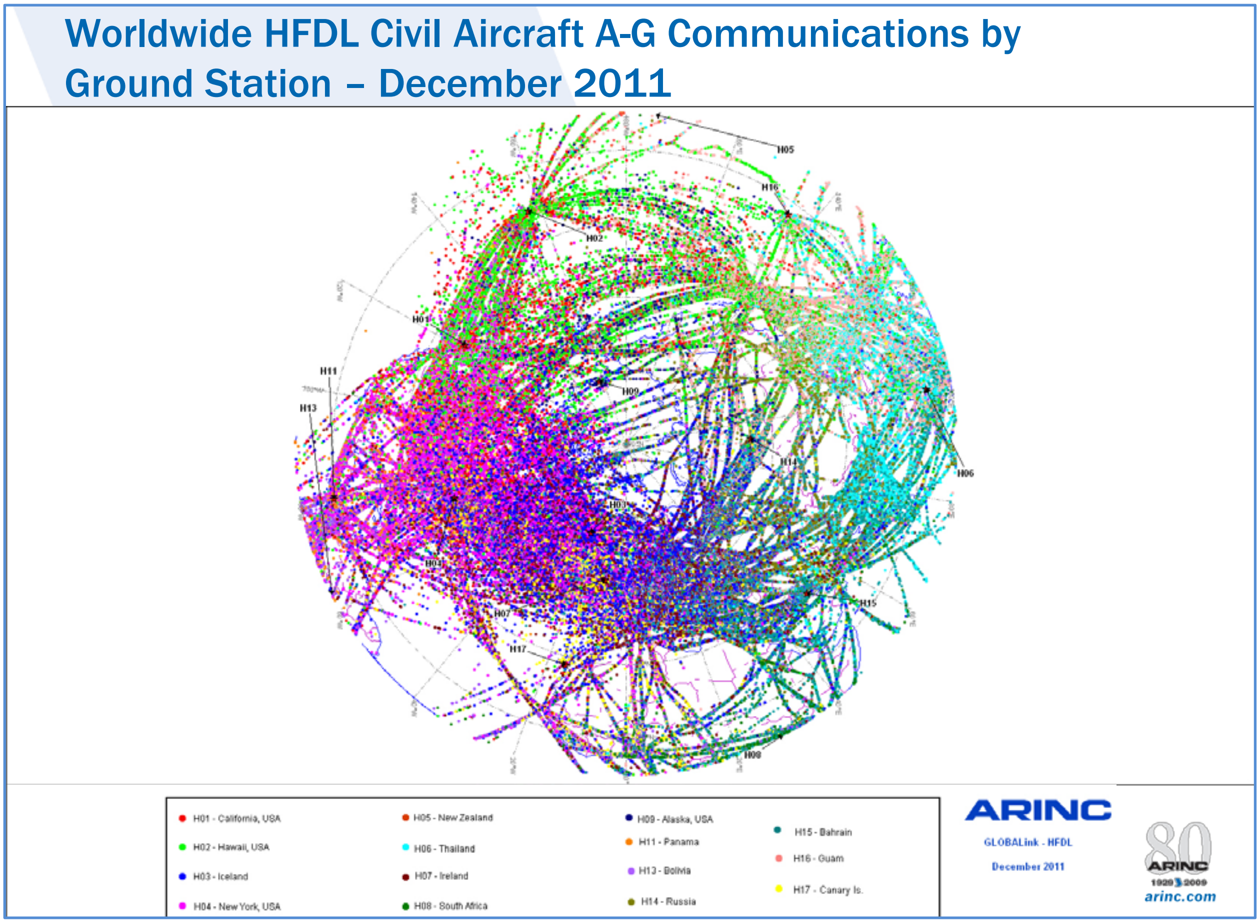


Figure 148 – HFDL Comm. (Dec. 2011) Overlaid on Invisible Polar Earth Projection

[Reference: Personal Communications with Bill Doyen, ARINC, July 23, 2013.]

16.3.3 SATCOM

Satellite communication (SATCOM) systems use satellites to relay voice and data between aircraft and ground stations. The satellites used for SATCOM include both geo-stationary (GEO) and those in low-earth polar orbits (LEO) depending upon the service network.

There are many government and commercial SATCOM service providers. All of the service providers, except one use geo-stationary satellites, whereby a minimum of 3 GEO satellites is necessary to obtain worldwide coverage below ~70 degrees North/South latitude; although, fewer satellites can be used to just cover the NAS. One service provider, Iridium uses low early orbit (LEO) satellites to provide total worldwide coverage (including the poles). Currently, there are no aviation SATCOM service providers using Medium Earth Orbit (MEO) or High Earth Orbit (HEO) satellites.

Two of the major providers include Iridium and Inmarsat, the architecture of which is described in the following subsections. For information regarding Iridium and Inmarsat SATCOM performance for aviation services, refer to Section 7.3.3.

16.3.3.1 Iridium (LEO)

[Reference: Iridium at www.iridium.com.]

Iridium provides complete worldwide satellite voice and data communications. The Iridium communications system architecture consists of three major components including: 1) a space segment, 2) a ground segment, and 3) the subscriber terminals.

The space segment architecture consists of a satellite constellation of 66 low earth orbit (LEO) satellites (plus 6 in-orbit spares) configured in a cross-linked and overlapping mesh to create its global coverage network (see Figure 149). In addition to in-orbit spares, 9 ground spares were built to replace failed satellites.

On the ground, the Iridium system is architected with a network that includes gateways which provide the connectivity between the Iridium communication system and terrestrial communication networks in Arizona and Alaska, a satellite network operations center in Virginia, a technical support center in Arizona, and four tracking and control stations that are all interconnected by fiber-optic and broadband satellite links.

Subscriber terminals include those installed on a variety of aircraft platforms from a broad segment of the market including air transport, business aviation, general aviation, as well as defense and government aircraft.

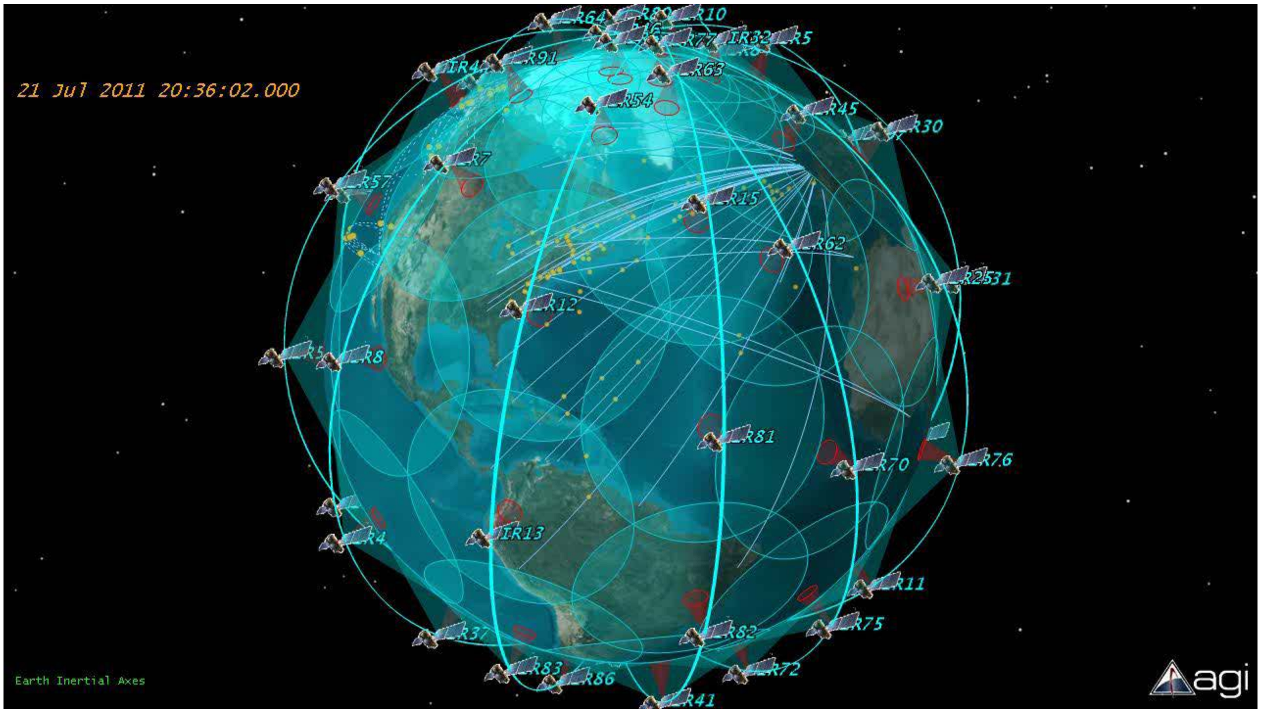


Figure 149 – Iridium Satellite Architecture

[Reference: "Revolutionizing Air Travel Through Aireon's Global Space-based ADS-B Surveillance," iCNS Conference Presentation, by Om P. Gupta, Aireon, page 6.]

16.3.3.2 Inmarsat (GEO)

[Reference: www.inmarsat.com.]

Inmarsat currently operates three constellations containing a total of 10 satellites located in geosynchronous orbit. The 10 satellites include three Inmarsat-4 series (I-4), four Inmarsat-3 series (I-3), and three Inmarsat-2 series (I-2) satellites. In the 2013-2014 timeframe, it is expected that Inmarsat will launch series 5 satellites (I-5), which will be the backbone of the Inmarsat Global Xpress network. See Figure 150 for the I-3 satellite locations. The I-3 and I-4 satellites currently provide communication services for aviation with coverage as indicated in Figure 151.

Inmarsat operates a ground network that connects customers using the Inmarsat satellites to terrestrial networks. Inmarsat's ground stations - known as satellite access stations (SAS) or land earth stations (LES) - act as traffic gateways between the terrestrial networks and the Inmarsat satellites. Located in Hawaii, The Netherlands, and Italy, the ground stations are manned and are monitored continuously from their Network Operations Centre (NOC) in London. As well as carrying user traffic, the data communications network connects more than 32 sites – including data centers in New York, Amsterdam, and Hong Kong.

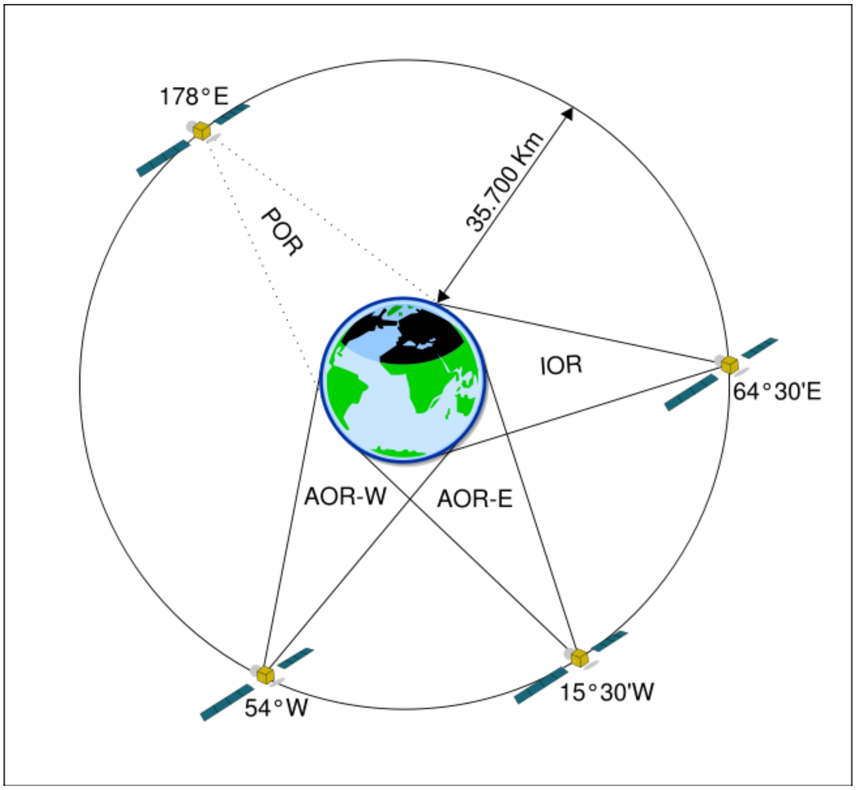


Figure 150 – Inmarsat-3 Satellite Locations

[Reference: Wikipedia at http://en.wikipedia.org/wiki/Inmarsat.]

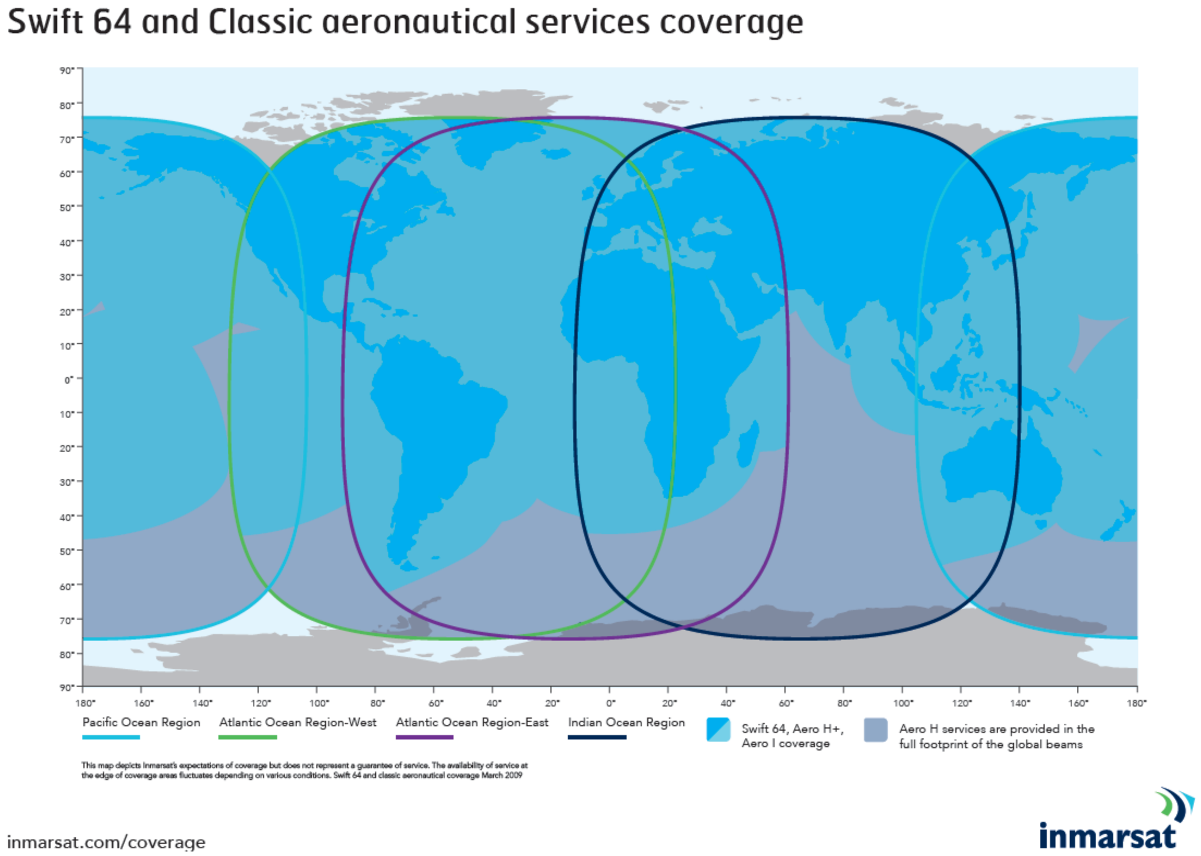


Figure 151 – Inmarsat I-3 / I-4 Aviation Coverage Map

[Reference: Inmarsat at http://www.inmarsat.com.]

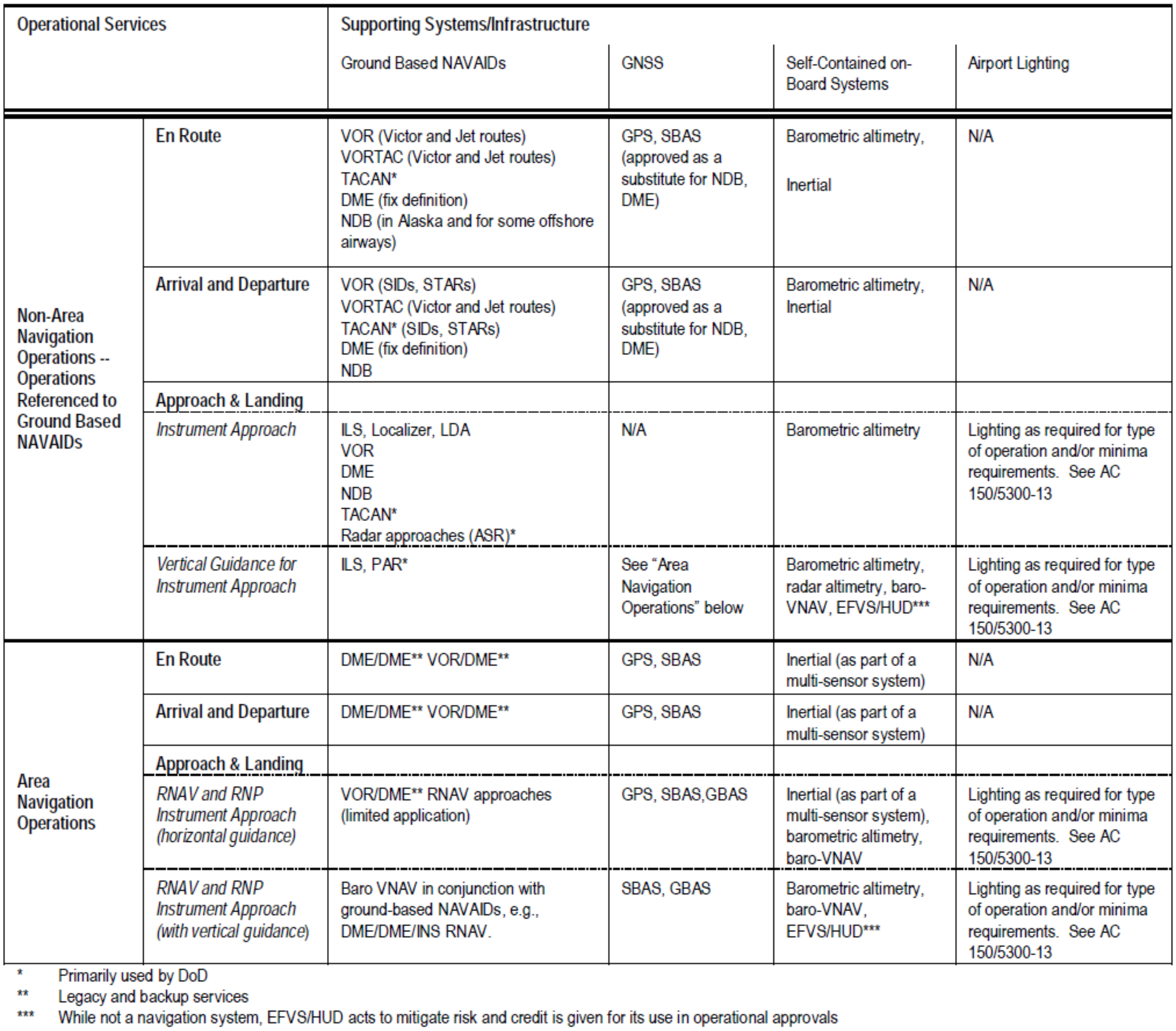
16.4 Navigation Infrastructure and Architecture

The current navigation infrastructure and services in the NAS are summarized in Figure 152. The FAA, DoD, as well as private entities sustain thousands of ground and satellite facilities dedicated to supporting navigation. This supporting infrastructure is made up of a mix of equipment to support VOR, DME, VORTAC, TACAN, NDB, ILS, GPS, WAAS, and LAAS. The use and approximate number of these systems have been tabulated as presented in Figure 153 (page 232). The existing NAVAID frequencies for these systems are given in Figure 154 (page 233).

As stated in the 2010 Federal Radio-navigation Plan published jointly by the Department of Defense, the Department of Homeland Security, and the Department of Transportation (in section 5.8 of the plan), the FAA is in the process of transitioning to provide Position/ Navigation/ Timing (PNT) services based primarily on GPS augmented by Aircraft-Based, Satellite-Based, and Ground-Based Augmentation Systems (ABAS, SBAS, and GBAS, respectively). "As a result of this transition, the need for ground-based navigation services will diminish, and the number of federally provided ground-based facilities will be reduced accordingly, but with sufficient time for users to equip with SATNAV avionics."

This federal radio-navigation plan goes on to state that: "GPS represents a fundamental departure from traditional ground-based navigation systems with respect to aviation operations. Ground-based systems provide services that are limited to the locations where they are installed.

VOR/DME and TACAN provide azimuth and distance relative to the facility, supporting point-to-point navigation. GPS supports area navigation (RNAV) and RNP operations. During transition, both types of users need to be accommodated. Most ground-based systems (such as an ILS) provide service to only a single runway. GPS approach operations can be made available to any existing runway in the NAS with or without ground-based PNT equipment. Required mitigations to terrain and obstructions, as well as airport improvements, are unchanged from ILS-based precision approach operations. GBAS supports precision approach operations to multiple runway ends at an airport. GBAS may eventually contribute to a higher acceptance rate than ILS, but mixed usage must be accommodated during transition."



Operational Services		Supporting Systems/Infrastructure			
		Ground Based NAVAIDs	GNSS	Self-Contained on-Board Systems	Airport Lighting
Non-Area Navigation Operations -- Operations Referenced to Ground Based NAVAIDs	**En Route**	VOR (Victor and Jet routes) VORTAC (Victor and Jet routes) TACAN* DME (fix definition) NDB (in Alaska and for some offshore airways)	GPS, SBAS (approved as a substitute for NDB, DME)	Barometric altimetry, Inertial	N/A
	Arrival and Departure	VOR (SIDs, STARs) VORTAC (Victor and Jet routes) TACAN* (SIDs, STARs) DME (fix definition) NDB	GPS, SBAS (approved as a substitute for NDB, DME)	Barometric altimetry, Inertial	N/A
	Approach & Landing				
	Instrument Approach	ILS, Localizer, LDA VOR DME NDB TACAN* Radar approaches (ASR)*	N/A	Barometric altimetry	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13
	Vertical Guidance for Instrument Approach	ILS, PAR*	See "Area Navigation Operations" below	Barometric altimetry, radar altimetry, baro-VNAV, EFVS/HUD***	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13
Area Navigation Operations	**En Route**	DME/DME** VOR/DME**	GPS, SBAS	Inertial (as part of a multi-sensor system)	N/A
	Arrival and Departure	DME/DME** VOR/DME**	GPS, SBAS	Inertial (as part of a multi-sensor system)	N/A
	Approach & Landing				
	RNAV and RNP Instrument Approach (horizontal guidance)	VOR/DME** RNAV approaches (limited application)	GPS, SBAS,GBAS	Inertial (as part of a multi-sensor system), barometric altimetry, baro-VNAV	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13
	RNAV and RNP Instrument Approach (with vertical guidance)	Baro VNAV in conjunction with ground-based NAVAIDs, e.g., DME/DME/INS RNAV.	SBAS, GBAS	Barometric altimetry, baro-VNAV, EFVS/HUD***	Lighting as required for type of operation and/or minima requirements. See AC 150/5300-13

* Primarily used by DoD
** Legacy and backup services
*** While not a navigation system, EFVS/HUD acts to mitigate risk and credit is given for its use in operational approvals

Figure 152 – Current Navigation Infrastructure Elements and Services

[Reference: 2010 Federal Radio-navigation Plan; published by the Department of Defense, Department of Homeland Security, and Department of Transportation; page 5-18; Table 5-1.]

NAVAID Type	Use	Number
VOR, VOR/DME and VORTAC	Defines Victor Airways and Jet Routes; supports feeder fixes for arrivals; provides non-precision approaches; defines departure paths. A VOR/DME combines VOR and DME. A VORTAC combines VOR and TACAN.	1,050 [FAA operates ~1000 DoD operations ~50]
TACAN (Tactical Navigation)	Defines Victor Airways and Jet Routes; supports feeder fixes for arrivals; provides non-precision approaches; defines departure paths; combines course with ranging information through DME.	130 stand-alone units + 90 mobile DoD units [FAA and DoD operate ~100 in NAS, DoD operates ~30 in overseas military installations]
DME and VOR/DME	Slant-range distance measuring capability used for RNAV and for defining points on approach and departure paths	1,100
NDB	Provides airway structure in remote locations, supports elements of instrument approaches	1,300 [Where: ~300 are federal, and ~1000 are non-federal owned by state, municipal, and airport authorities.]
ILS Cat. I	Precision approach down to Category I weather minima	1,300 [~1100 federal, and ~200 non-federal]
ILS Cat. II/III	Precision approach down to Category II/III weather minima	130
MLS	Microwave Landing System for approach and precision approach	Nil
GPS	Enroute, terminal navigation with precision approach and departure capabilities	1 [24+ satellite constellation operated by DoD, plus ground monitoring and control stations]
SBAS [WAAS]	Enroute, terminal navigation with precision approach and departure capabilities	1 [3 geostationary satellites, 38 reference stations, 3 master stations, 6 ground earth stations, 2 control centers]
GBAS [LAAS]	Precision approach down to Category I. Anticipated to support precision approach to Category II/III, as well as guided departure, surface, and terminal area operations.	2 [Newark, NJ and Houston, TX]

Figure 153 – Existing Number of Elements in Navigation Infrastructure

[References: Concept of Operations for NextGen APNT, published by the FAA, March 1, 2012; and the 2010 Federal Radio-navigation Plan, published by the DoD, DoHS, and DOT.]

NAVAID Type	Use	Frequency
VOR	Defines Victor Airways and Jet Routes; supports feeder fixes for arrivals; provides non-precision approaches; defines departure paths. A VORTAC combines VOR and TACAN.	108 to 117.975 MHz (VHF)
TACAN	Defines Victor Airways and Jet Routes; supports feeder fixes for arrivals; provides non-precision approaches; defines departure paths; combines course with ranging information through DME.	962 – 1215 MHz (UHF)
DME	Slant-range distance measuring capability used for RNAV and for defining points on approach and departure paths	962 – 1215 MHz (UHF)
NDB	Provides airway structure in remote locations, supports elements of instrument approaches	Aeronautical NDBs operate in the 190 to 415 kHz and 510 to 535 kHz (LF and MF)
ILS	Precision approach capability	Localizer: 108 – 111.975 MHz (VHF) Glideslope: 328 – 335.4 MHz (UHF) Marker Beacons: 74.8 – 75.2 MHz (VHF)
MLS	Not currently being used to support the microwave landing system. Plan to use spectrum for other aviation applications.	5.000 to 5.150 GHz (C Band)
GPS	Enroute, terminal navigation with precision approach and departure capabilities	L1: 1575.42 MHz L2: 1227.40 MHz L5: 1176.45 MHz (Future) (L Band)
SBAS [WAAS]	Enroute, terminal navigation with precision approach and departure capabilities	L1: 1575.42 MHz L5: 1176.45 MHz (Future) (L Band)
GBAS [LAAS]	Precision approach down to Category I. Anticipated to support precision approach to Category II/III, as well as guided departure, surface, and terminal area operations.	VHF Data Broadcast (VDB): 108 to 117.975 MHz (VHF)

Figure 154 – Existing NAVAID Frequencies

16.4.1 VOR, VOR/DME, VORTAC, and TACAN

The existing VOR, VOR/DME, VORTAC, and TACAN infrastructure is architected as a network of ground stations [with quantities as indicated in Figure 153 (page 232)] that are distributed throughout the NAS as depicted in Figure 155.

The FAA has already issued a proposed plan to transition the NAS to a performance-based navigation system that relies on GPS/GNSS and “area navigation everywhere” and “required navigation performance where beneficial,” instead of defining airways, routes and procedures using VORs and other legacy NAVAIDS. A minimum operational network of VORs and an “optimized network” of DMEs is planned to be retained, and this drawdown is proposed to be complete by January 1, 2020. Figure 156 illustrates the proposed VOR minimum operating network, where only ~50% of the VORs would be retained. In this figure, the 497 retained VOR are indicated with the green dots and the decommissioned VORs are indicated with red dots.

The FAA has indicated that ~80 percent of the VORs in the current NAS VOR network are past their service life, and replacement parts are becoming more difficult to obtain. The replacement of all the VORs has been estimated to cost over $1 billion. [FAA Presentation entitled “Alternative Positioning, Navigation, and Timing Initiative,” by Leo Eldredge, FAA, August 2010, slide 3.]

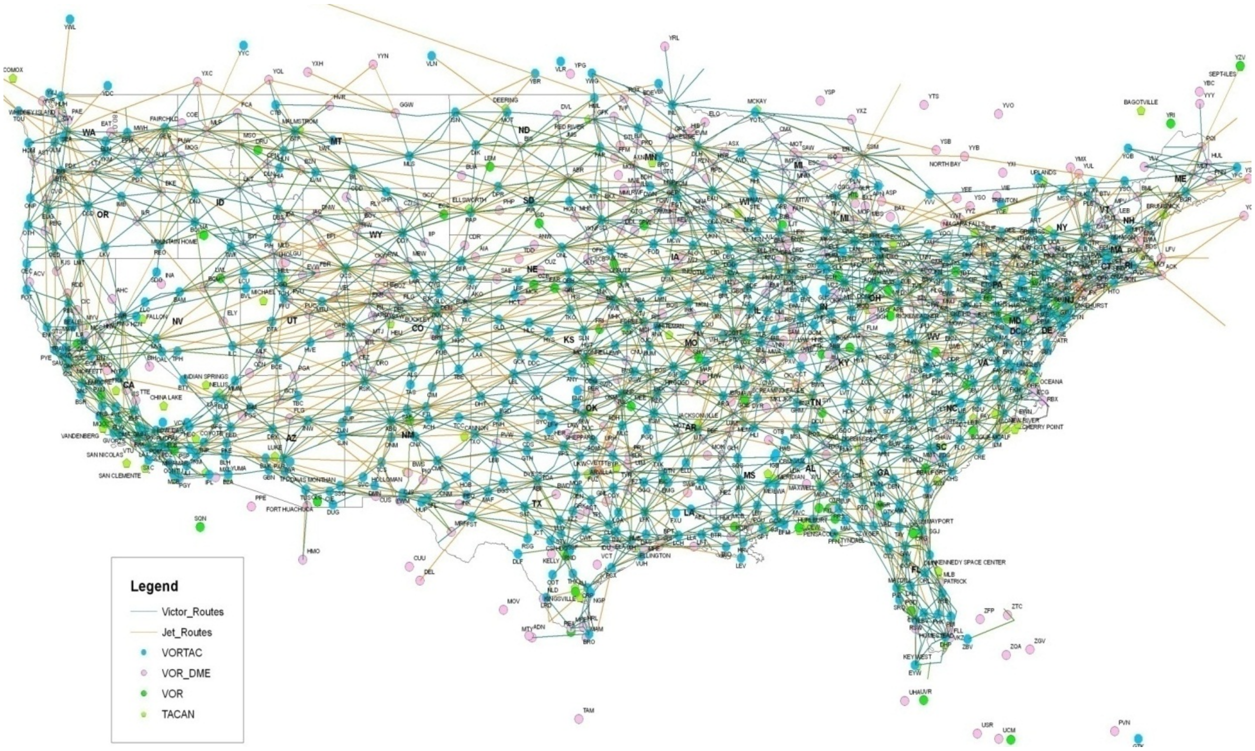


Figure 155 – VOR, VOR / DME, VORTAC, and TACAN Architecture

[Reference: FAA Presentation entitled “Alternative Positioning, Navigation, and Timing Initiative,” by Leo Eldredge, FAA, August 2010.]

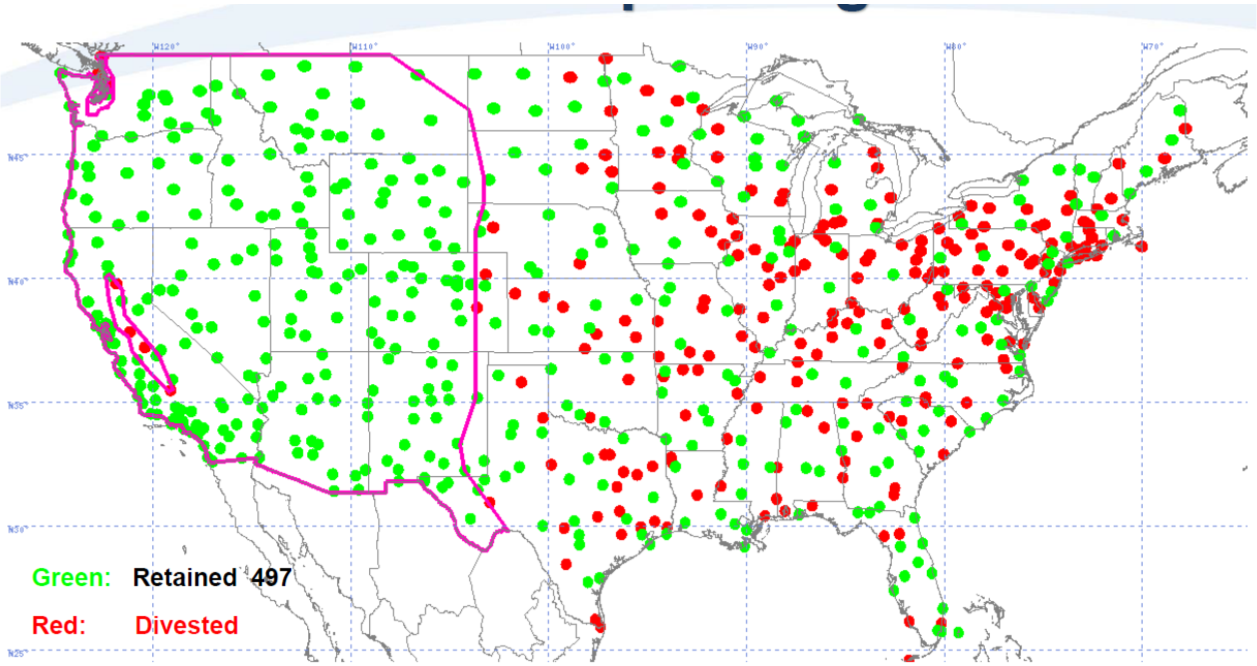


Figure 156 – VOR Proposed Minimum Operating Network Architecture

[Reference: FAA Presentation entitled “NextGen APNT Background,” presented by Leo Eldredge, FAA, presented at the APNT Industry Day, May 3, 2012, slide 8.]

16.4.2 DME

The existing NAS DME infrastructure is architected as a network of 1100 DME ground stations distributed throughout the NAS as depicted in Figure 157.

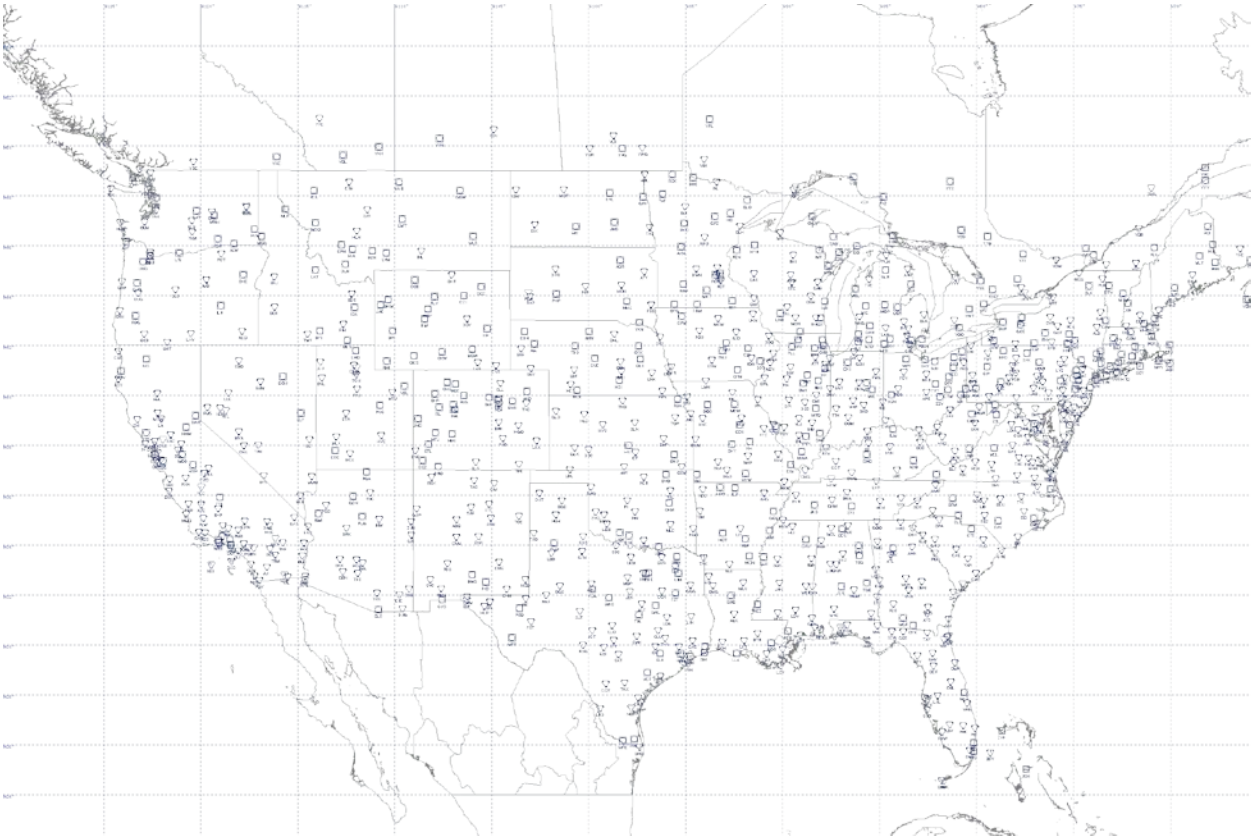


Figure 157 – DME Architecture – 1100 DMEs in Network

[Reference: FAA Presentation entitled "Alternative Positioning, Navigation, and Timing Initiative," by Leo Eldredge, FAA, August 2010.]

16.4.3 NDB

According to 2010 Federal Radio-navigation Plan, there are ~1300 non-directional beacons (NDBs) distributed throughout the NAS. Of these, ~300 are federally owned and ~1000 are non-federal owned by state, municipal, and airport authorities.

NDBs have been used historically to serve as: a) non-precision approach aids at some airports, b) as compass locators (generally co-located with the outer marker of an ILS to assist pilots in getting on the ILS course in a non-radar environment), and c) as enroute navigation aids. The FAA has begun decommissioning stand-alone NDBs as users equip with GPS and plans to retain NDBs essentially only in Alaskan airspace. No future civil aeronautical uses are envisioned for these bands after the aeronautical NDB system has been decommissioned throughout the rest of the NAS.

16.4.4 ILS

Instrument Landing Systems (ILS) are installed at airports to support precision approach and landing operations. ILS is typically installed at airports in the NAS that support air transport operations or heavy military operations. ILS systems capable of supporting Category I precision approach operations are installed at ~1300 runway ends in the NAS. ILS systems capable of supporting Category II or Category III precision approach operations are essentially only installed at large metropolitan airports in the NAS (~130 runway ends) plus a few military locations.

The existing ILS infrastructure consists of localizer and glide slope equipment that support providing guidance information to aircraft on approach and landing to a runway. ILS localizers may also provide horizontal departure guidance along the runway, or may also support providing non-precision approach guidance (horizontal-only) when the ILS glideslope is inoperative or is not installed on a given runway end (e.g., back coarse guidance).

ILS installations typically consist of localizer equipment (which supports providing horizontal guidance) and Glideslope equipment (which support providing vertical guidance), and on some installations, Marker Beacons (which indicate distance from the runway threshold as indicated on the published approach chart). Up to three marker beacons may be provided for a given approach, whereby (if provided) the outer marker is normally located approximately 4 NM from the runway threshold, the middle marker about 3500 feet from the runway, and inner marker about 1000 feet from the runway.

As depicted in Figure 158, glideslope ground equipment antenna are nominally located approximately 1000 feet beyond the close end of the approach runway threshold and offset to the side of the runway. Localizer ground equipment antennas are nominally located approximately 1000 feet beyond the far end of the approach runway.

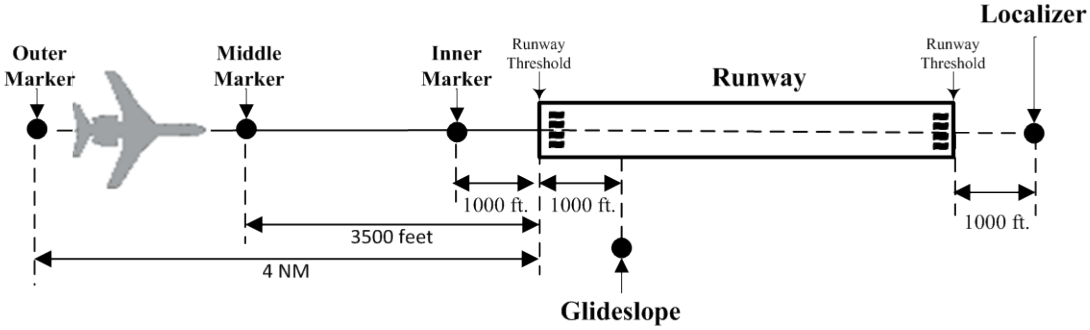


Figure 158 – Typical ILS Installation Architecture

16.4.5 GPS

The existing GPS satellite constellation is maintained by the United States DoD. The GPS system is architected to include a set of in-orbit satellites (as necessary to meet the performance specification “guarantees” of the 24-slot satellite constellation), a ground master control station [located at Schriever Air Force Base (AFB), formerly named Falcon AFB, which is about 20 km south of Colorado Springs, Colorado], and 10 monitor stations throughout the world such that at least two monitor stations have visibility to every GPS satellite in the sky. Figure 159 depicts this GPS system architecture. Figure 160 indicates the locations of the GPS control and monitor stations.

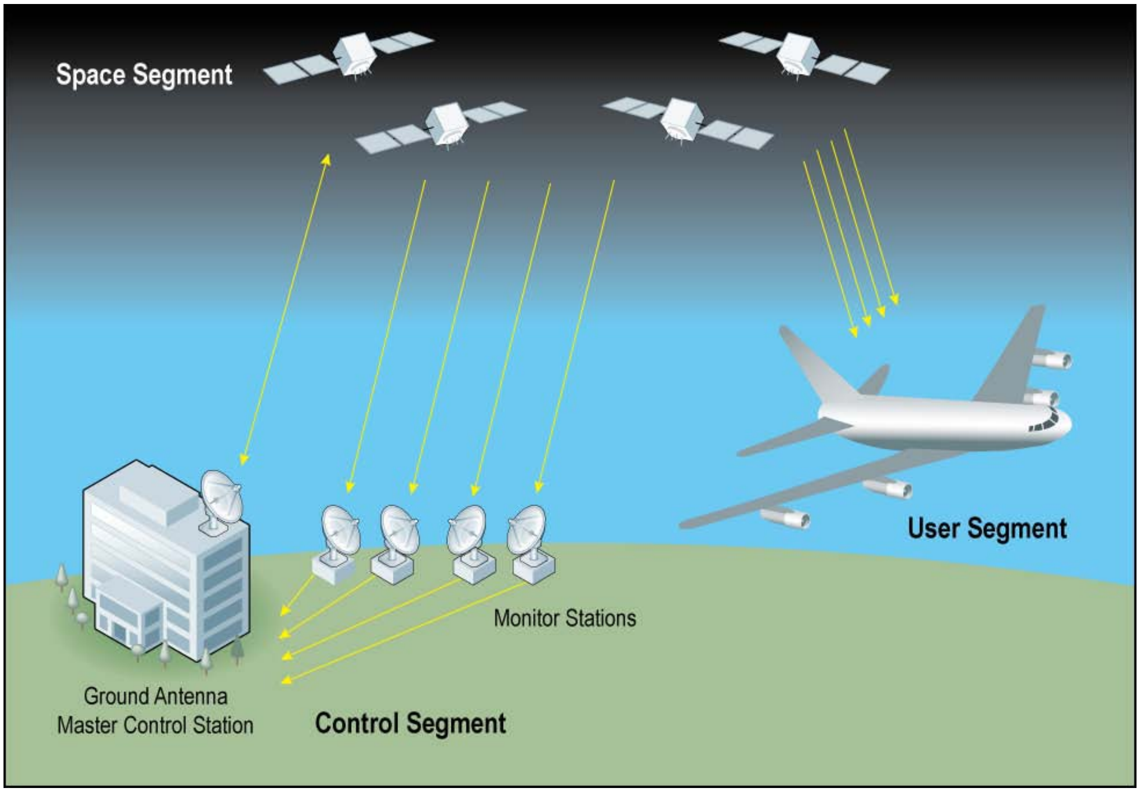


Figure 159 – GPS System Architecture

[Reference: 2010 Federal Radio-navigation Plan, published jointly by the DoD, DoHS, and DoT, Figure A-1.]

Figure 160 – GPS Control and Monitor Station Architecture

[Reference: http://www.kowoma.de/en/gps/control_segment.htm.]

16.4.6 WAAS

The existing Wide Area Augmentation System (WAAS) system architecture consists of 3 Geostationary Satellites, 38 reference stations, 3 master stations, 6 ground earth stations, and 2 operational control centers. This WAAS system architecture is depicted in Figure 161. The WAAS architectural elements are illustrated in Figure 162 (page 240).

The coverage volumes for the existing 3 WAAS Geostationary Satellites are depicted in Figure 163 (page 241), where the coverage of geostationary satellite PRN-133 is indicated by the yellow colored oval overlaid on the world map, PRN-135 coverage is indicated by the white colored oval, and PRN-138 coverage is indicated by the red colored oval.

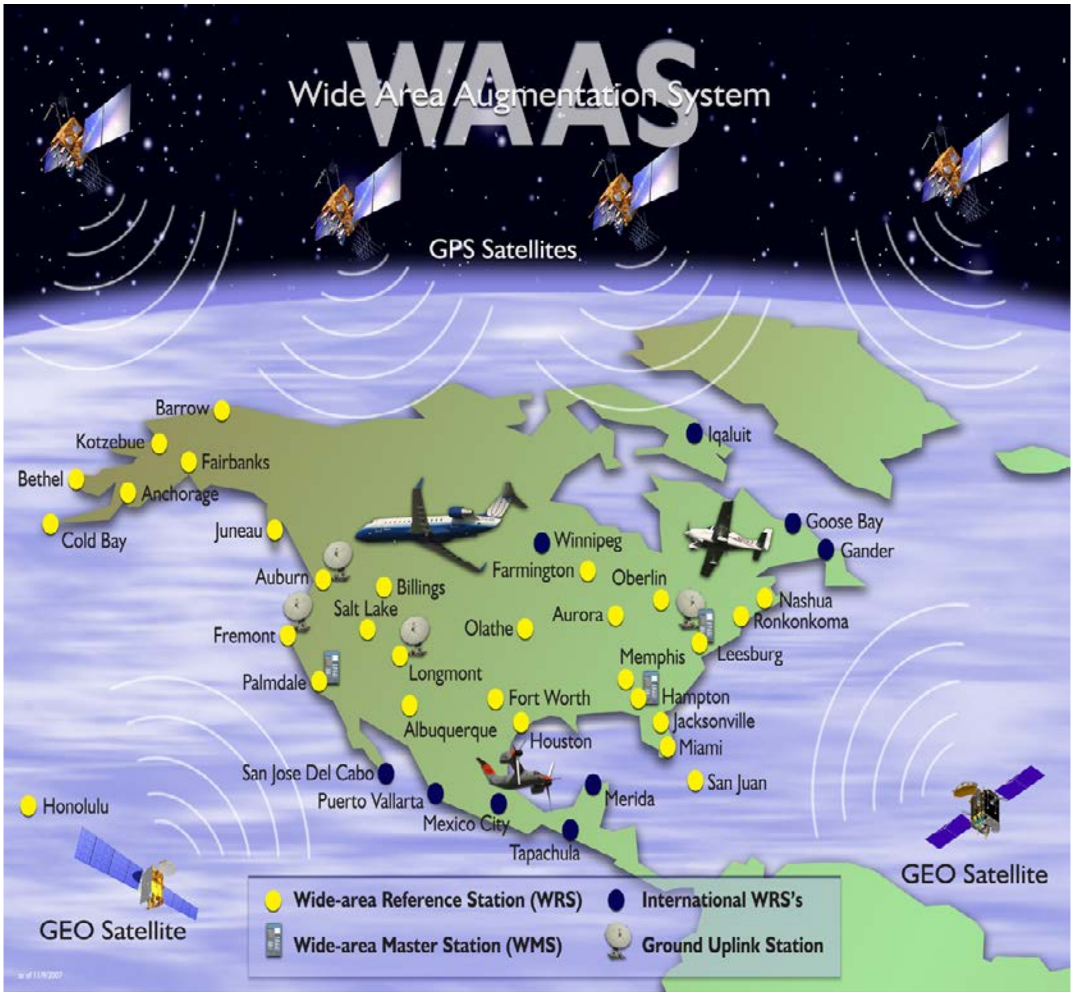


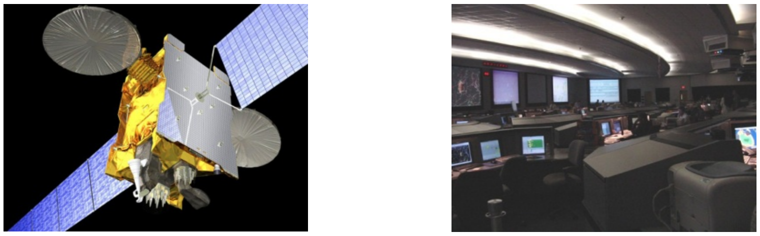
Figure 161 – Wide Area Augmentation System Architecture

[Reference: Wide Area Augmentation System (WAAS) Program Status Update Presentation, by Jason Burns, FAA, March 13, 2013.]

38 Reference Stations

3 Master Stations

6 Ground Earth Stations



3 Geostationary Satellites

2 Operational Control Centers

Figure 162 – WAAS Architectural Elements

[Reference: Wide Area Augmentation System (WAAS) Program Status Update Presentation, by Jason Burns, FAA, March 13, 2013.]

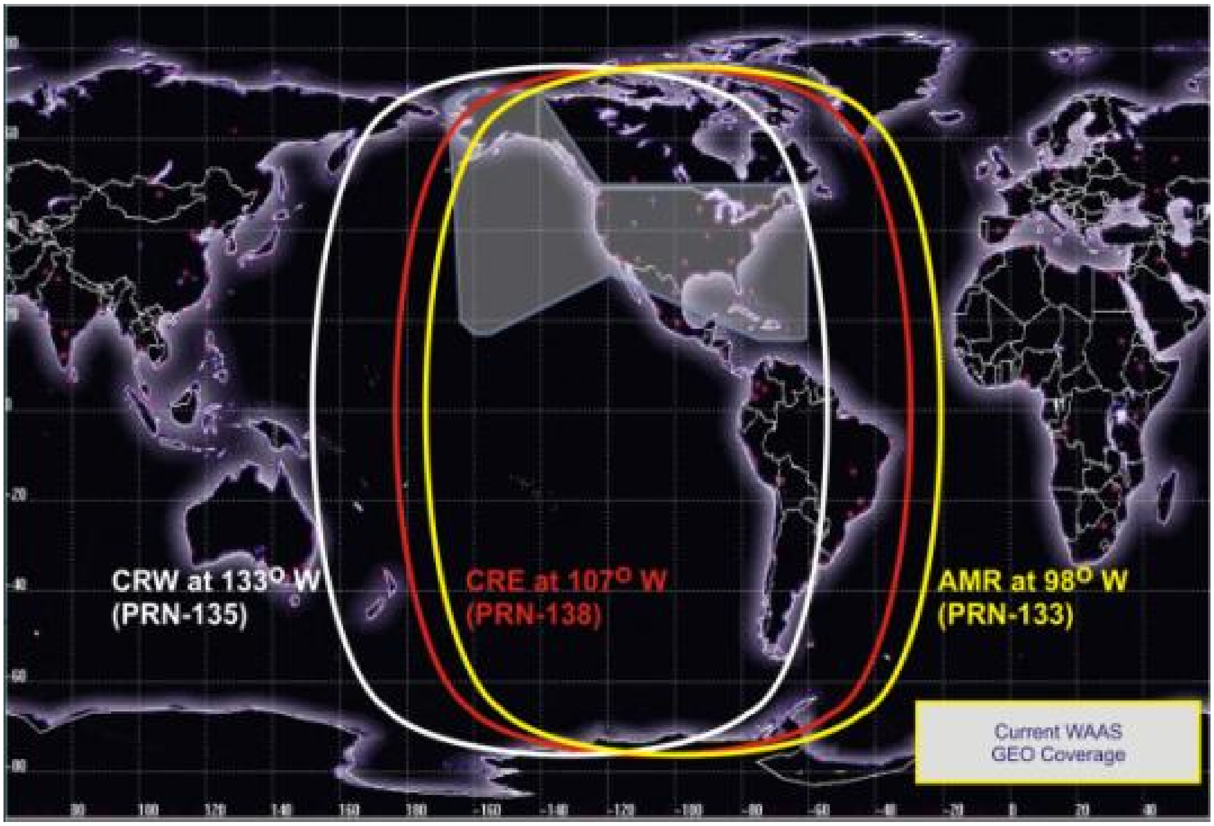


Figure 163 – WAAS Satellite Coverage

[Reference: Wide Area Augmentation System (WAAS) Program Status Update Presentation, by Jason Burns, FAA, March 13, 2013.]

16.4.7 GBAS

GPS Ground Based Augmentation Systems (GBAS) [also known as Local Area Augmentation Systems (LAAS)] are just beginning to emerge in the NAS. One GBAS station has been commissioned at the Newark New Jersey Airport. A second GBAS is expected to be commissioned soon at the Houston Texas Airport. In addition, there are a number of prototype demonstration systems in the NAS, including one at the FAA Tech Center at Atlantic City New Jersey Airport. All of the GBAS ground equipment is typically installed at a single airport on the airport property and typically includes 3 or 4 reference receivers, one GBAS ground facility, and at least one VHF Data Broadcast (VDB) system, as depicted in Figure 44.

The VDB is a ground-to-aircraft broadcast communication system that transmits satellite integrity information, satellite differential corrections, path information (e.g., approach path), and ground station information to users in the vicinity of the GBAS station. This information when combined with airborne GPS measurements results in better position accuracy and integrity bounds than can be achieved with un-augmented GPS.

GBAS can potentially be used to support a variety of aircraft operations including approach (non-precision and precision approach down to Category III), departure, surface, terminal area, and enroute operations; although, at the time of this writing, GBAS has been approved only for supporting approach operations down to Category I weather minima.

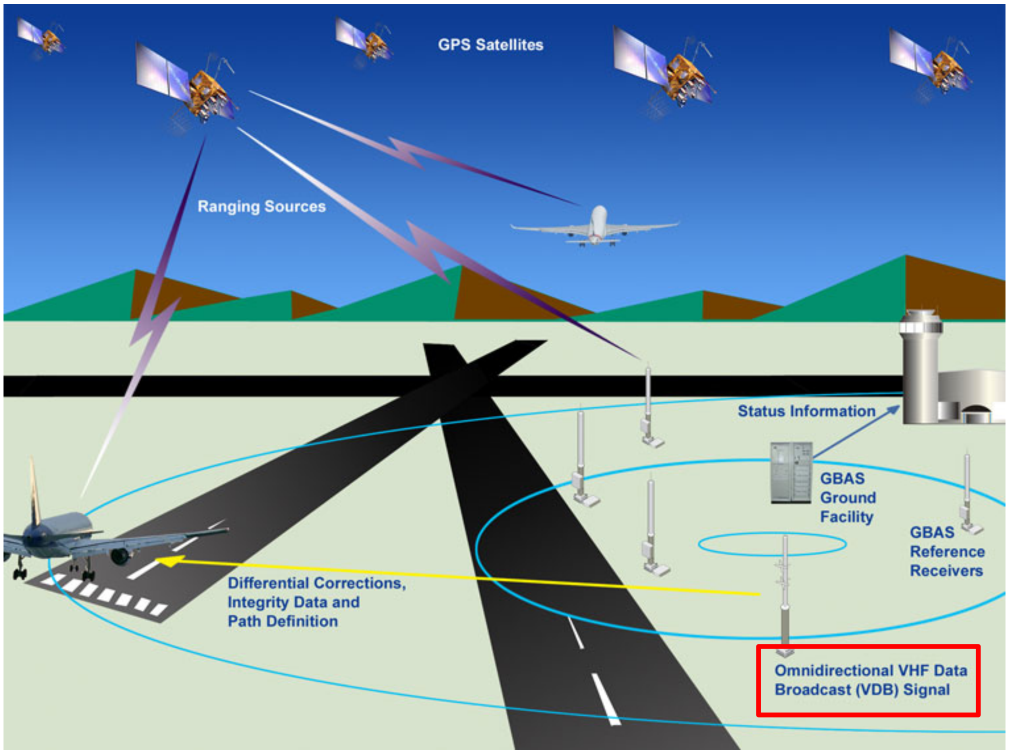


Figure 164 – GBAS / LAAS System Architecture

[Reference: Source FAA.]

16.5 Surveillance Infrastructure and Architecture

Today's NAS ATM surveillance infrastructure is based upon an architecture that includes radar and it is in the process of building an ADS-B Ground Network. In the future, it is expected that an ADS-B Satellite Network will be built as described in Section 10.1.11.3.

16.5.1 Radar

The existing NAS radar infrastructure is built on an architecture that includes Primary Surveillance Radars (PSR), Secondary Surveillance Radars (SSR), and Airport Surface Detection Equipment (ASDE).

16.5.1.1 Primary Surveillance Radar

[Reference: The source for the primary surveillance radar infrastructure information is "Surveillance / Positioning Backup Strategy Alternatives Analysis," FAA, January 8, 2007, Appendix A.]

Primary Surveillance Radar (PSR) is an independent surveillance system, where the determination of aircraft position is based on the reflected radio-frequency (RF) energy from aircraft, "independent" of any system on the aircraft. The PSR sends out a pulsed RF signal that reflects off of an aircraft within the coverage volume of the radar. A portion of this reflected energy returns to the PSR antenna, where it is detected and processed to determine the aircraft's slant range and azimuth. The information is used to generate a target report, which is sent via ground communication lines to the ATC automation system for tracking and display. When the PSR is co-located with an SSR, target correlation may be performed at the radar site prior to target report generation to enhance the reliability or confidence of the report before it is sent to the automation system.

The primary radar surveillance infrastructure includes approximately 200 terminal PSRs in the NAS are installed in locations to provide primary surveillance in terminal area airspace. Today, these systems consist of a mix of Airport Surveillance Radar Model 9 (ASR-9), ASR-7/8, and ASR-11 systems.

16.5.1.2 Secondary Surveillance Radar

[Reference: The source for the SSR infrastructure information is "Surveillance / Positioning Backup Strategy Alternatives Analysis," FAA, January 8, 2007, Appendix A.]

Secondary radar services are currently provided in high density terminal airspace (surrounding approximately the top 40 airports in terms of capacity), all enroute airspace above 18,000 feet above Mean Sea Level (MSL), and medium density terminal airspace above certain altitudes, as determined by proximate enroute SSR coverage.

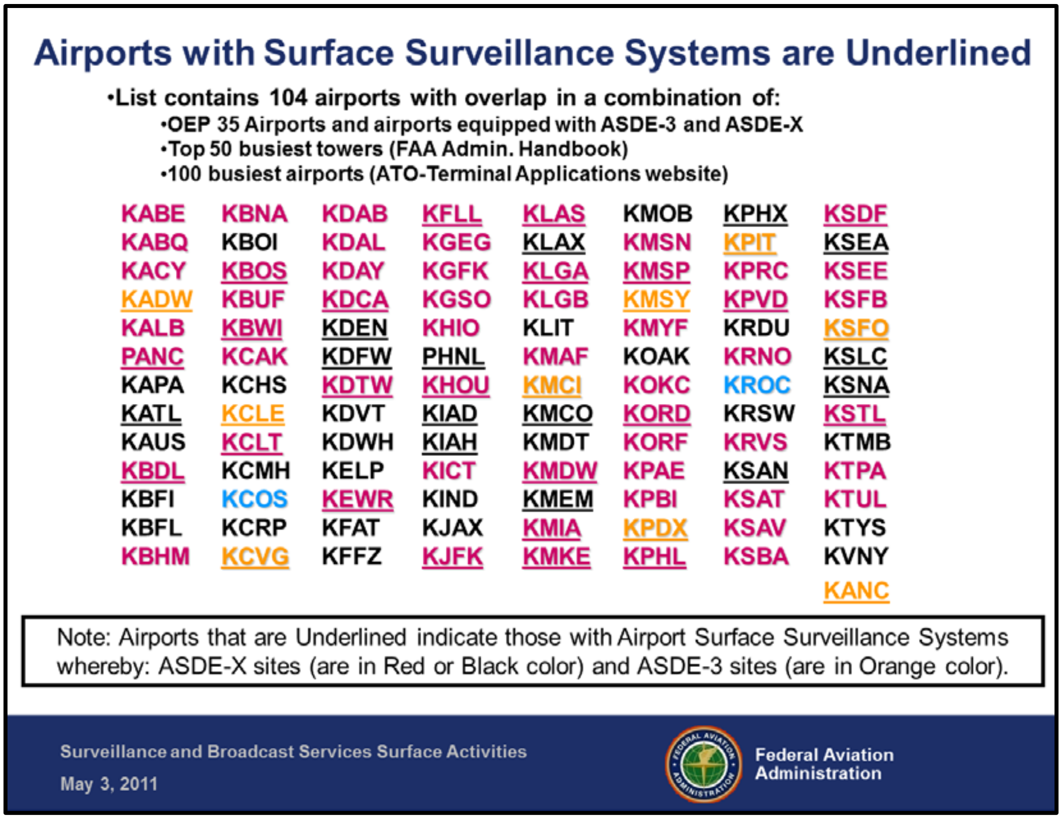
SSR is a cooperative surveillance system, where the determination of aircraft position is based on the SSR's interrogation of transponders on the aircraft; in other words, surveillance requires the "cooperation" of both aircraft and ground systems. Aircraft equipped with legacy transponders (Mode A, Mode C, or Mode S) are interrogated by the SSR to elicit beacon code and altitude information for each aircraft. The SSR processes the replies from the aircraft transponder to determine slant range, based on time of reply receipt, and azimuth based on antenna position at the time the reply is received. The SSR also correlates the identification and altitude information embedded in the replies with the position estimate to generate a target report for the aircraft. Target reports are sent via ground communication lines to the ATC automation system for tracking, correlation to flight plans (when available), and display to controllers.

The SSR infrastructure is built with an architecture that includes approximately 300 SSRs distributed throughout the NAS. Of the SSRs in the NAS, approximately 260 provide surveillance for enroute [which currently consist of a mix of Air Traffic Control Beacon Interrogator Model 6 (ATCBI-6) and Mode Select (Mode S) systems] and approximately 40 terminal SSRs provide secondary surveillance in high density terminal airspace [which currently consist of Mode S systems only].

16.5.1.3 Airport Surface Radar

Airport Surface Detection Equipment Model X (ASDE-X) uses multilateration to provide surface coverage of airport movement areas.

Currently, 44 airports in the NAS have been equipped with airport surface surveillance radars including 33 airports with ASDE-X and 9 airports with ADSE-3 technology. Figure 165 identifies the airports that have been equipped with each of these airport surface surveillance radar technologies.



Airports with Surface Surveillance Systems are Underlined

- List contains 104 airports with overlap in a combination of:
  - OEP 35 Airports and airports equipped with ASDE-3 and ASDE-X
  - Top 50 busiest towers (FAA Admin. Handbook)
  - 100 busiest airports (ATO-Terminal Applications website)

KABE
KABQ
KACY
KADW
KALB
PANC
KAPA
KATL
KAUS
KBDL
KBFI
KBFL
KBHM
KBNA
KBOI
KBOS
KBUF
KBWI
KCAK
KCHS
KCLE
KCLT
KCMH
KCOS
KCRP
KCVG
KDAB
KDAL
KDAY
KDCA
KDEN
KDFW
KDTW
KDVT
KDWH
KELP
KEWR
KFAT
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KHOU
KIAD
KIAH
KICT
KIND
KJAX
KJFK
KLAS
KLAX
KLGA
KLGB
KLIT
KMAF
KMCI
KMCO
KMDT
KMDW
KMEM
KMIA
KMKE
KMOB
KMSN
KMSP
KMSY
KMYF
KOAK
KOKC
KORD
KORF
KPAE
KPBI
KPDX
KPHL
KPHX
KPIT
KPRC
KPVD
KRDU
KRNO
KROC
KRSW
KRVS
KSAN
KSAT
KSAV
KSBA
KSDF
KSEA
KSEE
KSFB
KSFO
KSLC
KSNA
KSTL
KTMB
KTPA
KTUL
KTYS
KVNY
KANC

Note: Airports that are Underlined indicate those with Airport Surface Surveillance Systems whereby: ASDE-X sites (are in Red or Black color) and ASDE-3 sites (are in Orange color).

Surveillance and Broadcast Services Surface Activities
May 3, 2011

Federal Aviation Administration

Figure 165 – Airports with Surface Surveillance Systems

[Reference: FAA Surveillance and Broadcast Services Surface Activities Presentation, by Doug Arbuckle, dated May 3, 2011.]

16.5.1.4 System Performance

The performance of radar in terms of coverage, accuracy, update rate, and availability is identified in Figure 166.

System → Parameter ↓	Enroute SSR	Terminal SSR	Terminal PSR
Coverage	Range: 0 - 250 NM Azimuth: 0 - 360°	Range: 0 - 60 NM Azimuth: 0 - 360°	Range: 0.5 - 60 NM Azimuth: 0 - 360°
Positional Accuracy (RMS)	± 4370 ft (0.72 NM) @ 250 NM	± 1050 ft (0.17 NM) @ 60 NM	± 1020 ft (0.17 NM) @ 60 NM
Update Rate	~ 12 sec	~ 4.8 sec	~ 4.8 sec
Availability	≥ 0.9999578	≥ 0.9999578	≥ 0.99984

Figure 166 – Radar Systems Performance

[Reference: "Surveillance / Positioning Backup Strategy Alternatives Analysis," FAA, January 8, 2007, Appendix A.]

16.5.2 Emerging ADS-B NAS Ground Network

Networks of ADS-B ground stations and associated traffic surveillance receivers are being deployed by Air Traffic Service Providers to provide surveillance coverage to receive ADS-B OUT transmissions throughout the airspace to support the needs of Air Traffic Control. ADS-B ground station networks are being deployed in many countries (including the United States) for achieving improved traffic surveillance coverage over airspace regions where surveillance information was limited or for operational cost effectiveness (e.g., replacement of Secondary Surveillance Radars with ADS-B ground stations to obtain improved surveillance coverage at lower cost). ADS-B ground stations provide aircraft surveillance information that typically has better accuracy and updates rates than SSR for use in ATC automation systems and aircraft control services. In the future, it is expected that better surveillance information will provide the opportunity to safely reduce the existing aircraft separation standards and enable more efficient flight operations.

ADS-B ground stations receive and process the ADS-B OUT surveillance broadcasts by aircraft and airport ground vehicles for use by the ATC automation systems and for presentation on controller displays.

As part of the FAA's airspace improvement initiatives and path to NextGen and beyond, the FAA contracted the development of a network of ADS-B ground system transceivers that receive ADS-B broadcasts from equipped aircraft/vehicles and provide services for broadcasting Automatic Dependent Surveillance – Rebroadcast (ADS-R), Traffic Information Services – Broadcast (TIS-B), and Flight Information Services – Broadcast (FIS-B) information. The ADS-B ground network being deployed in the United States is expected to be fully operational in 2014 and is planned to contain 794 strategically located ground stations to receive ADS-B OUT transmissions by aircraft/vehicles in the National Airspace System (NAS). Figure 167 indicates the planned location of these ground stations (as indicated with the small triangles) as well as the coverage as a function of altitude. The ADS-B ground reception coverage as a function of altitude for each location is indicated in each location by color, whereby coverage at and above: a) 1500 feet is colored light brown, b) 1800 feet is colored dark blue, c) 5100 feet is colored red, d) 18000 feet is colored yellow, and e) 28000 feet is colored light blue.

A significant portion of this ADS-B ground station network is already operational at the time of this writing. Figure 168 illustrates the location of 594 ADS-B Ground Network stations deployed as of June 30, 2013. These ground stations and their network computers process and provide ADS-B information to the FAA at designated service delivery points. The FAA will utilize this information to provide ATC services. The FAA and its designated service providers supply weather information to the ground network for uplink on FIS-B and traffic information gathered through secondary surveillance radar and multilateration systems for uplink on TIS-B.

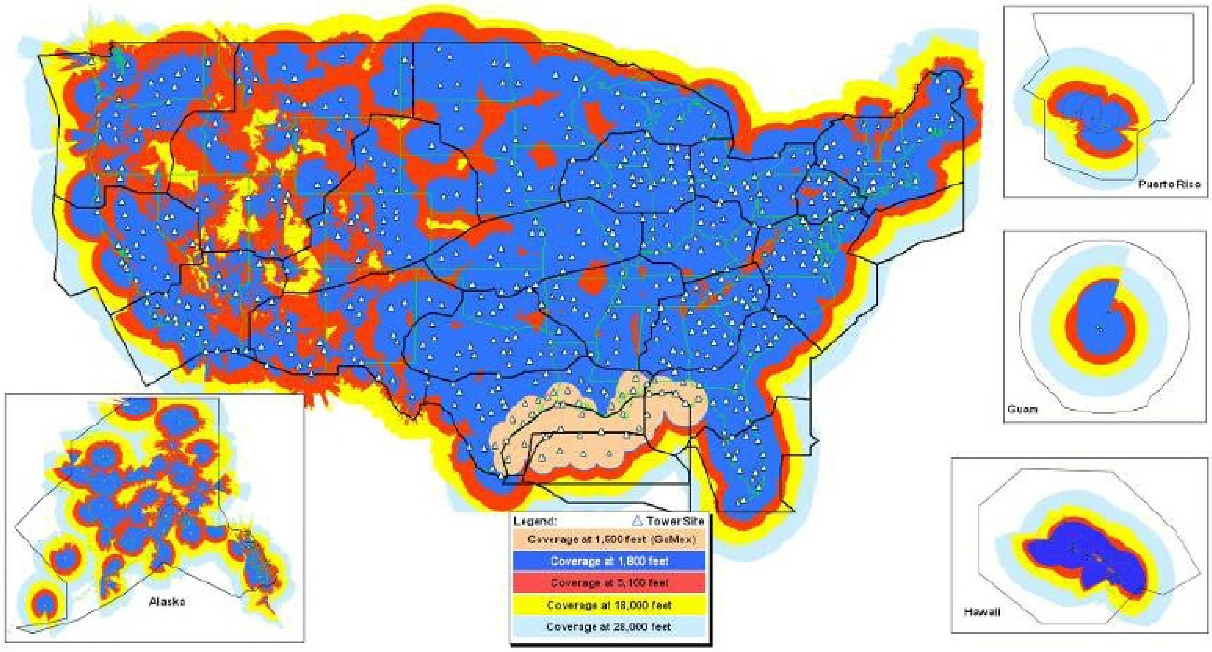
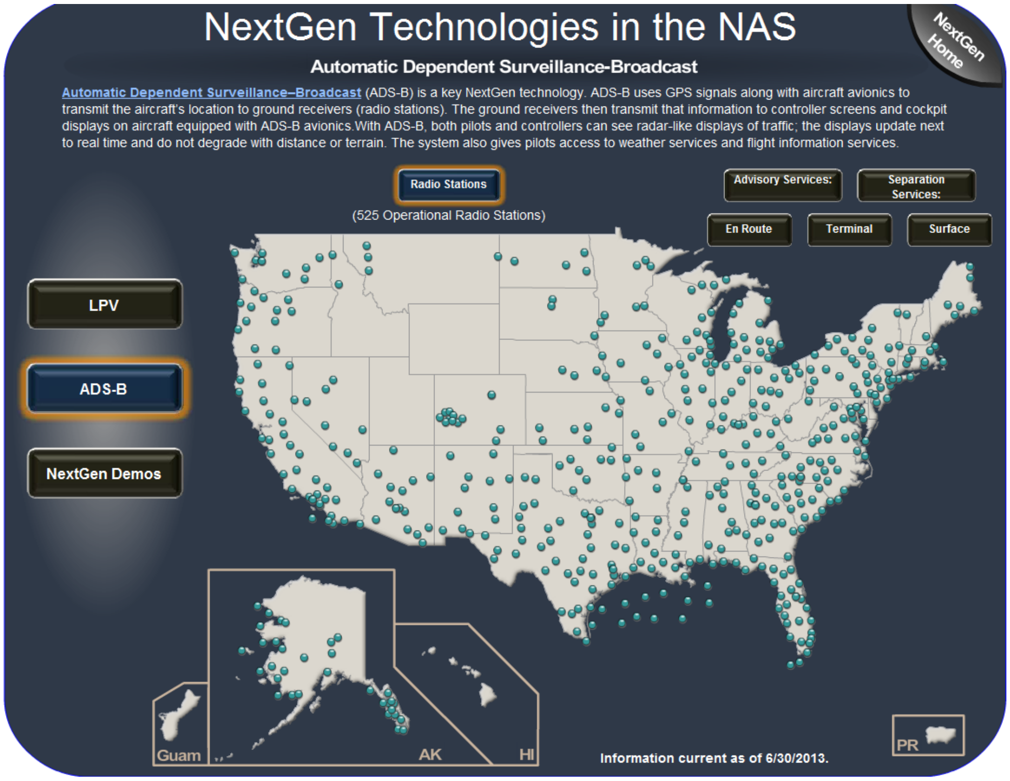


Figure 167 – ADS-B Planned 794 Ground Station Infrastructure and Coverage

[Reference: FAA Presentation entitled "Alternative Positioning, Navigation, and Timing Initiative," by Leo Eldredge, FAA, August 2010.]


NextGen Technologies in the NAS

Automatic Dependent Surveillance-Broadcast

Automatic Dependent Surveillance–Broadcast (ADS-B) is a key NextGen technology. ADS-B uses GPS signals along with aircraft avionics to transmit the aircraft's location to ground receivers (radio stations). The ground receivers then transmit that information to controller screens and cockpit displays on aircraft equipped with ADS-B avionics.With ADS-B, both pilots and controllers can see radar-like displays of traffic; the displays update next to real time and do not degrade with distance or terrain. The system also gives pilots access to weather services and flight information services.

(525 Operational Radio Stations)

Information current as of 6/30/2013.

Figure 168 – ADS-B Ground Station Deployment: 594 Stations as of June 30, 2013

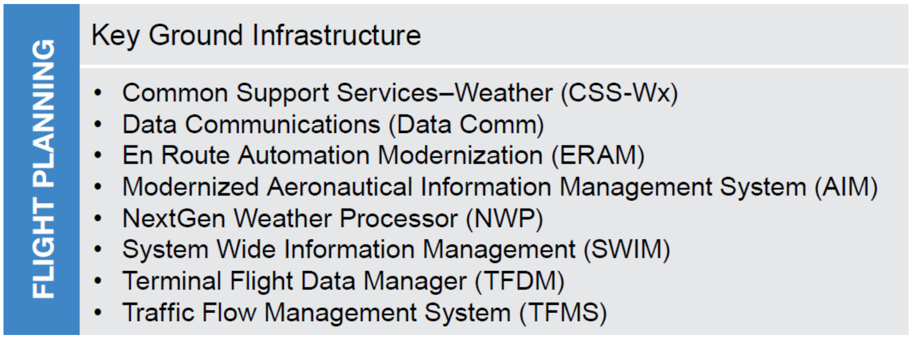
[Reference: http://www.faa.gov/nextgen/flashmap]

16.6 Key NAS Ground and Aircraft Infrastructure to Achieve FAA NextGen Vision

[Reference: NextGen Implementation Plan, FAA, June 2013.]

The FAA has identified in their NextGen implementation plan (dated June 2013) the key ground and avionics infrastructure necessary to realize the NextGen operational vision. This key ground and avionics infrastructure as presented in this plan as a function of aircraft flight phase is provided in figures as identified below:

1. Flight Planning (Figure 169),
2. Push back, taxi, and departure (Figure 170),
3. Climb and cruise (Figure 171),
4. Descent and approach (Figure 172), and
5. Landing, taxi, and arrival (Figure 173).



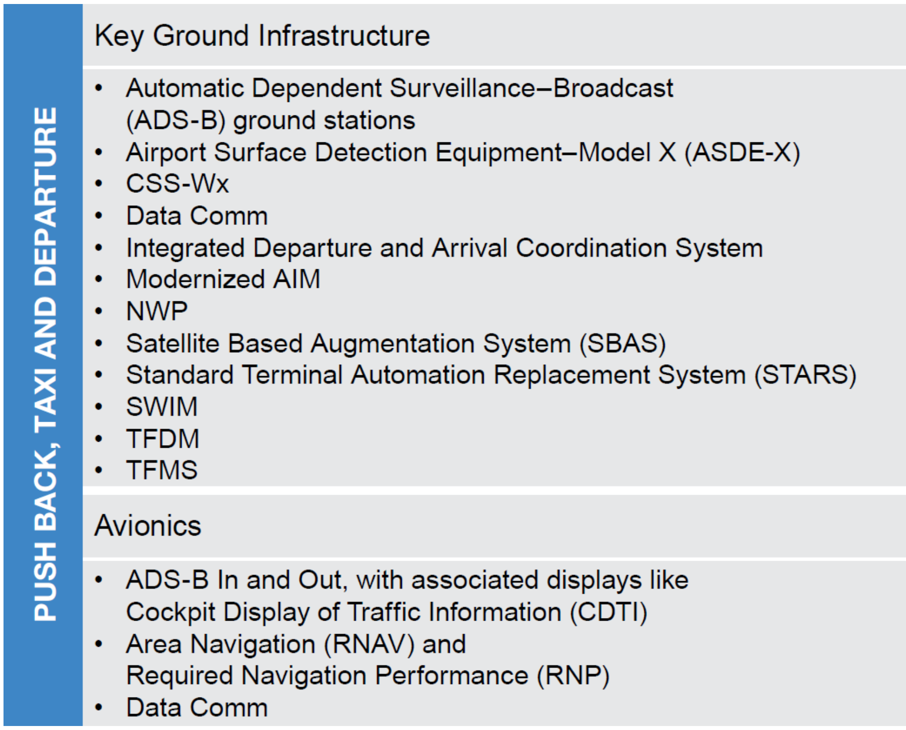
FLIGHT PLANNING

Key Ground Infrastructure

- Common Support Services–Weather (CSS-Wx)
- Data Communications (Data Comm)
- En Route Automation Modernization (ERAM)
- Modernized Aeronautical Information Management System (AIM)
- NextGen Weather Processor (NWP)
- System Wide Information Management (SWIM)
- Terminal Flight Data Manager (TFDM)
- Traffic Flow Management System (TFMS)

Figure 169 – NextGen Key Infrastructure: Flight Planning

[Reference: NextGen Implementation Plan, FAA, June 2013, page 24.]



PUSH BACK, TAXI AND DEPARTURE

Key Ground Infrastructure

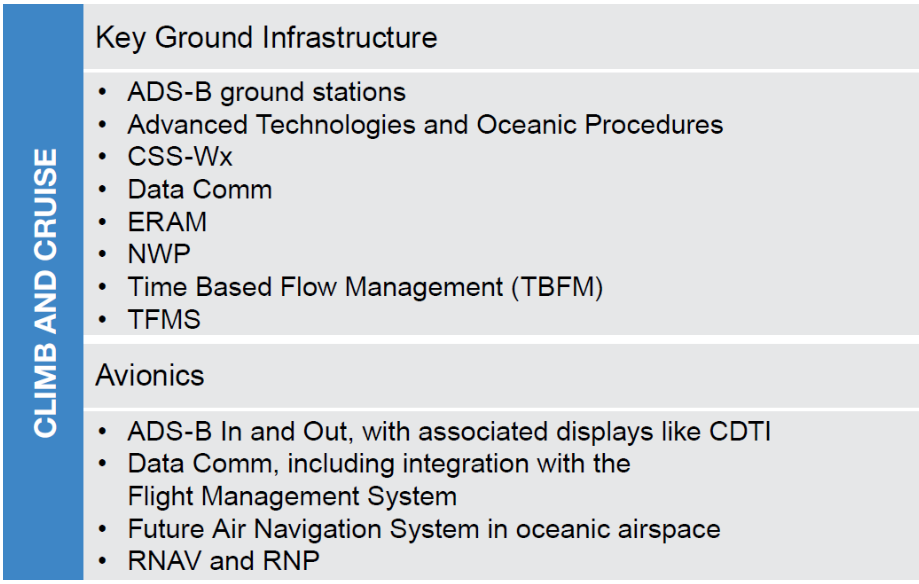
- Automatic Dependent Surveillance–Broadcast (ADS-B) ground stations
- Airport Surface Detection Equipment–Model X (ASDE-X)
- CSS-Wx
- Data Comm
- Integrated Departure and Arrival Coordination System
- Modernized AIM
- NWP
- Satellite Based Augmentation System (SBAS)
- Standard Terminal Automation Replacement System (STARS)
- SWIM
- TFDM
- TFMS

Avionics

- ADS-B In and Out, with associated displays like Cockpit Display of Traffic Information (CDTI)
- Area Navigation (RNAV) and Required Navigation Performance (RNP)
- Data Comm

Figure 170 – NextGen Key Infrastructure: Push Back, Taxi, and Departure

[Reference: NextGen Implementation Plan, FAA, June 2013, page 25.]



CLIMB AND CRUISE

Key Ground Infrastructure

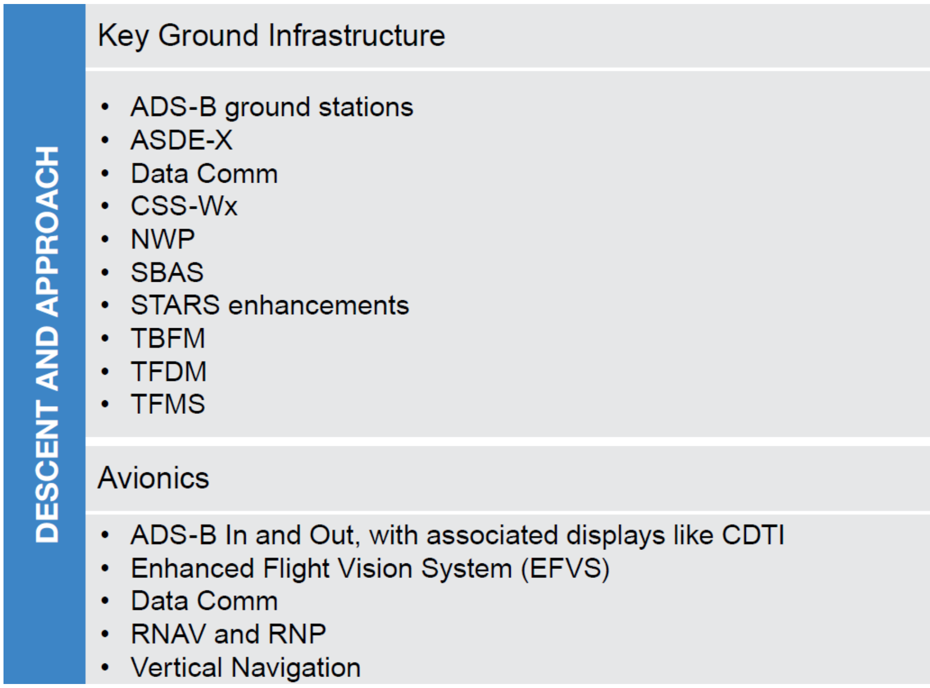
- ADS-B ground stations
- Advanced Technologies and Oceanic Procedures
- CSS-Wx
- Data Comm
- ERAM
- NWP
- Time Based Flow Management (TBFM)
- TFMS

Avionics

- ADS-B In and Out, with associated displays like CDTI
- Data Comm, including integration with the Flight Management System
- Future Air Navigation System in oceanic airspace
- RNAV and RNP

Figure 171 – NextGen Key Infrastructure: Climb and Cruise

[Reference: NextGen Implementation Plan, FAA, June 2013, page 25.]



DESCENT AND APPROACH

Key Ground Infrastructure

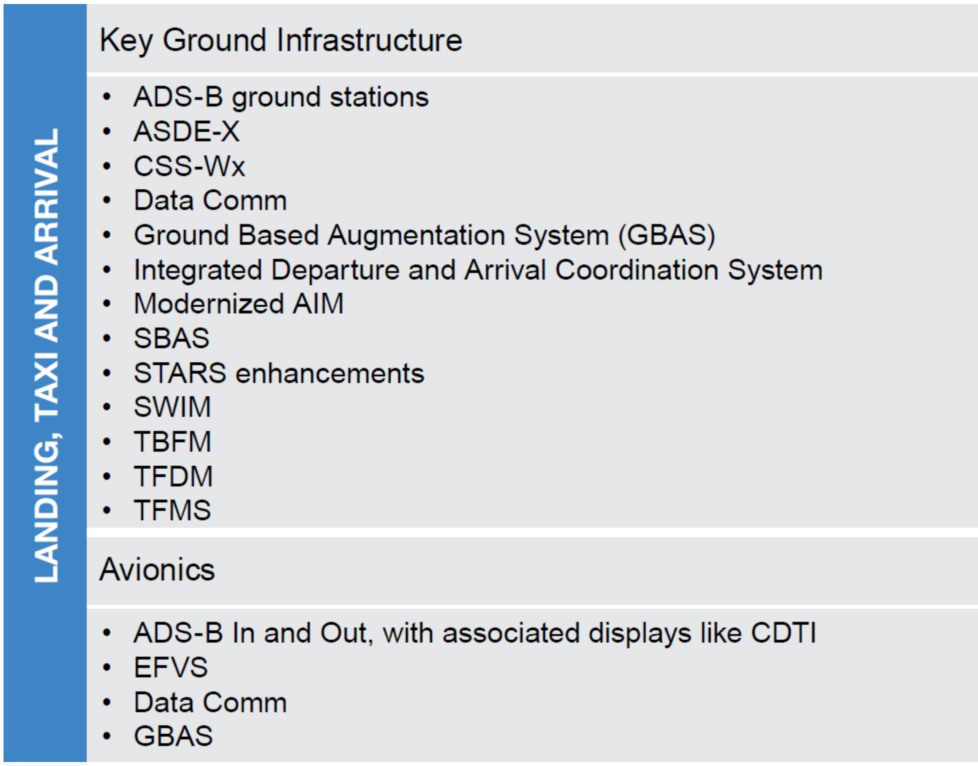
- ADS-B ground stations
- ASDE-X
- Data Comm
- CSS-Wx
- NWP
- SBAS
- STARS enhancements
- TBFM
- TFDM
- TFMS

Avionics

- ADS-B In and Out, with associated displays like CDTI
- Enhanced Flight Vision System (EFVS)
- Data Comm
- RNAV and RNP
- Vertical Navigation

Figure 172 – NextGen Key Infrastructure: Descent and Approach

[Reference: NextGen Implementation Plan, FAA, June 2013, page 26.]



LANDING, TAXI AND ARRIVAL

Key Ground Infrastructure

- ADS-B ground stations
- ASDE-X
- CSS-Wx
- Data Comm
- Ground Based Augmentation System (GBAS)
- Integrated Departure and Arrival Coordination System
- Modernized AIM
- SBAS
- STARS enhancements
- SWIM
- TBFM
- TFDM
- TFMS

Avionics

- ADS-B In and Out, with associated displays like CDTI
- EFVS
- Data Comm
- GBAS

Figure 173 – NextGen Key Infrastructure: Landing, Taxi, and Arrival

[Reference: NextGen Implementation Plan, FAA, June 2013, page 27.]

17 IDENTIFICATION OF INFRASTRUCTURE REQUIRED FOR EACH CANDIDATE

This section of the report identifies the airborne and ground infrastructure (including changes to the existing infrastructure) required by each of the A-A and A-G candidates.

The term "infrastructure" for the purposes of this section of the report is defined to include the basic physical and organizational structures needed for the operation of the A-A or A-G communication system candidate.

It is known that additional infrastructure needs and changes will be required to many other NAS elements to support various intended operations. However, the focus of this section is to identify just the infrastructure to support the various A-A and A-G communication candidates.

17.1 Introduction

The future ATM communications infrastructure is expected to provide an integrated, global network that will incorporate a ground segment, an air-to-ground segment, and an air-to-air segment.

The ground network is the backbone of the NextGen Net-Centric Environment, carrying inter-facility data in the NextGen network. The ground network will also provide essential support for the air-to-ground segment, by transporting data to and from the appropriate ground radio equipment.

The air-to-ground segment will carry data from ground systems to the cockpit and vice versa. This critical portion of the NAS communications enables the delivery of ATC clearances and information, real-time surveillance, weather data, relevant security information to the cockpit, and enables the negotiation of trajectories and separation responsibility contracts.

The air-to-air segment will allow aircraft to share critical real time information, including, for example, surveillance, navigation/intent, and sensed environmental information (e.g., weather data).

17.2 Infrastructure for Air-to-Air Communication Candidates

The twelve air-to-air communication candidates have been identified and described previously in this report. The airborne and ground infrastructure needed (including changes to the existing infrastructure) required for each of the A-A candidates is identified in Figure 174 and Figure 175. *Note on these figures that the column labeled "ground" (for ground infrastructure) includes all the "non-airborne" infrastructure elements, and thus includes identification of satellites for the SATCOM candidates.*

This information will be utilized in subsequent A-A communication candidate analyses (e.g., to establish cost or relative cost estimates) to be completed in FY2014.

		Infrastructure			
		Note: Depending upon the application(s) supported, additional airborne and/or ground infrastructure may be needed as well as changes to the existing infrastructure.			
		Infrastructure Required		Changes to Existing Infrastructure	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-A	Air-to-Air (A-A) Comm. Candidates				
1	VHF A-A	VHF Data Radios & Antennas	None	- VHF communication radios replaced with VDR capable radios. System integrated with avionics - Long term, the use of directional antennas with directional gain would enable higher order modulations and better band reuse - Future: Candidate for integrated/ software radios and multi-function integrated antennas	None
2	UHF A-A	UHF Data Radios & Antennas	None	- New UHF communication radios and antennas integrated with avionics - Future: Candidate for integrated/ software radios and multi-function integrated antennas	None
3	L-Band A-A	L Band Data Radios & Antennas	None	- New L-band communication radios & antennas or upgrade to existing L-band radios and antennas, integrated into the avionics systems and aircraft. - Future: Candidate for integrated/ software radios and multi-function integrated antennas	None
4	S-Band A-A	S Band Data Radios & Antennas	None	- New S-band radios, and antennas - Future: Candidate for integrated/ software radios and multi-function integrated antennas	None
5	C-Band A-A	C Band Data Radios & Antennas	None	- New C-band radios and antennas - Future: Candidate for integrated software radios / antennas, directional antennas	None
6	X-Band A-A	X Band Data Radios & Antennas	None	- New X-band data radios and antennas or possible changes/ integration with the airborne WxR depending upon the frequency and modulation selected - Future: Candidate for integrated software radios / antennas, directional antennas, integrated with WxR function	None
7	Optical A-A	Optical Data Radios & optical antennas	None	- New optical radios and antennas - RF digitizer - Optical antenna pointing systems, smaller collectors, deformable mirrors / collectors - Future: System highly integrated with avionics	None
8	Hybrid RF/Optical A-A	Hybrid RF/optical data radios & antennas	None	- New RF/optical radios and antennas - RF digitizer - Optical antenna pointing systems, smaller collectors, deformable mirrors / collectors - Hybrid RF/optical systems - Future: System highly integrated with avionics, software radios	None

Figure 174 – Infrastructure Required for A-A Candidates (Part 1 of 2)

		Infrastructure			
		Note: Depending upon the application(s) supported, additional airborne and/or ground infrastructure may be needed as well as changes to the existing infrastructure.			
		Infrastructure Required		**Changes to Existing Infrastructure**	
#	**Communications Candidates**	**Airborne**	**Ground**	**Airborne**	**Ground**
A-A	Air-to-Air (A-A) Comm. Candidates				
9	LEO SATCOM A-A (One Hop through Satellite)	SATCOM Radios & Antennas (e.g., omni for standard Iridium, directional for Iridium NEXT and beyond)	LEO SATCOM infrastructure including satellites, Network Operating Centers (NOCs), and satellite control & monitor stations, with on-satellite routing from aircraft-to-aircraft.	- Changes to CMU to accommodate A-A SATCOM. An issue, Iridium is a closed system (currently does not allow developmental access to design) - Future: Candidate for embedded software radio integrating all SATCOM and ground communications systems	SATCOM Infrastructure upgraded to accommodate A-A routing.
10	GEO SATCOM A-A (One Hop through Satellite)	SATCOM Radios & Antennas	GEO SATCOM infrastructure including satellites, NOCs, and satellite control & monitor stations, with on-satellite routing from aircraft-to-aircraft.	- Changes to CMU to accommodate A-A SATCOM. - Future: Candidate for embedded software radio integrating all SATCOM and ground communications systems	SATCOM Infrastructure upgraded to accommodate A-A routing.
11	MEO SATCOM A-A (One Hop through Satellite)	SATCOM Radios & Antennas	MEO SATCOM Infrastructure including satellites, Network Operating Stations, and satellite control & monitor stations, with on-satellite routing from aircraft-to-aircraft.	- Changes to CMU to accommodate A-A SATCOM. - Future: Candidate for embedded software radio integrating all SATCOM and ground communications systems	None. New MEO service.
12	GEO + HEO SATCOM A-A (One Hop through Satellite)	SATCOM Radios & Antennas (requires independent dual antenna pointing system -- higher cost)	GEO + HEO SATCOM Infrastructure including combination of GEO and HEO satellites with coverage in the desired operation coverage region, with NOCs and satellite control & monitor stations, with on-satellite routing from aircraft-to-aircraft.	- Changes to CMU to accommodate A-A SATCOM. - Future: Candidate for embedded software radio integrating all SATCOM and ground communications systems	- Possible change to existing SATCOM GEO configuration to become a hybrid GEO/HEO configuration that can accommodate A-A routing, or potentially new GEO/HEO service with no changes to existing GEO service - Requires a high-bandwidth ground link between both satellite services to complete hybrid circuit

Figure 175 – Infrastructure Required for A-A Candidates (Part 2 of 2)

17.3 Infrastructure for Air-to-Ground Communication Candidates

The nineteen air-to-ground communication candidates have been identified and described previously in this report. The airborne and ground infrastructure needed (including changes to the existing infrastructure) required for each of the A-G candidates is identified in the following three figures (Figure 176 to Figure 178). As *note previously, the term “ground” on these figures includes all the “non-airborne” infrastructure elements.*

This information will be utilized in subsequent A-G communication candidate analyses (e.g., to establish cost or relative cost estimates for the candidates) to be completed in FY2014.

		Infrastructure			
		Note: Depending upon the application(s) supported, additional airborne and/or ground infrastructure may be needed as well as changes to the existing infrastructure.			
		Infrastructure Required		Changes to Existing Infrastructure	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-G	Air-to-Ground (A-G) Comm. Candidates				
1	HF A-G	HF Radio, Power Amplifier (PA), coupler, & Antennas	- HF worldwide A-G communications system infrastructure - Connection to data service provider	- Ability to band aggregate multiple HF channels - Future: Candidate for software radio, more highly integrated with avionics	- Ability to allocate and band aggregate multiple HF channels.
2a	VHF A-G: Use 112 to 118 MHz	VHF Radios & Antennas (112 to 118 MHz)	- VHF A-G communications terrestrial ground system network - Connection to data service provider	- None at minimum - Future: Candidate for software radio, more highly integrated with avionics	- Ground VOR systems vacate 112 to 118 MHz band in regions where it is intended to be used for A-G Com.
2b	VHF A-G: Improve VHF Efficiency	VHF Radios & Antennas (118 to 137 MHz)	- VHF A-G communications terrestrial ground system network - Connection to data service provider	- Improved communications waveform - Future: Candidate for software radio, more highly integrated with avionics	- Improved communications waveform
2c	VHF A-G: Low Band (Ground-to-Air only)	VHF Low Band Radio and Antenna (VHF DTV Freq.)	- DTV transmit ground stations - Terrestrial communication network from service provider to DTV stations - Connection to data service provider	- VHF Low Band Radio (receive-only) and VHF Low Band Antenna suitable for aircraft installation - Future: Candidate for software radio, more highly integrated with avionics	- Additional DTV ground stations to satisfy the needs of aviation - DTV connection with aeronautical service provider
3a	UHF A-G: Aviation Allocation	UHF Radios & Antennas (New UHF aviation allocation)	- UHF A-G communications terrestrial network - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- Connection to service provider - Likely integration of UHF groundstations with VHF groundstations
3b	UHF A-G: High Band (Ground-to-Air only)	UHF Radios & Antennas to cover this new spectrum area (UHF DTV freq.)	- DTV transmit ground stations - Terrestrial communication network from service provider to DTV stations - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- Connection to service provider - Likely integration of UHF groundstations with VHF groundstations
3c	UHF A-G: Other	UHF Radios & Antennas to cover this new spectrum area (e.g., ~800 MHz)	- Future concept, requires ground towers, base stations, connectivity to Network operations - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- Connection to service provider - Likely integration of UHF groundstations with VHF groundstations
4	L-Band A-G	L-Band Radios & Antennas to cover this new spectrum area (e.g., DME band)	- L-Band A-G communications terrestrial network including ground towers and base stations - Connection to data service provider	- Depending upon frequency selected, changes to existing airborne L-band equipment may be needed - Future: Candidate for software radio, more highly integrated with avionics	- New system - Connection to ground data service infrastructure - Likely integration with ADS-B L-band ground station network
5	S-Band A-G	S-Band Radios & Antennas to cover this new spectrum area (New aviation allocation in 2-4 GHz)	- S-Band A-G communications terrestrial network including ground towers and base stations - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- New system - Connection to ground data service infrastructure
6a	C-Band A-G: MLS band	C-Band Radios & Antennas (~5 GHz)	- C-Band A-G communications terrestrial network including ground towers and base stations - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- New system - Connection to ground data service infrastructure
6b	C-Band A-G: Radar Alt.	C-Band Radios & Antennas (4.2 - 4.4 GHz)	- Ground towers, base stations - Connection to data service provider	- If comm can be down without interference to Radar Altimeter function, then no changes to existing airborne infrastructure required, otherwise changes to Radar Altimeter would be necessary. - Future: Candidate for software radio, more highly integrated with avionics	- New system, but may re-use of ground radar facilities - Connection to ground data service infrastructure
6c	C-Band A-G: AeroMACS	C-Band Radios & Antennas (~5 GHz)	- C-Band A-G systems located at major airports with antennas and ground radios - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- New system - Connection to ground data service infrastructure
7	Optical A-G	Optical radio and antennas (~430 to 790 THz)	- Ground tower(s) to elevate and support optical links for on and near airport communications, optical radios, modems - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- New system - Connection to ground aero data service infrastructure
8	Hybrid RF/Optical A-G	- Hybrid RF/Optical radio - RF and Optical antennas	- Ground tower(s) to elevate and support RF/optical links for on and near airport communications, RF/optical radios, modems - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- New system - Connection to ground aero data service infrastructure

Figure 176 – Infrastructure Required for A-G Candidates (Part 1 of 3)

		Infrastructure			
		Note: Depending upon the application(s) supported, additional airborne and/or ground infrastructure may be needed as well as changes to the existing infrastructure.			
		Infrastructure Required		Changes to Existing Infrastructure	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-G	Air-to-Ground (A-G) Comm. Candidates				
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)	Future concept: K to W (likely Ku) band radio and antenna	- New ground towers for K to W band (likely Ku band) Ground-to-Air transmissions, radios, modems - Connection to data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- This is a new system. No changes to existing infrastructure / may reuse ground infrastructure (e.g. Qualcomm Ku band air-to-ground system) - Connection to ground aero data service infrastructure
10	DTV VHF/UHF Network	Future concept: VHF/UHF radio and antenna	- Expanded use of existing DTV VHF/UHF transmitters to communicate from ground to air - Additional towers needed to get coverage in aero desired regions - Connection to aero data service provider	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- Reuse of existing VHF/UHF DTV network (expanded as needed to get coverage in desired regions) - Connection to ground aero data service infrastructure
11a	Cellular Network: Aircell	Aircell radio & antenna (~800 MHz)	- Network of towers, base stations, and network distribution backbone - Connection to aero data services	- At a minimum, no changes to existing airborne infrastructure is required - Future: Additional system availability foreseen, network is becoming loaded to design parameters. Additional spectrum needed and higher order modulation. Candidate for software radio, more highly integrated with avionics	- No changes required, although, future will need additional system bandwidth, higher availability, higher QOS, and link security
11b	Cellular Network: LTE+	Future concept: airmobile in the 700, 1700, or 1900 MHz radio and antenna	- Commercial LTE terrestrial network is available now, however it is not optimized for air mobile use - Connection to aero data services	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- Ground terrestrial network needs to be modified to support aero mobile use - Towers need to have upward facing antennas and interference rejection
11c	Cellular Network: AWS	Future concept: ~1700 MHz uplink client-to-tower and ~2100 MHz downlink tower to client radio, antenna	- Advance Wireless Service (AWS) bands including possible reallocation of 1700 MHz split band and other NTIA identified bands - Connection to aero data services	- New system, no changes to existing airborne infrastructure required - Future: Candidate for software radio, more highly integrated with avionics	- Changes required to support aero-mobile application include upward directed antennas (as opposed to just downward terrestrial), ground backhaul, and connection to aviation data service provider.
12	LEO SATCOM Network (e.g., Iridium Next+)	SATCOM Radios & Antennas	- LEO SATCOM Satellites and ground infrastructure to support (NOC, gateways to terrestrial networks, satellite monitoring & control stations) - Connection to aero data services	- Existing Iridium system, no change required - Future: Iridium NEXT and beyond will however require a new radio module and a larger or possibly a controllable beam directional antenna to achieve the higher data rates exceeding 128 kbps - Future: Candidate for software radio, more highly integrated with avionics	- None to already planned Iridium Next infrastructure. Both Iridium "standard" and Iridium "NEXT" will include a complete ground operations center (3 commercial NOCs globally)
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)	SATCOM Radios & Antennas	- GEO SATCOM Satellites and ground infrastructure to support (NOC, gateways to terrestrial networks, satellite monitoring & control stations) - Connection to data service provider	- New radio Ka, new stack, modem, new antenna (directional) 30" x 60" more or less, L-band back-up, antenna - Future: Candidate for software radio, more highly integrated with avionics	- New proposed Inmarst (Global Express) infrastructure, wide area network connectivity, fiber backbone, three I-5 satellites for global reach (spot beam)
14	MEO SATCOM Network (e.g. GlobalStar+)	SATCOM Radios & Antennas	- MEO SATCOM Satellites and ground infrastructure to support (NOC, gateways to terrestrial networks, satellite monitoring & control stations) - Connection to data service provider	- New system, S-band radio, modem, protocol stack, fuselage antenna - Future: Candidate for software radio, more highly integrating with avionics	- New system, no changes to existing airborne infrastructure required - Connection to ground infrastructure
15	VHF A-A Hopping for long range A-G Com.	VHF Radios & Antennas (118 to 137 MHz)	- Existing VHF terrestrial network (starts communication, prior to A-A hopping using VHF). - Long range communications NOC - Connection to data service provider	- Modifications to VHF Data radios - Future: Candidate for software radio, more highly integrated with avionics	- Connection to ground infrastructure to route long-range A-G comm using VHF A-A hopping network
16	UHF A-A Hopping for long range A-G Com.	UHF Radios & Antennas (New aviation allocation)	- Existing VHF terrestrial network (starts communication, prior to A-A hopping using UHF). - Long range communications NOC - Connection to data service provider	- Modifications to VHF Data radios - New UHF radios and antennas - Future: Candidate for software radio, more highly integrated with avionics	- Connection to ground infrastructure to route long-range A-G comm using UHF A-A hopping

Figure 177 – Infrastructure Required for A-G Candidates (Part 2 of 3)

		Infrastructure			
		Note: Depending upon the application(s) supported, additional airborne and/or ground infrastructure may be needed as well as changes to the existing infrastructure.			
		Infrastructure Required		Changes to Existing Infrastructure	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-G	Air-to-Ground (A-G) Comm. Candidates				
17	L-Band A-A Hopping for long range A-G Comm.	L-Band Radios & Antennas (New aviation allocation in ~1 to 2 GHz -- May be in DME band)	- Existing VHF terrestrial network (starts communication, prior to A-A hopping using L-Band) - Long range communications NOC - Connection to data service provider	- Modifications to VHF Data radios - New L-Band radios and likely antennas - Future: Candidate for software radio, more highly integrated with avionics	- Connection to ground infrastructure to route long-range A-G comm using L-Band A-A hopping network
18	X-Band	X-Band Radios & Antennas (8 to 12 GHz)	- X-Band terrestrial network consisting of ground stations, network operations centers - Connection to data service provider	- New X-band data radio, modem, and antenna or possible changes/ integration with the airborne WxR depending upon the frequency and modulation selected - Future: Candidate for integrated software radios / antennas, directional antennas, integrated with WxR function	- Connection to ground infrastructure to route A-G comm using X-Band Network
19	GEO + HEO SATCOM Network	SATCOM Radios & Antennas (requires independent dual antenna pointing system -- higher cost)	- GEO and HEO SATCOM Satellites and ground infrastructure to support (NOC, gateways to terrestrial networks, satellite monitoring & control stations) - Connection to data service provider	- Directional tracking SATCOM antenna - Future: Candidate for software radio, more highly integrated with avionics	- New system - no changes to existing systems unless system becomes part of a hybrid global system then infrastructure may be partially shared - Connection to ground infrastructure

Figure 178 – Infrastructure Required for A-G Candidates (Part 3 of 3)

18 IDENTIFICATION OF ARCHITECTURE NEEDS, SYSTEMS, AND INTERFACE CHANGES FOR EACH CANDIDATE

This section of the report identifies the architectural needs and an initial list of systems and interfaces that need to change for each of the A-A and A-G communications candidates.

The term "architecture" for the purposes of this section of the report is defined to include the basic structural form of the physical elements of the A-A and A-G communication system candidates.

The term "interface" for the purposes of this section of the report is defined as the boundary between systems.

18.1 Introduction

The future NAS communications A-A and A-G architectures are intended to support air traffic management applications by providing the necessary communications at required quality of service (QOS) levels commensurate with the supported applications. The A-A and A-G communication candidates are as identified and described previously in this report.

18.2 Architecture & Systems/Interface Changes for Air-to-Air Communication Candidates

The architectural needs and initial list of systems and interfaces that need to change for each of the A-A candidates is identified in the following three figures (Figure 179 to Figure 181). *Note on these figures that the column labeled "ground" includes all the "non-airborne" elements, and thus includes identification of satellites for the SATCOM candidates.*

		Architecture Needs & Systems/Interface Changes			
		Note: Depending upon the application(s) supported, additional airborne and/or ground architecture needs and systems/interface changes may be necessary consistent with the operational, performance, and safety requirements for the intended operation(s) and integration with aircraft / ground infrastructure.			
		Architecture Needs		Systems and Interfaces that need to change	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-A	Air-to-Air (A-A) Comm. Candidates				
1	VHF A-A	- At least one VDR radio, modem, antenna or combination antenna. More likely will be integrated with existing dual or triple redundant VHF/VDR radios and antennas that also support A-G communications, which would need the capability to simultaneously listen on multiple frequencies (e.g., one or more A-A com. frequency and one or more A-G com. frequency). - Future: software radio, multi-function / directional antenna, and link security.	None	- VDR and Communications Management Unit (CMU) at a minimum. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize the A-A information, as well as integrate the comm system onto the aircraft. Changes to the radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None
2	UHF A-A	- At least one UHF radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security.	None	- None at a minimum, but likely CMU. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize the A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None
3	L-Band A-A	- At least one L-band radio, modem, and one antenna, or depending upon frequency may be integrated with L-band radios and antennas and require L-band suppression. - Future: software radio, multi-function / directional antenna, and link security.	None	- CMU - L-band interference control systems. Depending upon frequency, directional pointing control may be required to maintain A-A Link without interference to satellites in the shared band. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None
4	S-Band A-A	- At least one S-band A-A radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security.	None	- None at a minimum, could be stand alone. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None
5	C-Band A-A	- At least one C-band A-A radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security.	None	- None at a minimum, could be stand along, but likely at least the CMU. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None

Figure 179 – Architecture Needs & Systems/Interface Changes for A-A Candidates (Part 1 of 3)

		Architecture Needs & Systems/Interface Changes			
		Note: Depending upon the application(s) supported, additional airborne and/or ground architecture needs and systems/interface changes may be necessary consistent with the operational, performance, and safety requirements for the intended operation(s) and integration with aircraft / ground infrastructure.			
		Architecture Needs		Systems and Interfaces that need to change	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-A	Air-to-Air (A-A) Comm. Candidates				
6	X-Band A-A	- At least one X-band A-A radio, modem, and antenna. - Future: software radio and link security.	None	- None at a minimum, but likely CMU and WxR. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None
7	Optical A-A	- At least one radio, modem, and optical antenna [likely will require multiple optical antennas to get coverage all around the aircraft if required for the intended application(s)]. - Future: software radio and link security.	None	- None at a minimum, but likely CMU. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None
8	Hybrid RF/Optical A-A	- At least one radio, modem, and multiple antennas (at least one at RF frequency, and at least one optical). Will likely require multiple optical antennas to get coverage all around the aircraft if required for the intended application(s). - Future: software radio, and link security.	None	- None at a minimum, but likely CMU. - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None
9	LEO SATCOM A-A (One Hop through Satellite)	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Future: software radio and link security	- LEO SATCOM architecture including satellites (>50) for worldwide coverage, several Network Operating Centers (NOCs), and several satellite control and monitor stations. - The system should be capable of direct routing of messages from aircraft-to-aircraft. - Note that at least 50 LEO satellites are architecturally necessary for worldwide coverage (e.g., Iridium has 66 satellites plus 6 in-orbit spares).	- CMU - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	- Satellite not a bent pipe. Onboard switch to process and route information, eliminating the need (and latency, and additional BW) associated with NOC routing.
10	GEO SATCOM A-A (One Hop through Satellite)	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Future: software defined radio and link security	- GEO SATCOM architecture including at least 1 GEO satellite for NAS coverage and 3 for "worldwide" coverage (between ~ +/-70 degrees latitude) [additional satellites as needed for redundancy], several Network Operating Centers (NOCs), and several satellite control & monitor stations. - System should be capable of direct routing of messages from aircraft-to-aircraft.	- CMU - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	- Satellite not a bent pipe. Onboard switch to process and route information, eliminating the need (and latency, and additional BW) associated with NOC routing.
11	MEO SATCOM A-A (One Hop through Satellite)	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Future: software radio and link security	- MEO SATCOM architecture including at least 10 satellites for "worldwide" coverage [would like additional satellites for redundancy], several NOCs, and several satellite control & monitor stations. with routing from aircraft-to-aircraft. - System should be capable of direct routing of messages from aircraft-to-aircraft.	- CMU - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	None, new MEO system.

Figure 180 – Architecture Needs & Systems/Interface Changes for A-A Candidates (Part 2 of 3)

		Architecture Needs & Systems/Interface Changes			
		Note: Depending upon the application(s) supported, additional airborne and/or ground architecture needs and systems/interface changes may be necessary consistent with the operational, performance, and safety requirements for the intended operation(s) and integration with aircraft / ground infrastructure.			
		Architecture Needs		Systems and Interfaces that need to change	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-A	Air-to-Air (A-A) Comm. Candidates				
12	GEO + HEO SATCOM A-A (One Hop through Satellite)	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Dual independent antenna pointing system - Future: software defined radio and link security	- Augmented GEO + HEO satellite system architecture including combination of GEO and HEO satellites with coverage in the desired operation coverage volume, several NOCs, and several satellite control & monitor stations, with routing from aircraft-to-aircraft. Includes at least 1 satellite for U.S. NAS coverage or 3 GEO satellites for "worldwide" coverage below within ~ +/-70 degrees latitude, plus several (>=3) HEO satellites for north polar coverage. - System should be capable of direct routing of messages from aircraft-to-aircraft.	- CMU - Depending upon the application(s) supported and aircraft architecture, changes may be needed to control, display, and generate/utilize A-A information, as well as integrate the comm system onto the aircraft. Changes to the CMU, radio cabinet, radio tuning, displays, traffic computer, FMS, WxR, avionics busses, and other systems are possible.	- Satellite not a bent pipe. Onboard switch to process and route information, eliminating the need (and latency, and additional BW) associated with NOC routing.

Figure 181 – Architecture Needs & Systems/Interface Changes for A-A Candidates (Part 3 of 3)

18.3 Architecture & Systems/Interface Changes for Air-to-Ground Communication Candidates

The architectural needs and initial list of systems and interfaces that need to change for each of the A-G candidates is identified in the following four figures (Figure 182 to Figure 185). As *noted previously, the term "ground" on these figures includes all the "non-airborne" elements.*

		Architecture Needs & Systems/Interface Changes			
		Note: Depending upon the application(s) supported, additional airborne and/or ground architecture needs and systems/interface changes may be necessary consistent with the operational, performance, and safety requirements for the intended operation(s) and integration with aircraft / ground infrastructure.			
		Architecture Needs		Systems and Interfaces that need to change	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-G	Air-to-Ground (A-G) Comm. Candidates			Depending upon the application(s) supported, additional airborne systems/interface changes may be needed to control, display, and to generate/utilize the A-G information. Changes to the CMU, displays, traffic computer, FMS, WxR, or other systems are possible.	Depending upon the application(s) supported and the sources and users of the A-G information, additional ground systems and interfaces may need to be changed.
1	HF A-G	- Depending upon intended application(s), likely dual HF radios, modems, PAs, couplers, and antennas. - Future: software radio and link security	- Same as today's HF worldwide system architecture, with set of ~15 HF ground stations, wide area ground network, central processing, and interfaces with at least ATC and AOC.	- HF data radio capable of communications on band aggregated channels. - Interface with Communications Management Unit (CMU).	- HF ground systems to dynamically allocate and communicate on aggregated channels - Ground interconnect to FAA data network and AOC
2a	VHF A-G: Use 112 to 118 MHz	- Airborne VHF radio and antennas that can also meet the requirements of operating in the 112 to 118 MHz band. - Future: software radio, multi-function / directional antenna, and link security	- Ground VHF network built to accommodate operationally required coverage volume. To cover all of the NAS in a redundant configuration requires ~650 ground stations. - Ground VHF radio and antennas that can also meet the requirements of operating in the 112 to 118 MHz band, interconnected with a wide area ground network, and interfaces with ATC and AOC.	- VHF radios (including tuning)	- Ground systems that can utilize the 112 to 118 MHz, in addition to the 118 to 137 MHz. It may require VHF Comm radios to have additional FM immune receivers (per ILS LOC and VOR requirements), as it is closer to FM broadcasters. - Ground interconnect to FAA data network and AOC
2b	VHF A-G: Improve VHF Efficiency	- Same as today's, at least one VHF radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security	- Same as VHF ground network, which is built to accommodate operationally required coverage volume. To cover all of the NAS in a redundant configuration requires ~650 ground stations.	- VHF radios	- VHF radios
2c	VHF A-G: Low Band (Ground-to-Air only)	- At least one VHF low-band radio, modem, and one VHF low-band antenna - Future: software radio, multi-function / directional antenna, and link security	- Reuse existing DTV transmitter stations to insert a secure proprietary Ground-to-Air broadcast (~1 Mbps per today's standard). - The number of stations could just utilize the existing DTV transmit stations (includes at least all major cities / airport regions), or could lay down a larger network to provide greater coverage. - Network communication backbone from service provider to DTV transmit stations	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- Service provider to serve data to DTV stations for broadcast - DTV stations to receive and broadcast aviation data
3a	UHF A-G: Aviation Allocation	- At least one UHF radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security	- Ground UHF network built to accommodate operationally required coverage volume. To cover all of the NAS in a redundant configuration, would require approx. the same number of stations as today's VHF (~650 ground stations). - Network communications from service provider	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link
3b	UHF A-G: High Band (Ground-to-Air only)	- At least one UHF radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security	- New spectrum allocations, towers spaced ~250 miles, ground radios, modems, access to backbone connection to aero services provider (e.g., FAA, AOC, etc.)	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link
3c	UHF A-G: Other	- At least one UHF radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security	- New spectrum allocations, towers spaced ~250 miles, ground radios, modems, access to backbone connection to aero services provider (e.g., FAA, AOC, etc.)	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link
4	L-Band A-G	- At least one L-Band radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security	- Ground network of towers spaced ~200 miles (~800 to cover NAS), ground radios, modems, access to backbone to aero services provider (e.g., FAA, AOC)	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link - May leverage ADS-B L-band ground station network
5	S-Band A-G	- At least one S-Band radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security	- New system - requires ground towers spaced ~150 miles or closer to accommodate range limit, ground radios, modems, access for backbone connection to aero services provider (e.g., FAA, AOC)	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link

Figure 182 – Architecture Needs & Systems/Interface Changes for A-G Candidates (Part 1 of 4)

		Architecture Needs & Systems/Interface Changes			
		Note: Depending upon the application(s) supported, additional airborne and/or ground architecture needs and systems/interface changes may be necessary consistent with the operational, performance, and safety requirements for the intended operation(s) and integration with aircraft / ground infrastructure.			
		Architecture Needs		Systems and Interfaces that need to change	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-G	Air-to-Ground (A-G) Comm. Candidates			Depending upon the application(s) supported, additional airborne systems/interface changes may be needed to control, display, and to generate/utilize the A-G information. Changes to the CMU, displays, traffic computer, FMS, WxR, or other systems are possible.	Depending upon the application(s) supported and the sources and users of the A-G information, additional ground systems and interfaces may need to be changed.
6a	C-Band A-G: MLS band	- At least one C-Band radio, modem, and antenna. - Future: software radio, multi-function / directional antenna, and link security	- New system - requires ground towers spaced ~130 miles or closer to accommodate range limit, ground radios, modems, access for backbone connection to aero services provider (e.g., FAA, AOC)	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link
6b	C-Band A-G: Radar Alt.	- At least one C-Band radio, modem, and antenna. - Future: integrated with radar altimeter, software radio, multi-function / directional antenna, and link security	- New system - requires ground towers spaced ~130 miles or closer to accommodate range limit, ground radios, modems, access for backbone connection to aero services provider (e.g., FAA, AOC).	- Possible change to radar altimeter - Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link
6c	C-Band A-G: AeroMACS	- At least one C-Band radio, modem, and antenna. - Future: software radio, and link security	- New system - requires ground antennas sited to obtain coverage at major airports (short range system) - Communication backbone to service provider	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link
7	Optical A-G	- At least one radio, modem, and multiple optical antennas for 360 degree coverage. - Future: software radio and link security	- RF and Optical transmitter / receiver hybrid system - Free-space optical antenna, multi-aperture, adaptive optics, deformable mirror, beam scintillation adaptive systems - Ground tower(s) to elevate and support optical link for LOS communication on and near airport vicinity - Ground tower(s) for RF link - Communications backbone to service provider	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- New optical system - Interface with aero data service provider
8	Hybrid RF/Optical A-G	- At least one radio, modem, and optical and RF antennas. - Future: software radio and link security	- Optical transmitter / receiver system - Free-space optical antenna, multi-aperture, adaptive optics, deformable mirror, beam scintillation adaptive systems - Ground tower(s) to elevate and support optical link for LOS communication on and near airport vicinity - Communications backbone to service provider	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- New RF/optical system - Interface with aero data service provider
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)	- At least one radio, modem, and antenna. - Future: software radio, directional antenna, and link security	- New ground towers spaced / optimized for K to W band (likely Ku band) propagation and SATCOM avoidance - Requires new tower system commensurate with shorter wavelengths and required antenna pointing (North) to avoid interfering with SATCOM	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- New system - Interface with aero data service provider
10	DTV VHF/UHF Network	- At least one radio, modem, and antenna. - Future: software radio and link security	- Ground network of towers, radios, ground fiber backhaul - Connection to aero services provider	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- Additional DTV towers and radios to cover aero desired coverage volume - Interface with aero data service provider

Figure 183 – Architecture Needs & Systems/Interface Changes for A-G Candidates (Part 2 of 4)

		Architecture Needs & Systems/Interface Changes			
		Note: Depending upon the application(s) supported, additional airborne and/or ground architecture needs and systems/interface changes may be necessary consistent with the operational, performance, and safety requirements for the intended operation(s) and integration with aircraft / ground infrastructure.			
		Architecture Needs		Systems and Interfaces that need to change	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-G	Air-to-Ground (A-G) Comm. Candidates			Depending upon the application(s) supported, additional airborne systems/interface changes may be needed to control, display, and to generate/utilize the A-G information. Changes to the CMU, displays, traffic computer, FMS, WxR, or other systems are possible.	Depending upon the application(s) supported and the sources and users of the A-G information, additional ground systems and interfaces may need to be changed.
11a	Cellular Network: Aircell	- At least one radio covering the 800 MHz Aircell band(s), modem, and antenna. - Future: software radio and link security	- Ground network of towers, radios, ground fiber backhaul - Connection to aero services provider - Additional system availability, bandwidth, and link security need for use safety services	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- No changes required at a minimum, although, future will need additional System bandwidth, higher availability, higher QOS, and link security which will require changes to network, communication protocols, backhaul network
11b	Cellular Network: LTE+	- LTE software radio that covers the LTE cell band(s), Doppler correction, modem, protocol stack, broader band UHF controllable beam directional antenna - *Note that without changes to existing ground network parameters, link will have unacceptable remaining timing and interference issues* - Future: System integrated with avionics	- Ground network, towers spaced with optimal cell size based upon frequency and BW demands (today ~5 to 100 km), ground backhaul, connection to aero service provider	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- Requires modifications to the ground systems to support aero mobile use. Providers not generally interested - concern for air-to-ground interference - Requires network redesign
11c	Cellular Network: AWS	- At least one AWS radio, modem, controllable beam directional antenna - Future: integrated software radio, and link security	- Ground network, towers, upward directed antennas, Doppler corrected radios, ground fiber backhaul, connection to aero service provider	- Interface between data radio and on-aircraft consumer of the data (e.g., FMS, Traffic computer, displays, etc.)	- Additional backhaul network capacity - Antenna systems - Connection to aero service provider
12	LEO SATCOM Network (e.g., Iridium Next+)	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Future: software radio, optical radio, and link security	- LEO SATCOM architecture including satellites (>50) for worldwide coverage, several Network Operating Centers (NOCs), and several satellite control and monitor stations. - Note that at least 50 LEO satellites are architecturally necessary for worldwide coverage (e.g., Iridium has 66 satellites plus 6 in-orbit spares).	- At a minimum, the SATCOM radios and CMU	- None at a minimum - Likely change to have additional backhaul network capacity
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Future: software radio, optical radio, and link security	- GEO SATCOM architecture including at least 1 GEO satellite for NAS coverage and 3 for "worldwide" coverage (between ~ +/-70 degrees latitude) [additional satellites as needed for redundancy], several Network Operating Centers (NOCs), and several satellite control & monitor stations.	- At a minimum, the SATCOM radios and CMU	- None at a minimum - Likely change to have additional backhaul network capacity
14	MEO SATCOM Network (e.g. GlobalStar+)	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Future: software radio, optical radio, and link security	- MEO SATCOM architecture including at least 10 satellites for "worldwide" coverage [would like additional satellites for redundancy], several NOCs, and several satellite control & monitor stations - Communications backbone link to service provider	- At a minimum, the SATCOM radios and CMU	- Connection to backbone network
15	VHF A-A Hopping for long range A-G Com.	- At least one VHF A-A hopping radio, modem, and antenna - Future: software radio and link security, VHF directional antenna	- Ground VHF terrestrial network for LOS communications with "close" aircraft [~650 VHF ground stations cover existing NAS] - Long Range A-G communications router to select HF, SATCOM, or A-A hopping - Communications backbone link to service provider	- At a minimum, the VHF Data radio	- Long Range A-G communications routing to select HF, SATCOM, or A-A hopping

Figure 184 – Architecture Needs & Systems/Interface Changes for A-G Candidates (Part 3 of 4)

Architecture Needs & Systems/Interface Changes

Note: Depending upon the application(s) supported, additional airborne and/or ground architecture needs and systems/interface changes may be necessary consistent with the operational, performance, and safety requirements for the intended operation(s) and integration with aircraft / ground infrastructure.

		Architecture Needs		Systems and Interfaces that need to change	
#	Communications Candidates	Airborne	Ground	Airborne	Ground
A-G	Air-to-Ground (A-G) Comm. Candidates			Depending upon the application(s) supported, additional airborne systems/interface changes may be needed to control, display, and to generate/utilize the A-G information. Changes to the CMU, displays, traffic computer, FMS, WxR, or other systems are possible.	Depending upon the application(s) supported and the sources and users of the A-G information, additional ground systems and interfaces may need to be changed.
16	UHF A-A Hopping for long range A-G Com.	- At least one UHF A-A hopping radio, modem, and antenna - Future: software radio and link security, UHF directional antenna	- Ground VHF terrestrial network for LOS communications with "close" aircraft [~650 VHF ground stations cover existing NAS] - Long Range A-G communications router to select HF, SATCOM, or A-A hopping (first A-G leg is VHF, then A-A UHF hopping) - Communications backbone link to service provider	- At a minimum, the VHF Data radio (communicating to UHF hopping radio) and CMU - New UHF radio / antenna	- Long Range A-G communications routing to select HF, SATCOM, or A-A hopping
17	L-Band A-A Hopping for long range A-G Comm.	- At least one L-Band A-A hopping radio, modem, and antenna - Future: software radio and link security, L-Band directional antenna	- Ground VHF terrestrial network for LOS communications with "close" aircraft [~650 VHF ground stations cover existing NAS] - Long Range A-G communications router to select HF, SATCOM, or A-A hopping (first A-G leg is VHF, then A-A L-Band hopping) - Communications backbone to service provider	- At a minimum, the VHF Data radio (communicating to L-Band hopping radio) and CMU - New or modifications to L-Band radios	- Long Range A-G communications routing to select HF, SATCOM, or A-A hopping
18	X-Band	- At least one X-band A-G radio, modem, and antenna. - Future: software radio and Link security.	- X-band towers, radios in and around the major airports for short-range surface/terminal area communications - Communications backbone link to service provider	- At a minimum, CMU and likely the WxR	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Com Link and have additional backhaul network capacity
19	GEO + HEO SATCOM Network	- At least one SATCOM radio, modem, and steerable antenna (e.g., ESA electronic steerable array) - Dual independent antenna pointing system - Future: software defined radio, optical radio, and Link security	- Augmented GEO + HEO satellite system architecture including combination of GEO and HEO satellites with coverage in the desired operation coverage volume, several NOCs, and several satellite control & monitor stations, with routing from aircraft-to-aircraft. Includes at least 1 satellite for U.S. NAS coverage or 3 GEO satellites for "worldwide" coverage below within ~ +/-70 degrees latitude, plus several (>=3) HEO satellites for north polar coverage.	- At a minimum, the SATCOM radios and CMU	- None at a minimum - Likely change to interface with service provider to select appropriate A-G Link and have additional backhaul network capacity

Figure 185 – Architecture Needs & Systems/Interface Changes for A-G Candidates (Part 4 of 4)

19 IDENTIFICATION AND EVALUATION OF THREATS, VULNERABILITIES, RISKS, AND MITIGATION METHODS

This section identifies and evaluates the threats, vulnerabilities, and resulting risks of A-A and A-G communication systems and identifies methods than may be used to mitigate the vulnerabilities in the computing environment and communication technologies. Systems such as A-A and A-G communications are subject to serious threats that can have adverse effects on organizational operations and assets, individuals, other organizations, and the Nation by exploiting both known and unknown vulnerabilities to compromise the confidentiality, integrity, or availability of the information being processed, stored, or transmitted by those systems. The threats to such systems can include purposeful attacks, environmental disruptions, human/machine errors, and structural failures, and can result in harm to not only the users of the air transportation system and those on the ground, but also to the national, international, and economic interests.

This assessment has followed the guidelines used to perform such risk assessments as documented in industry safety assessment standards including:

- NIST Special Publication 800-30 (Revision 1), "Information Security Guide for Conducting Risk Assessments," United States Department of Commerce, September 2012,
- NIST Special-Publication 800-53 (Final Public Draft Revision 4), "Security and Privacy Controls for Federal Information Systems and Organizations," United States Department of Commerce, April 2013,
- FIPS Publication 199, "Standards for Security Categorization of Federal Information and Information Systems," U.S. Department of Commerce, February 2004,
- Airworthiness Security Process Specification, RTCA/EUROCAE, DO-326A (Draft Version Dated October 15, 2012), and
- ARINC Report 811, "Commercial Aircraft Information Security Concepts of Operation and Process Framework," AEEC, December 2005.

Other National Institute of Standards and Technology (NIST), RTCA/EUROCAE, and Federal Information Processing Standards Publications (FIPS PUB) guidance and standards were also leveraged in the assessment process.

Furthermore, the assessment of A-A and A-G communications in this section has leveraged the security assessment process documented by NASA as part of their assessments of the Control and Non-payload Communications (CNPC) system intended to support UAS Integration in the NAS. *[Reference: "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, by NASA Glenn Research Center.]*

While the assessment described in this section broadly analyzes the threats, vulnerabilities, risks, and mitigations for the entire A-A and A-G communications system, the primary focus is on identifying and evaluating the threats, vulnerabilities, risks, and mitigations in the communications computing environment and in the communication technologies areas.

Risk assessments should not simply be one-time activities that provide permanent and definitive information for decision makers to guide and inform responses to information security risks. Rather, risk assessments should be utilized on an ongoing basis throughout the system life cycle, not just during the system development cycle as risks change over time (e.g., new threats, new vulnerabilities, probabilities change over time, etc.).

The subsections below contain:

- Background information and definitions relevant for this security assessment (Section 19.1)
- Security challenges and airworthiness security (Section 19.2)
- Communications systems architectures for the purposes of this initial security assessment (Section 19.3)
- Security objectives and characterizations for A-A and A-G communication systems (Section 19.4)
- Threats (Section 19.5)
- Vulnerabilities (Section 19.6)
- Evaluation of Threats/Vulnerabilities [i.e., Risk Assessment] (Section 19.7)
- Methods to Mitigate Vulnerabilities / Security Controls (Section 19.8)
- NAS Information System Security Objectives per ARINC Report 811 (Section 19.9)
- Assessment Conclusion (Section 19.10)

19.1 Background and Definitions for Threats, Vulnerabilities, Risks, and Mitigations

The subsections below provide background information and definitions for the terms threats, vulnerabilities, risks, and mitigations in the context of an information security risk assessment for the A-A and A-G communication technology candidates.

19.1.1 Background

Today's A-A and A-G communication systems are largely implemented using federated systems, isolated from cabin and passenger-related systems.

As NAS communication and information systems become more networked, there is the potential for increased cyber-attacks, not unlike those experienced by corporate information systems. Figure 186 and Figure 187 provide high-level diagrams illustrating notionally the networked aircraft communication and information systems, domains, and interconnections.

The A-A and A-G communication links, if unprotected, are vulnerable to attack by a variety of threats both internal and external to the aircraft. Attackers will attempt to exploit vulnerabilities in the communication/information systems, including for example, any interfaces between passenger systems and cabin systems and between cabin systems and cockpit systems.

Aircraft information security is necessary to mitigate the risk of external and internal attacks to an acceptable level, to protect aircraft information systems, and to protect the confidentiality, integrity, and availability of information processed by those systems.

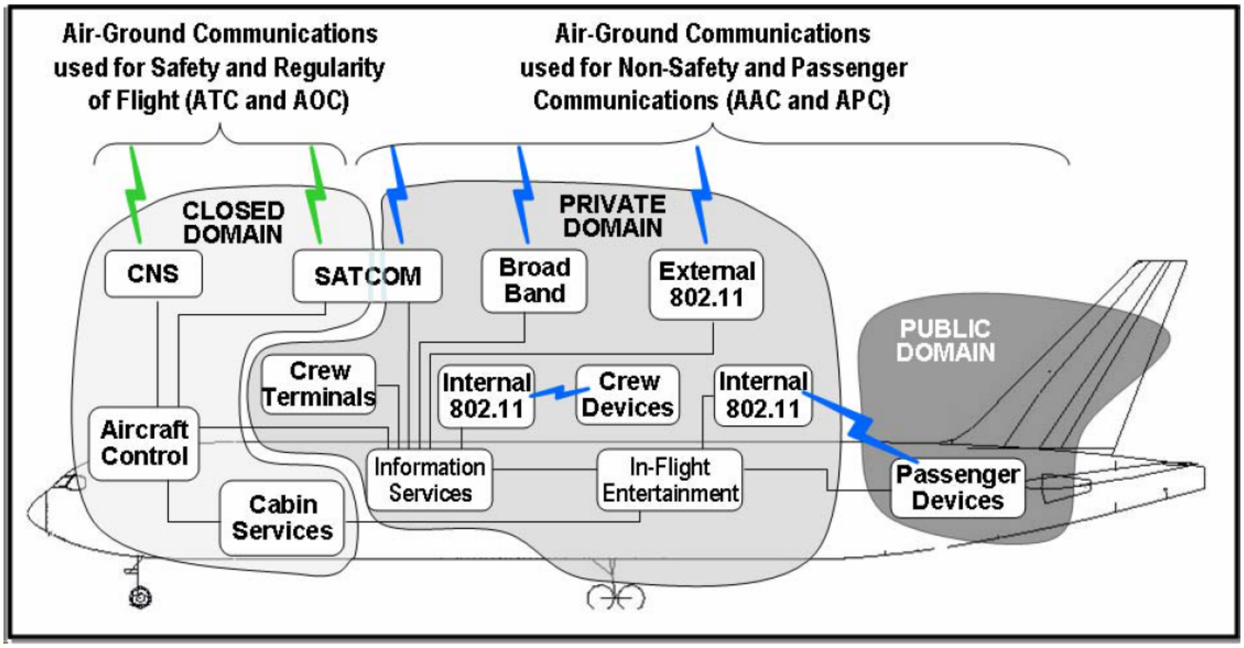


Figure 186 – Networked Aircraft Communication and Information Systems and Domains

[Reference: Commercial Aircraft Information Security – An Overview of ARINC Report 811, by M. Olive, R. Oishi, and S. Arentz, 25th Digital Avionics Systems Conference, IEEE, October 15, 2006, minor modification of figure from ARINC Report 811, "Commercial Aircraft Information Security Concepts of Operation and Process Framework," AEEC, December 20, 2005, Figure 2-3.]

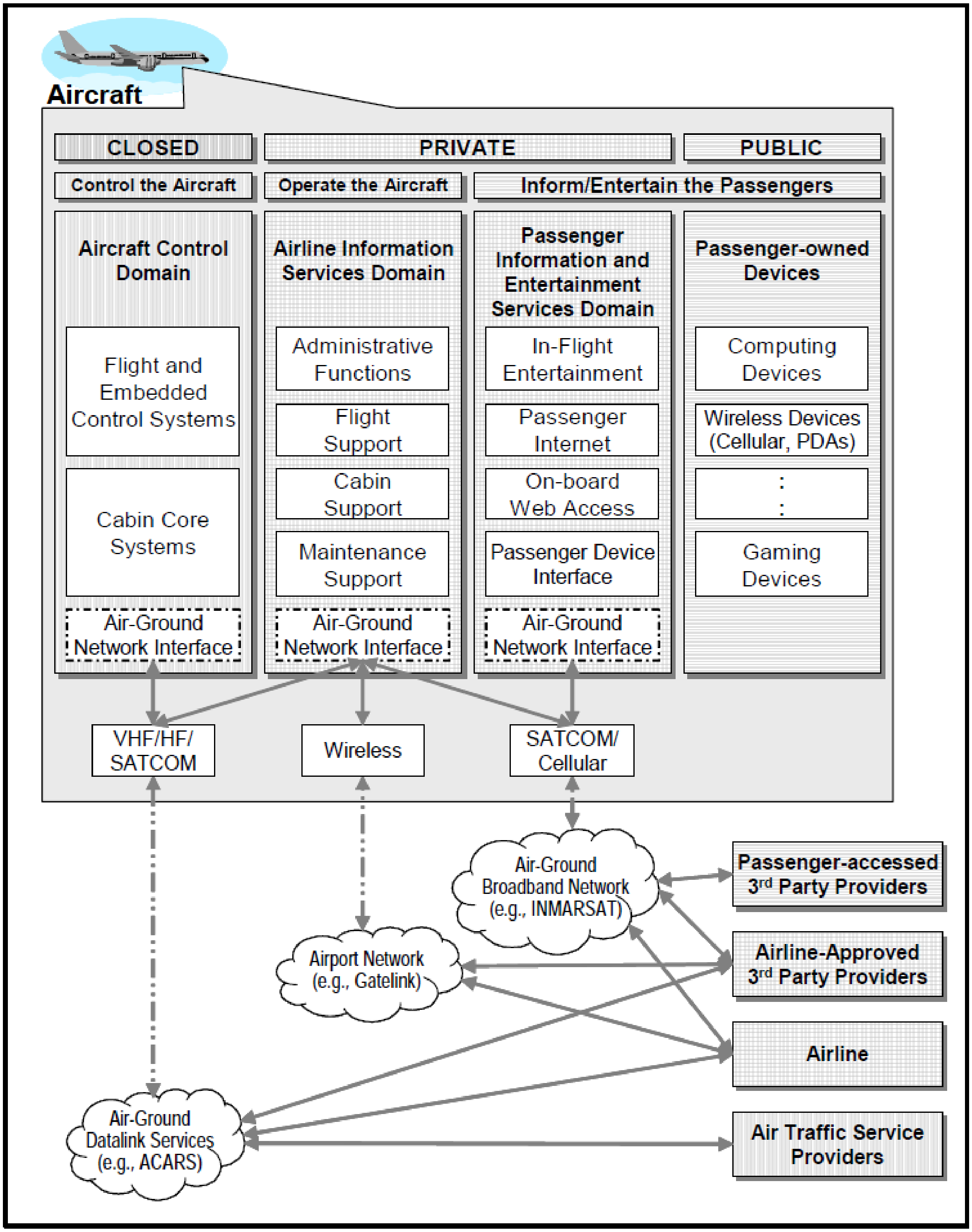


Figure 187 – Aircraft Network Domains and Interconnections

[Reference: ARINC Report 811, "Commercial Aircraft Information Security Concepts of Operation and Process Framework," AEEC, December 20, 2005, Figure 2.]

19.1.2 Threats

A threat is any circumstance or event with the potential to adversely impact organizational operations and assets, individuals, other organizations, or the Nation through an information system via unauthorized access, destruction, disclosure, or modification of information, and/or denial of service. Threat events are caused by threat sources. A threat source is characterized as: (i) the intent and method targeted at the exploitation of a vulnerability; or (ii) a situation and method that may accidentally exploit a vulnerability. *[Reference: NIST SP-800-30 (Rev. 1), page 8.]*

In general, types of threat sources include: (i) hostile cyber or physical attacks; (ii) human errors of omission or commission; (iii) structural failures of organization-controlled resources (e.g., hardware, software, environmental controls); and (iv) natural and man-made disasters, accidents, and failures beyond the control of the organization.

A threat is the potential for a particular threat-source to successfully exercise a particular vulnerability.

A threat can be either "intentional" (i.e., intelligent; e.g., an individual cracker or a criminal organization) or "accidental" (e.g., the possibility of a computer malfunctioning, or the possibility of an "act of God" such as an earthquake, a fire, or a tornado) or otherwise result from a circumstance, capability, action, or event. A known threat-source does not present a risk when there is no vulnerability that can be exercised.

Practically anyone and anything can, under the “right” circumstances, be an attacker (i.e., the source of a threat action). Attackers can take one or more of the following threat actions against an asset:

- Access – simple unauthorized access
- Misuse – unauthorized use of assets (e.g., identity theft, setting up a porn distribution service on a compromised server, etc.)
- Disclose – the threat agent illicitly discloses sensitive information
- Modify – unauthorized changes to an asset
- Deny access – includes destruction, theft of a non-data asset, etc.

The attack (also called threat action) can be active when the attacker attempts to alter system resources or affect their operation: so it compromises Integrity or Availability. An “attack” can also be passive, in that it attempts to learn or make use of information from the system but does not affect system resources: so it compromises Confidentiality.

Each of these threat actions affects different assets differently, which drives the degree and nature of the potential risk associated with the threat.

Figure 188 illustrates the relationship between an attacker (which is the source of threat actions), vulnerability, and threat consequences.

```
+ - - - - - - - - - - - -  +  + - - - - - - +  + - - - - - - - - - - -+
| An Attack:              |  | Counter-    |  | A System Resource:   |
| i.e., A Threat Action   |  |  measure(s) |  | Target of the Attack |
| +----------+            |  |             |  | +-----------------+  |
| |          |<=================||<=========                     |  |
| | Attacker |  Passive   |  |             |  | |  Vulnerability  |  |
| |          |<=================>||<========>                    |  |
| |          | or Active  |  |             |  | +-------|||-------+  |
| +----------+  Attack    |  |(one form of |  |          VVV         |
|                         |  | mitigation) |  | Threat Consequences  |
+ - - - - - - - - - - - -  +  + - - - - - - +  + - - - - - - - - - - -+
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Figure 188 – Relationship Between Threat Action, Vulnerability, and Consequences

[Reference: "Internet Engineering Task Force, Network Working Group, RFC 2828," The Internet Society, by R. Shirey, May 2000, page 12.]

19.1.3 Vulnerabilities

A vulnerability is a weakness in an information system, its system security procedures, internal controls, or implementation that could be exploited by a threat source. Most information system vulnerabilities can be associated with security controls that either have not been applied (either intentionally or unintentionally), or have been applied, but retain some weakness. However, it is also important to allow for the possibility of emergent vulnerabilities that can arise naturally over time as organizational missions/business functions evolve, environments of operation change, new technologies proliferate, and new threats emerge. *[Reference: NIST SP-800-30 (Rev. 1), page 9.]*

An attacker uses the features and weaknesses of the system itself to attack it and other systems. These exploitable conditions of the assets of the system are its vulnerabilities. There are four classes of vulnerabilities as identified in Figure 189. This above definition of vulnerabilities excludes conditions caused by the attack (those are the threat conditions), but includes both intended and unintended conditions.

Vulnerabilities can arise through deficiencies in following *[Reference: RTCA DO-326A (draft), Section 4.2.4]*:

- Requirements: systems can possess all the required functions and features but still contain vulnerabilities that render it unsuitable or ineffective with respect to security due to incomplete, invalid, or inconsistent requirements.
- Development: vulnerabilities can be introduced as a result of poor development standards, incorrect design choices, or by systems not meeting their specifications.
- Operations: systems can still be constructed correctly to a correct specification but vulnerabilities can still exist as a result of inadequate controls on the operation.
- Security environment: systems can be constructed correctly to a correct specification with adequate controls on the operation, but vulnerabilities can be introduced as a result of inadequate controls upon external organizations, external systems, or external interfaces.

Class of Vulnerability	Description
Inherent vulnerabilities	Intended conditions that can be exploited by an attack
Potential for vulnerabilities	Identified potential for unintended conditions in an implemented system which could result in an expressed vulnerability
Expressed vulnerabilities	Identified unintended conditions which can result in the failure of a security countermeasure or that can be exploited by an attack
Well-known vulnerabilities	Vulnerabilities that have been documented in previous use of some portion of the system

Figure 189 – Classes of Vulnerabilities

[Reference: RTCA DO-326A (draft), Table 4-3.]

19.1.4 Risks

Risk is the overall negative impact to the system when considering the probability that a vulnerability is exploited by a threat-source.

<u>Risk</u> is defined to be a measure of the extent to which an entity is threatened by a potential circumstance or event, and is typically a function of: (i) the adverse impacts that would arise if the circumstance or event occurs; and (ii) the likelihood of occurrence.

<u>Information security risks</u> are those risks that arise from the loss of confidentiality, integrity, or availability of information or information systems and reflect the potential adverse impacts to organizational operations (i.e., mission, functions, image, or reputation), organizational assets, individuals, other organizations, and/or the Nation. *[Reference: NIST SP-800-30 (Rev. 1), page 6.]*

The level of <u>impact</u> from an information threat event is the magnitude of harm that can be expected to result from the consequences of unauthorized disclosure of information, unauthorized modification of information, unauthorized destruction of information, or loss of information or information system availability. *[Reference: NIST SP-800-30 (Rev. 1), page 11.]*

<u>Risk identification</u> is the process by which risks to the system are identified and prioritized so appropriate resources are allocated to mitigate the overall impact to the system. Assessing risk requires the analysis of threats and vulnerabilities to determine the extent to which circumstances or events could adversely impact the system and the likelihood that such circumstances or events will occur.

Figure 190 illustrates a generic risk model including the key risk factors discussed above and the relationship among the factors.

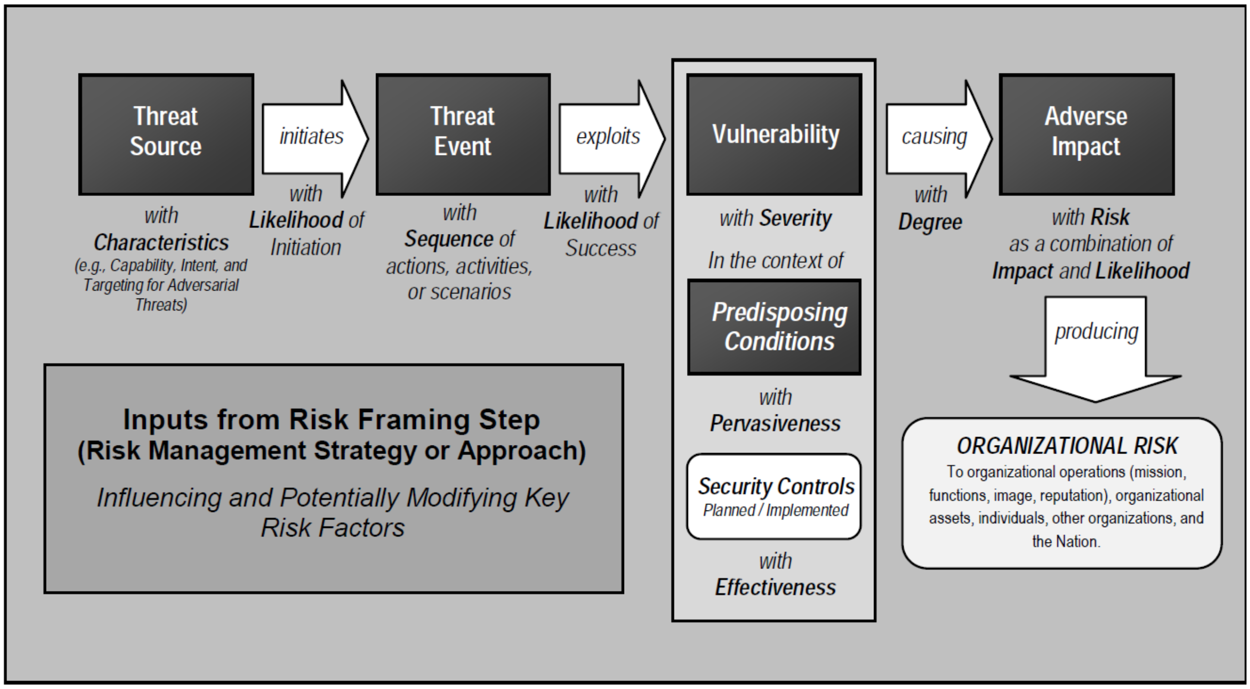


Figure 190 – Generic Risk Model

[Reference: NIST SP-800-30 (Rev. 1), "Information Security Guide for Conducting Risk Assessments," September 2012, Figure 2, page 12.]

19.1.5 Mitigations / Security Controls

Mitigation is the effort to avoid (totally eliminate), lessen the likelihood, and/or reduce the impact that a potential threat has on the system. Given a specific security risk, security controls can be identified to mitigate the risk.

The selection and implementation of security controls for communication and information systems as well as organizations are important tasks that can have major implications on the operations and assets of organizations as well as the welfare of individuals and the Nation. Security controls are the safeguards/countermeasures prescribed for communication and information systems or organizations that are designed to: (i) protect the confidentiality, integrity, and availability of information that is processed, stored, and transmitted by those systems/organizations; and (ii) satisfy a set of defined security requirements. *[Reference: NIST SP-800-53 (draft Rev. 4), page 1.]*

19.2 Security Challenges and Airworthiness Security

Threats to A-A and A-G communication systems can be categorized as to one or more security challenge that they might cause to the system include the following:

- Integrity: Data must be protected from either deliberate or accidental modification.
- Authentication: All parties transmitting air traffic management data must be trusted and able to prove their identity.

- Non-repudiation: Communicating parties cannot deny the transmission of safety-relevant air traffic management decisions. *[The "non-repudiation" challenge is discussed in this report using the terminology "denial of services."]*
- Availability/Continuity: Services offered by the new air traffic management infrastructure must remain reliable and accessible to all authorized parties. *[The "availability/continuity" challenge is discussed in this report using the terminology "denial of services."]*
- Data Separation: While the secrecy of air traffic management data may not be paramount, shared functional resources must provide assurance that the data belonging to one safety critical function not be subverted by another function. *[The "data separation" challenge is discussed in this report using the terminologies of "loss of integrity" and "denial of services."]*
- Confidentiality: Securing data from unauthorized access. Some users (e.g., airlines) may want at least some of their information on the communications to be private/proprietary.

Airworthiness security is the protection of the airworthiness of an aircraft from the information security threat: harm due to human action (accidental, casual, or purposeful) using access, use, disclosure, disruption, modification, or destruction of data and/or data interfaces. This includes the consequences of malware and forged data and of access of other systems to aircraft systems. [*Reference: draft version of RTCA/DO-326A.*]

19.3 Communications Architectures for the Purposes of Security Assessment

Two basic communications architectures have been analyzed for supporting both A-A and A-G communications: 1) direct path communications, and 2) networked communications. These baseline architectures are intended to be generic system instantiations in an attempt to reduce all of the various communications architectures associated with each candidate technology into a simplified representative configuration for the purposes of this threats /vulnerabilities /mitigations /risks security assessment.

Relevant to A-A communications, the architectures depicted in Figure 191 and Figure 192 illustrate direct A-A communications paths between two aircraft. These architectures, for the purposes of this assessment, adequately describe all the A-A candidates. The technology candidates represented by the Figure 191 architecture include all direct A-A communications whereby each aircraft has transmitters and receivers that transmit information directly between the aircraft without any intervening node (e.g., A-A candidates 1 to 8). The technology candidates represented by the Figure 192 architecture include the set of direct A-A communications candidates whereby each aircraft has transmitters and receivers that transmit information between the aircraft with an intervening node that is either satellite based (e.g., candidates A-A candidates 9 to 12) or where there is an intervening terrestrial FAA system (like ADS-R which rebroadcasts information received on one data link to a second data link, which potentially could be used for candidates 1 to 8). The architecture depicted in Figure 193 is a networked A-A communications path between two aircraft. Networked A-A communications are possible, but no candidate has been identified to date that utilizes such a communication path, primarily because no operational need has been identified for such a configuration.

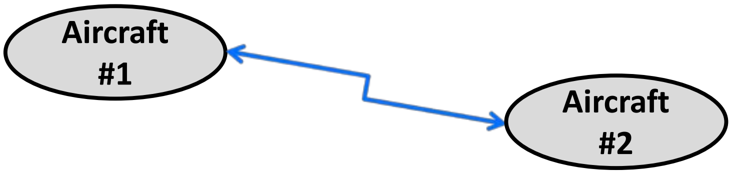


Figure 191 – Generic A-A Direct Communications System Architecture #1

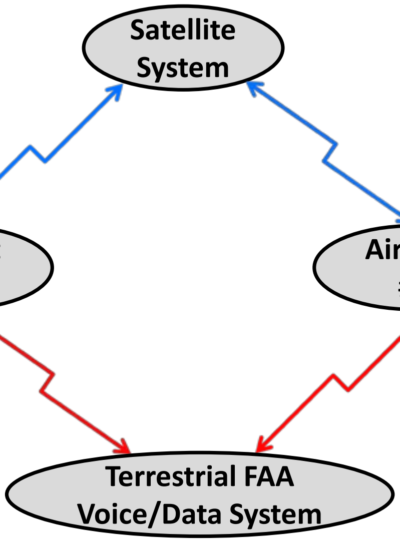


Figure 192 – Generic A-A Direct Communications System Architecture #2

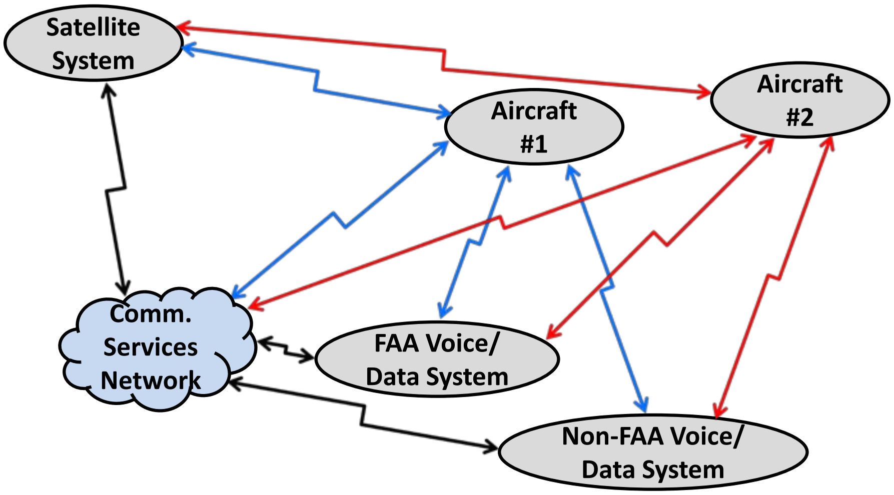


Figure 193 – Generic A-A Networked Communications System Architecture

Relevant to A-G communications, the architectures depicted in Figure 194 through Figure 197 adequately describe all the A-G candidates for the purposes of this assessment. The technology candidates represented by the Figure 194 architecture include direct A-G communications whereby each aircraft directly communicates with an FAA voice/data system that is directly connected to the ground node without any intervening node (e.g. A-G candidates 2 to 8, and 18). The candidates represented by the Figure 195 architecture include those candidates whereby the aircraft and ground node directly communicate via SATCOM, without any intervening network or node (e.g., A-G candidates 1, 9 to 13, and 19). The candidates represented by the Figure 196 architecture illustrate networked communications candidates whereby the ground nodes communicates with a communication services network that has access to one or more communication links to the aircraft. The candidates represented by the Figure 197 architecture illustrate hopping A-G communications candidates that rely on a direct FAA voice/data system link to an aircraft within the coverage volume of a terrestrial-based voice/data system that through a series of one or more hops between intermediate aircraft forwards the information being communicated to the aircraft or ground node for which the communication was intended (e.g., A-G candidates 15 to 17).

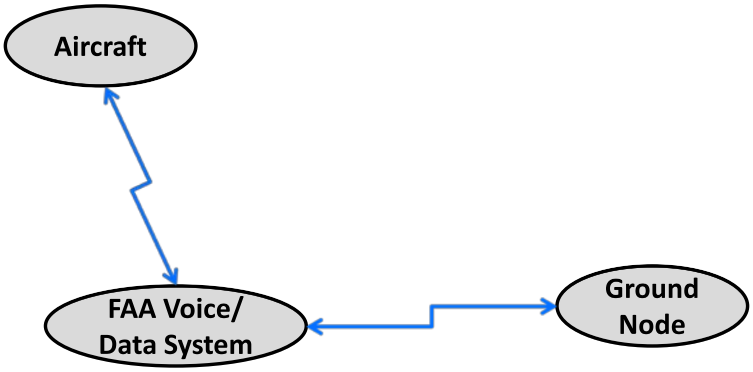


Figure 194 – Generic A-G Direct Communications System Architecture #1

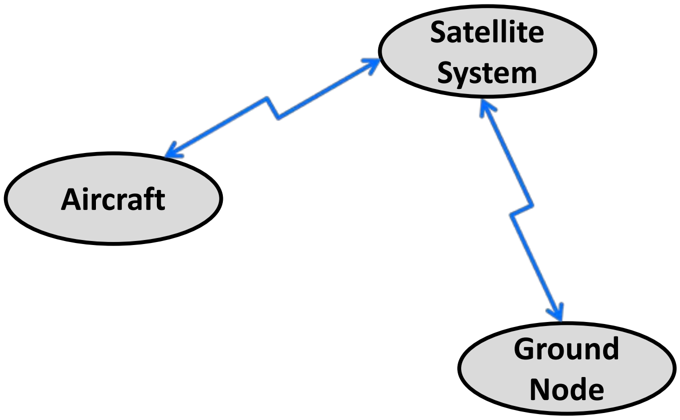


Figure 195 – Generic A-G Direct Communications System Architecture #2

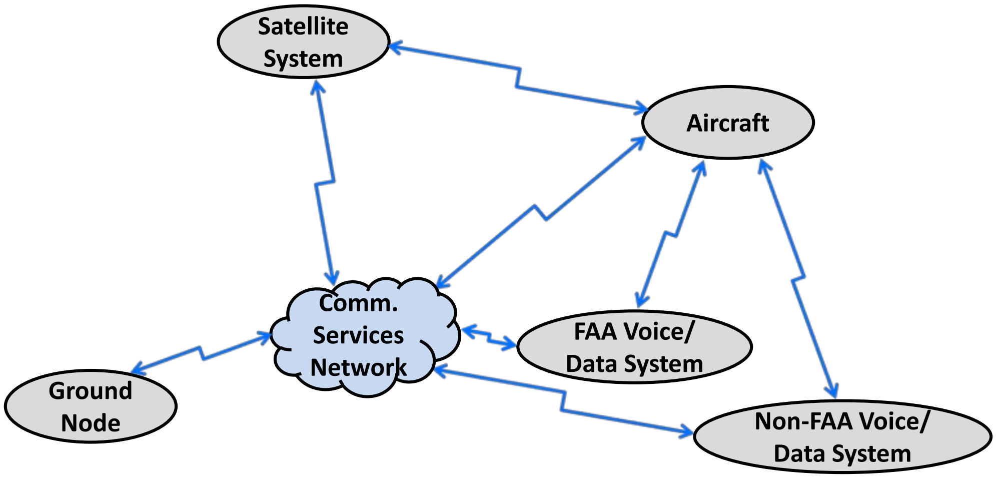


Figure 196 – Generic A-G Networked Communications System Architecture

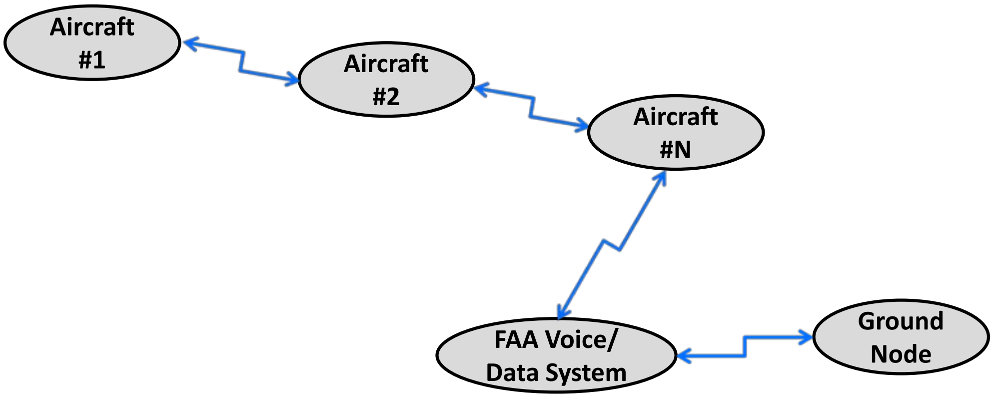


Figure 197 – Generic A-G Communications via A-A Hopping System Architecture

19.4 Security Objectives and Characterization

This subsection defines and provides a preliminary security objectives characterization of the security category of A-A and A-G NAS communications of ATM-relevant information. Because all the information exchange and future applications that utilize the information have not been defined, this assessment is preliminary.

The U.S. Department of Commerce, as developed by NIST, developed the “Standards for Security Categorization of Federal Information and Information Systems” (FIPS PUB 199). This standard is intended to be used by all the federal agencies to categorize all information and information systems, which is relevant for the NAS A-A and A-G communications. It establishes security objectives categories for both information types and information systems.

The security categories are based on the potential impact should certain events occur which jeopardize the information and information systems needed to accomplish the mission, protect its assets, fulfill its legal responsibilities, maintain its day-to-day functions, and protect individuals.

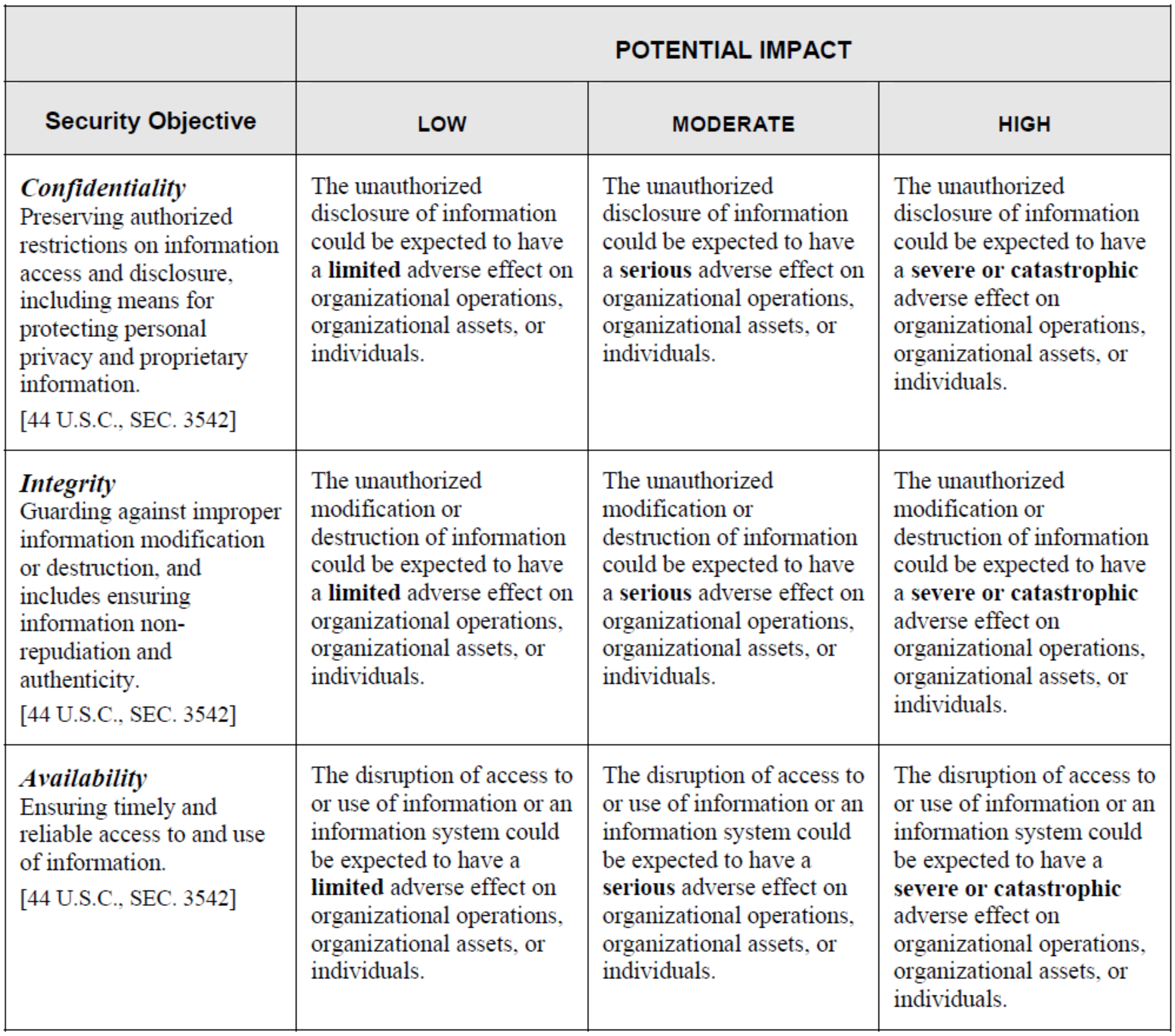
Security categories are to be used in conjunction with vulnerability and threat information in assessing the risk.

An information type is a specific category of resources, a set of user or system identified components, or functions that comprise an information system. An information system is a set of information resources combined into a system providing a defined purpose. The combination of security categorization, vulnerability, and threat information is used to assess risk to an organization. FIPS PUB 199 also defines Security Objectives and Potential Impact on Organizations and Individuals. Figure 198 defines and shows the relationships of security objectives and potential impacts that are used to determine the security categorizations, as specified in FIPS PUB 199.

Security categorization is the characterization of information types and information systems based on assessment of the potential impact relevant to the security objectives of confidentiality, integrity, and availability. As specified in FIPS PUB 199, these security objectives are specified as:

- Confidentiality Security Objective: Preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information.
- Integrity Security Objective: Guarding against improper information modification or destruction, and includes ensuring information non-repudiation and authenticity.
- Availability Security Objective: Ensuring timely and reliable access to and use of information.

Security categorization starts with the identification of information systems and the information types that support the overall communications system. Security categorization is a fundamental step for securing information and information systems.



	POTENTIAL IMPACT		
Security Objective	**LOW**	**MODERATE**	**HIGH**
Confidentiality Preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information. [44 U.S.C., SEC. 3542]	The unauthorized disclosure of information could be expected to have a **limited** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized disclosure of information could be expected to have a **serious** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized disclosure of information could be expected to have a **severe or catastrophic** adverse effect on organizational operations, organizational assets, or individuals.
Integrity Guarding against improper information modification or destruction, and includes ensuring information non-repudiation and authenticity. [44 U.S.C., SEC. 3542]	The unauthorized modification or destruction of information could be expected to have a **limited** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized modification or destruction of information could be expected to have a **serious** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized modification or destruction of information could be expected to have a **severe or catastrophic** adverse effect on organizational operations, organizational assets, or individuals.
Availability Ensuring timely and reliable access to and use of information. [44 U.S.C., SEC. 3542]	The disruption of access to or use of information or an information system could be expected to have a **limited** adverse effect on organizational operations, organizational assets, or individuals.	The disruption of access to or use of information or an information system could be expected to have a **serious** adverse effect on organizational operations, organizational assets, or individuals.	The disruption of access to or use of information or an information system could be expected to have a **severe or catastrophic** adverse effect on organizational operations, organizational assets, or individuals.

Figure 198 – Security Objectives and Categorization by Potential Impact

[Reference: FIPS Publication 199, "Standards for Security Categorization of Federal Information and Information Systems," U.S. Department of Commerce, February 2004, page 6.]

A security categorization was conducted on the generic A-A and A-G communications system and its individual functions (information types). The information types identified for A-A categorization process are: surveillance (e.g., ADS-B), collision avoidance (e.g., TCAS), navigation/intent information, environmental information, and party line.

The information types identified for A-G categorization process are: Air Traffic Control Communications (e.g., clearances), Automatic Dependent Surveillance – Contract (ADS-C), Flight Information Services (e.g., Traffic Info., Weather Info., ATIS, NOTAM, VOLMET, RVR), Alerting Services (both collision avoidance and non-collision avoidance), Airborne Access to SWIM, Navigation Information (e.g., GBAS VDB), Traffic Surveillance (e.g., TIS-B, ADS-R), AOC Communications (both flight trajectory relevant and business relevant), and UAS Control and Non-Payload Communications (which includes consideration of telecommands, non-payload telemetry, navigation aids data, ATC voice relay, ATS data relay, target tracking data, airborne

WxR download data, and non-payload video downlink data). In addition, while not ATM-relevant, a row has been added to characterize Passenger Entertainment Communications.

An impact value of Low (L), Moderate (M), or High (H) was assigned to the loss of confidentially (C), integrity (I), and availability (A) for each information type based on the definitions found in Figure 198 (page 277). The generalized format from FIPS Publication 199 for expressing the Security Categorization (SC) for an information type is given as:

SC$_{\text{Information\_Type}}$ = {(**confidentiality**, *impact*), (**integrity**, *impact*), (**availability**, *impact*)}

The results from the initial security categorization for the information types for A-A and A-G communications are presented in Figure 199 and Figure 200, respectively. The categorization of the information types was conducted based on the expected operational impact caused by the loss of confidentiality, integrity, and availability, with due consideration given to the operational aspects of the current and expected future ATM uses of the A-A and A-G information communicated in the NAS. Then an overall security categorization was determined for each information type by selecting the highest impact value for each information type.

Once the security categorization of the information types was completed, security categorizations for the overall A-A and A-G communication systems were conducted. The generalized format from FIPS Publication 199 for expressing the Security Categorization (SC) for an information system is:

SC$_{\text{Information\_System}}$ = {(**confidentiality**, *impact*), (**integrity**, *impact*), (**availability**, *impact*)}

The security categorization for the A-A and A-G communication systems (referred to as $SC_{\text{A-A\_Communications}}$ and $SC_{\text{A-G\_Communications}}$, respectively) can be determined by selecting the highest impact value for each information type that is supported by a given communication link. Thus, for example, if a given A-G communication link supports more than one information types identified, then the more stringent (maximum) value for low/moderate/high impact for confidentiality, integrity, and availability would apply, where this maximum impact for confidentiality, integrity, and availability is referred to in the equations below as $\text{Max}(I_C)$, $\text{Max}(I_I)$, and $\text{Max}(I_A)$, respectively.

$SC_{\text{A-A\_Communications}}$ = {(confidentiality, $\text{Max}(I_C)$), (integrity, $\text{Max}(I_I)$), (availability, $\text{Max}(I_A)$)}

$SC_{\text{A-G\_Communications}}$ = {(confidentiality, $\text{Max}(I_C)$), (integrity, $\text{Max}(I_I)$), (availability, $\text{Max}(I_A)$)}

Information Type	**Impact Value**			**SC for Overall Information Type**
	C	**I**	**A**	
Surveillance (e.g., ADS-B)	*L*	*M*	*M*	*M*
Collision Avoidance (e.g., TCAS)	*L*	*M*	*M*	*M*
Navigation / Intent (e.g., Intended path/trajectory information)	*L*	*M*	*L*	*M*
Environmental Information (e.g., Weather Radar data, icing, ride quality, and other pilot reports)	*L*	*M*	*L*	*M*
Party Line (e.g., Broadcast to nearby NAS users)	*L*	*M*	*M*	*M*
Most Stringent A-A Comm. Security Categorization	**L**	**M**	**M**	

Figure 199 – A-A Communications Security Categorization

Notes:

1) Security Objectives: C = Confidentiality, I = Integrity, A = Availability

2) Potential Impacts: L = Low, M = Moderate, H = High

3) *Security characterization needs to be revisited with each specific intended application.*

Information Type	**Impact Value**			**SC for Overall Information Type**
	C	**I**	**A**	
Air Traffic Control Communications (e.g., clearances, enroute/ TRACON/ approach/surface control)	*L*	*M*	*M*	*M*
Automatic Dependent Surveillance – Contract (ADS-C)	*L*	*M*	*M*	*M*
Flight Information Services (e.g., Traffic Info., Weather Info., ATIS, NOTAM, VOLMET, RVR)	*L*	*M*	*M*	*M*
Alerting Services – Collision Avoidance (e.g., Automated CAS)	*L*	*M*	*M*	*M*
Alerting Services – Non-Collision Avoidance (e.g., Search & Rescue)	*L*	*M*	*L*	*M*
Airborne Access to SWIM	*L*	*M*	*L*	*M*
Navigation Information (e.g., GBAS VDB)	*L*	*H*	*M*	*H*
Traffic Surveillance (e.g., TIS-B, ADS-R)	*L*	*M*	*M*	*M*
AOC Communications – Flight Trajectory Relevant	*L*	*M*	*M*	*M*
AOC Communications – Business Related	*M*	*L*	*L*	*M*
UAS Control and Non-Payload Communications (CNPC): (Includes consideration of Telecommands, non-payload telemetry, navigation aids data, ATC voice relay, ATS data relay, target tracking data, airborne WxR download data, and non-payload video downlink data) *[Reference: "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, NASA GRC, page 7.]*	*L*	*M*	*M*	*M*
Passenger Entertainment Communications	*L*	*L*	*L*	*L*
Most Stringent A-G Comm. Security Categorization	**M**	**H**	**M**	

Figure 200 – A-G Communications Security Categorization

Notes:

1) *Security Objectives: C = Confidentiality, I = Integrity, A = Availability*
2) *Potential Impacts: L = Low, M = Moderate, H = High*
3) *Security characterization needs to be revisited with each specific intended application.*

19.5 Threats

As defined previously, a threat is the potential for a particular threat-source to successfully exercise a particular vulnerability. *[Reference: NIST SP-800-30, August 2008, page 12.]* Threat-sources are result from any circumstance or event that can cause harm to the system, including its processing environment.

Figure 201 below identifies 8 threat types and over 60 threat sources applicable to NAS communication systems. These threats are generally applicable to all communication technology candidates. Some candidates are more vulnerable to these threats than other candidates.

Figure 201 – Threats to A-A and A-G Communication Systems

Threat Type	Threat Description	Threat-source
IT System Threats	Acts or incidents that are carried out by adversarial IT systems that affect the dependability of the target IT system. Such malicious acts often have negative repercussions on the confidentiality, integrity, and availability of system data. Various methods that are used to carry out the mal-intent are listed. IT system threats could lead to the loss of confidentiality, integrity, and availability.	• Virus • Key Logger • Malware • Worms • Trojan horse • Security Patching • Denial-of-Service • Security processes not followed • Equipment Failure • Software Miss Function • Capacity Saturation • System errors, deficiencies, and omissions • Counterfeit sub-systems or parts
Comm. Link Threats	A type of attack that attempts to disrupt networks in the wireless/radio domain. Communication link threats manipulate the link spectrum to gain access to a system or deny legitimate users access to information exchange using the spectrum. Methods used to carry out communication link threats are listed.	• Jamming • Spoofing • Denial-of-Service • Intentional/ Unintentional Interference • De-Sensitize Receiver
Human Threats	Threats to an information system that involves a user, operator, designer, or other attacker. Research has shown that the most vulnerable point of most information systems is the human. Types of human threats are listed.	• Hackers • Criminals • Terrorists • Spy • Saboteurs • Technicians • Users • Employees • Contractors • Partners • Manufactures • Vandals • Destructive Individuals • Malicious insiders
Physical Threats	Threats that can physically affect the information system - apart from protecting it electronically. Protecting the information system components from physical damage is a component of information assurance. Physical security describes measures that are designed to protect equipment from physical damage and also deny access to unauthorized	• Fire • Water • Air Pollution • Blunt Force • Explosives

Threat Type	Threat Description	Threat-source
	personnel from physically accessing a facility, resource, or stored information.	
Environmental Threats / Nature	Threats posed by the environment that are generally caused by natural occurrences in nature. Although environmental threats may not have a high probability of occurrence, it is only a matter of time that determines when it occurs.	• Climatic • Hurricane • Tornado • Flooding • Tsunami • Wind • Lightning • Rain • Snow • Ice • Animals / Insects • Extreme Temperature • Seismic • Volcanic • Chemical • Nuclear or EM • Geo-Magnetic (Solar) • Ionospheric storms • Meteors
Utility Threats	Threats borne by a utility, for which the system may rely on, or may be physically located near the system, which if compromised, can have adverse effects on the operation of the system.	• Electrical Power • Air Conditioning • Heat • Voltage Spikes/Current Surge • Natural Gas • Telecommunications • Back-up power systems

[Reference: Threat table is based upon Table 2 in the "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, by NASA Glenn Research Center.]

A more detailed description of the threats identified in computing environment and communication technologies (i.e., including IT System and Comm. Link threat types) as well as the human threats are described in greater detail below. The descriptions are based upon those described in the "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, by NASA Glenn Research Center.

- **IT System Threats** – Acts or incidents that are carried out by adversarial IT systems which affect the dependability of the target IT system. Such malicious acts can impact the confidentiality, integrity, and/or availability of the A-A and A-G communication systems. Various methods that are used to carry out the mal-intent are identified below.
  - **Virus** – A computer virus is a program or piece of code that is loaded onto computer resources with knowledge by operator/maintainer and runs against his/her wishes. Viruses can replicate themselves. Computer viruses are man-made. A simple virus that can make a copy of itself over and over is relatively easy to produce. Even such a simple virus is dangerous because it could quickly use all available memory and bring the system to a halt. Viruses are also

capable of being transmitted across networks and bypassing security measures.

- **Key-logger** – Key-logger is the action of tracking (or logging) the keys stuck on a keyboard, typically in a covert manner so that the person using the keyboard is unaware that their actions are being monitored. There are numerous key-logging methods, ranging from hardware and software-based approaches to electromagnetic and acoustic analysis. This could potentially allow perpetrators to retrieve login/password information and could lead to rogue users masquerading as Air Traffic Controllers or AOC.
- **Malware** – Malware, short for malicious software, is software (or script or code) designed to disrupt computer operation, gather sensitive information, or gain unauthorized access to computer systems. It is a general term used to describe any kind of software or code specifically designed to exploit a computer, or the data it contains, without consent. Malware includes computer viruses, worms, Trojan horses, spyware, dishonest adware, and other malicious programs.
- **Worms** – A computer worm is a self-replicating malware computer program, which uses a computer network to send copies of itself to other nodes on the network and it may do so without any user intervention. Unlike a computer virus, it does not need to attach itself to an existing program. Worms almost always cause at least some harm to the network, even if only by consuming bandwidth, whereas viruses almost always corrupt or modify files on a targeted computer.
- **Trojan horse** – A Trojan horse is a self-replicating type of malware which gains privileged access to the operating system while appearing to perform a desirable function but instead drops a malicious payload, often including a backdoor allowing unauthorized access to the target computer. These backdoors tend to be invisible to average users, but may cause the computer to run slow because it may be performing other malicious functions. Trojans do not attempt to inject themselves into other files like a computer virus.
- **Denial-of-service** (DOS) – DOS is an attempt to make a computer or network resource unavailable to its intended users. DOS attacks generally consist of the concerted efforts of a person, or multiple people to prevent a system from functioning efficiently or at all, temporarily or indefinitely.
- **Security Patching** – Security patching is the process of using automatic updating mechanisms to update system software. Automated software updates have the possibility of creating security issues.
- **Security process not followed** – Human error accounts for most security breaches. Security training is important for employees to follow proper security procedures.
- **Equipment Failure** – Equipment failure, without redundant backup means can affect NAS operations and should be mitigated through the use of redundant backup equipment.
- **Software Miss Function** – Software miss function due to corrupt software can affect NAS operations and should be mitigated through the use of rigorous software development and maintenance processes.

  - **Capacity Saturation** – Capacity saturation of a system can degrade performance and lead to a situation where peak demand cannot be supported.

  - **System errors, deficiencies, and omissions** – System errors, deficiencies, and omissions are caused by either incorrect implementation or inputs that result in a system vulnerability. Such problems are caused by system developers, users, data entry clerks, and system operators during all phases of the systems life cycle. For example, programming and development errors are often called "bugs".

    Counterfeit sub-systems / parts / software – Counterfeit sub-systems, parts, or software is a threat to the confidentially, integrity, and/or availability of A-A and A-G NAS communications. It has been estimated by the International Anti-Counterfeiting Coalition that 5 to 7% of the world trade is in counterfeit goods. Counterfeit items may be developed for business reasons, but may not have the functionality/performance needed for by the communication system, or may be developed with malicious intent.

- **<u>Communication Link Threats</u>** – A type of attack that attempts to disrupt networks in the wireless/radio domain. Communication link threats manipulate the communication link spectrum to gain access to a system or deny legitimate users access to information exchange using the spectrum. Methods used to carry out communication link threats are identified below. Communication link threats could lead to loss communications confidentiality, integrity, and/or availability.

  - **Jamming** – Jamming is the transmission of signals that totally disrupt communications in at least one region by decreasing the signal-to-noise ratio. Jamming may be intentional or unintentional and it occurs when radiated energy interferes with desired signals being transmitted in the same frequency band as the jamming energy. APPENDIX B: Public Notice – FCC Enforcement Advisory for Jamming Devices (Section 35 on *page 575) contains a copy of the Federal Communications Commission (FCC) public notice regarding the enforcement for Jamming Devices dated March 6, 2012.*

  - **Spoofing** – Spoofing, also known as address forgery or a host hijack is a hijacking technique in which as attacker masquerades as a trusted host to conceal his identity in order to misdirect a user, hijack a site, or gain access to a network.

  - **Denial of Service (DoS)** – DOS is an attempt to make a network resource unavailable to its intended users. While the specific means of a DoS attack may vary, it consists of concerted efforts by a single or multiple attackers to prevent a service from functioning efficiently.

  - **Intentional / Unintentional Interference** – Interference is caused by non-desired signals (in frequency, geographic region, or time) that are either man made or the result of a nature that partially or totally interfere with the reception of the intended transmissions.

  - **Desensitize Receiver** – Desensitization is a form of interference where a receiver is unable to receive a weak signal that it might otherwise be able to receive when there is no interference. This is typically caused by a nearby transmitter with a strong signal on a close frequency, which overloads the receiver and makes it unable to fully receive the desired signal. The interference signal may be at a different frequency than the desired signal, but the spurious signals caused by the interfering signal can show up at the same frequency desired signal. It is these spurious signals that degrade the ability of the receiver by raising the minimum detectable signal level.

- **Human Threats** – Threats to an information system that involves a user, operator, designer, or attacker. Research has shown that the most vulnerable point of most information systems is the human factor. Types of human threats are identified below. Human threats can result loss of communications confidentiality, integrity, and/or availability.
  - **Hackers** – One who accesses a computer system by circumventing security measures.
  - **Criminals** – A criminal is person or group of individuals who commit acts that breach common rules or laws for personal gain.
  - **Terrorists** – Terrorist is a person or group of individuals who perform acts of unlawful violence in order to achieve political, religious, or ideological goals.
  - **Spy** – A spy is usually part of an organization, institution, or government where the effort is based on potential or actual enemies.
  - **Saboteurs** – A saboteurs is one who performs a conscious act (known as sabotage) to willfully interfere with established work processes/procedures in order to negatively affect operations.
  - **Technicians** – Technicians that work on low-level technical issues, may fix a specific issue at a sub-system level, but inadvertently create a security hole at the system level.
  - **Users**
    - User Error – Users of a system who inadvertently create a security vulnerability.
    - Abuse of rights – Users of a system who have certain privileges such as system administrators, and do not follow procedures/guidelines on how to maintain system security.
  - **Employees** – Employees should be trained in maintaining security. Employees use tools to accomplish their tasks, but in doing so may create vulnerabilities. For example, tools such as USB flash drives, collaboration software, peer-to-peer applications, and remote login, create the potential for security violations.
  - **Contractors and Partners** – Contractors and partners typically pose a greater risk to security than do employees. They may not be sufficiently trained for security of the specific operational equipment, or may have differing agendas / security priority, as do employees.
  - **Manufacturers** – Manufacturers may deliberately or inadvertently provide a hole

in the security of communication systems, associated with the manufacturing of equipment to be used as part of the communication and information system.

- **Vandals** – Vandals destroy property in response to anger, envy, or opportunistic behavior.
- **Destructive Individuals / Malicious Insiders** – Destructive individuals or malicious insiders have no ideological goal but destroy to harm an organization, system, or destroy for pleasure.

19.6 Identification of Vulnerabilities in the Computing Environment, Communication Technologies, and Communication Protocols

A vulnerability is a weakness in the system that can be exploited intentionally or accidentally. The identification of the system vulnerabilities (flaws or weaknesses) that could be exploited by potential threat-sources is a key step in the security assessment process. The identification of vulnerabilities can take many forms based on various types of threat sources being considered in the assessment.

The vulnerabilities identified in subsections below target the vulnerabilities for future A-A and A-G communication systems, specifically in the areas of the computing environment, communications technologies, and communications protocols. Vulnerabilities to other portions of the system are outside the scope of this report.

19.6.1 Vulnerabilities in the Computing Environment and Communication Technologies

For the purposes of this risk assessment, as there is no physical system or detailed system baseline design to evaluate, a list of common IT system vulnerabilities and other communications-related vulnerabilities that would likely apply to future A-A and/or A-G NAS communication systems was developed. Once an actual potential future communication system is defined in greater detail, these vulnerabilities would need to be re-evaluated to reflect the configuration, information being used, and intended operations of the implemented system.

Figure 202 identifies and describes potential vulnerabilities applicable to future A-A and A-G communication environment and technologies. *Note that* APPENDIX C: GPS Vulnerabilities *(Section 36 on page 579) overviews GPS navigation system vulnerabilities as described in an FAA report.*

Figure 202 – Vulnerabilities in the Computing Environment and Comm. Technologies

Vulnerability Identifier	Vulnerability Description
V.ACCESS	**System allows authorized personnel unauthorized access via user error, system error, or a technical attack for malicious or non-malicious purposes.**
V.ACCESS.DISABLE	System does not prevent deliberate disablement or modification of security functions by an authorized user in order to enable other attacks.
V.ACCESS.EAVESDROP	System does not prevent an authorized user from eavesdropping on messages that they are not authorized to read over a communications link.
V.ACCESS.MASQUERADE	System does not prevent an end user from masquerading as another type of end user to deceive other users of the system.
V.ACCESS.TECHNICIAN	System does not prevent a technician from masquerading as an end user of the system in order to deceive users of the system.
V.ACCESS.INFO-ACCESS	System does not prevent an authorized user from gaining unauthorized access to the system or to information controlled by it.
V.ACCESS.RESOURCE	System does not prevent authorized users from gaining unauthorized access to a resource or to information not directly controlled by the system via user error, system error, or a technical attack.
V.DENIAL	**The system's resources may become exhausted due to system error, non-malicious user actions, or denial-of-service (DoS) attack.**
V.DENIAL.DISRUPT	System does not prevent an attacker from disrupting a communications link in order to reduce the availability of the system.
V.DENIAL.FLOOD	System does not prevent an attacker from flooding a communications link with injected messages in order to reduce the availability of the system.
V.DENIAL.JAM	System does not prevent an attacker from jamming packets on a communication link in order to reduce the availability of the system.
V.DENIAL.MALFORM	System does not prevent an attacker from injecting malformed messages into a communications link in order to reduce the availability of the system.
V.DENIAL.OTHER-SYSTEMS	The resources of other NAS systems may become exhausted due to a system error, non-malicious user actions, or denial-of-service (DoS) attack against the system.
V.ENTRY	**The system does not prevent unauthorized users from gaining access via either technical or non-technical means for malicious purposes.**
V.ENTRY.ALTER	The system does not prevent an attacker from delaying/deleting/ injecting/modifying/re-directing/re-ordering/replaying or otherwise altering messages on a communications link.
V.ENTRY.EAVESDROP	The system does not prevent an attacker from eavesdropping the messages transmitted over a communications link.

Vulnerability Identifier	Vulnerability Description
V.ENTRY.IMPERSONATE	The system does not adequately authenticate a user in order to prevent the impersonation of another user by an attacker.
V.ENTRY.MALFORM	The system does not prevent an attacker from injecting malformed messages into a communications link in order to gain control of a system component (e.g., buffer overflow attack).
V.ENTRY.SOFTWARE	The system and/or configuration management process does not prevent an authorized user from introducing unauthorized software (malicious or otherwise) into a system.
V.ENTRY.VULNERABILITIES	Known/unknown vulnerabilities in operating system (OS) and supporting utilities are exploited.
V.FAILURE	**The secure state of the system could be compromised in the event of a system crash.**
V.FAILURE.DENIAL	System loses security configuration information during failure and as a result is unable to re-establish communications upon re-start resulting in denial-of service.
V.FAILURE.DISABLE	System recovers from failure by re-initializing with security function disabled.
V.FAILURE.FALLBACK	System enables use of security credentials which have previously been compromised during failure recovery.
V.FAILURE.LOG	System compromises security information by writing to unprotected log during failure.
V.OBSERVE	**Events occur in the system's operation that compromise security, but due to flaws in its specification, design, or implementation, may lead a competent user or security administrator to believe that it is still secure.**
V.OBSERVE.LOG-OVERKILL	Ineffective feedback between security operations and security development can lead to a security compromise going undetected because too much log information is collected and an administrator is unable to identify the most serious problems.
V.OBSERVE.LOG-PROTECT	The lack of a real-time independent reporting system can lead to a security compromise going undetected because an attacker is able to modify or destroy an alarm or log before they reach the user or technician.
V.OBSERVE.REPORT	The lack of a real-time independent reporting system can lead to a security compromise going undetected due to poor reporting of security events.
V.OBSERVE.UNABLE	The system is insensitive to certain events that may lead to a security compromise going undetected because the system is unable to detect the problem – for example unable to detect a physical connection being broken.
V.OBSERVE.DISCLOSURE	Records of security events may be disclosed to unauthorized individuals or processes.
V.OPERATE	**Security failures may occur because of improper operation of the system (e.g., the abuse of authorized privileges).**

Vulnerability Identifier	Vulnerability Description
V.OPERATE.DELIBERATE	The system design does not foster proper security implementation / management. This may lead to security mechanisms being deliberately circumvented by the user (e.g., because security is so cumbersome that effective operation is not possible otherwise).
V.OPERATE.NON-SECURITY	Non-security function or process can be modified or rendered inoperable for the purpose of enabling another attack.
V.TRACEABLE	**Improper metrics development can lead to security relevant events not being traceable to the user or process associated with the event.**
V.TRACEABLE.UNABLE	Improper metrics development can lead to a security compromise being detected but the system is unable to identify the user or process associated with the event due to lack of log information.
V.TRANSMISSION	**Transmission of information can be susceptible to link impairments and affect guaranteed timely delivery of information.**
V.TRANSMISSION.CONTINUITY	Interruption of link continuity can affect the delivery of information and lead to loss of functionality due to delay or loss in delivery of information.
V.TRANSMISSION.QOS	Absence of any guaranteed QoS can introduce latency/decay, jitter and/or packet loss, affecting the delivery of information and lead to loss of functionality.

[Reference: Based upon vulnerabilities identified in Table 3 of "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, by NASA Glenn Research Center.]

19.6.2 Additional Vulnerabilities Specific to Technology Candidates

This section identifies additional vulnerabilities specific to each communication technology candidate. Figure 203 identifies the additional vulnerabilities specific to the A-A candidate technologies. Figure 204 and Figure 205 (pages 291 and 292) identify the additional vulnerabilities specific to the A-G candidate technologies.

#	Communications Candidates	Candidate Specific Vulnerabilities
A-A	Air-to-Air (A-A) Comm. Candidates	
1	VHF A-A	- Interference from natural and man-made interference (e.g., FM radio) - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas
2	UHF A-A	- Interference from natural and man-made interference - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - Spectrum currently not categorized for aero mobile use, however as digital cable/ fiber to the home increases, demand for broadcast TV will decrease likely freeing up this band
3	L-Band A-A	- Interference from natural and man-made interference - Interference with same band SATCOM - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - No broadband L-Band spectrum available unless future re-assignments take place - Mobile satellite allocations are a major part of this band area, and depending upon spectrum allocation will need technology for controlling beams to prevent interference (similar to Qualcomm's Ku band air-to-ground directional antenna approach)
4	S-Band A-A	- Interference from natural and man-made interference - Interference with mobile SATCOM - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas
5	C-Band A-A	- Interference from natural and man-made interference - Interference with mobile SATCOM
6	X-Band A-A	- Interference from natural and man-made interference - Interference with weather radar
7	Optical A-A	- Environmental conditions attenuating or obscuring link: fog, rain, clouds, smoke, haze, bright lights (e.g., sun) - Difficulty establishing and maintaining link: Pointing accuracy under all dynamic conditions
8	Hybrid RF/Optical A-A	- For optical: Environmental conditions attenuating or obscuring link: fog, rain, clouds, smoke, haze, bright lights (e.g., sun) - Difficulty establishing and maintaining optical link: Pointing accuracy under all dynamic conditions
9	LEO SATCOM A-A (One Hop through Satellite)	- Slight signal fading in heavy rain - Satellite failures - Meteors / collisions with satellites - Coverage outages/holes - Long mean time to repair - Worldwide control and monitor facilities
10	GEO SATCOM A-A (One Hop through Satellite)	- Moderate to very significant signal fading in heavy rain - Potential loss of signal on ground (taxi, tarmac), especially in rain conditions - Satellite failures - Meteors / collisions with satellites - Solar storms - Long mean time to repair
11	MEO SATCOM A-A (One Hop through Satellite)	- Slight signal fading in heavy rain - Potential loss of signal on ground (taxi, tarmac) - Satellite failures - Meteor, solar storms - Long mean time to repair - Coverage outages
12	GEO + HEO SATCOM A-A (One Hop through Satellite)	- Moderate to significant signal fading in heavy rain - Potential loss of signal on ground (taxi, tarmac) - Satellite failures - Meteor / collisions with satellites - Long mean time to repair - Coverage outages

Figure 203 – Additional Vulnerabilities Specific to the A-A Technology Candidates

#	Communications Candidates	Candidate Specific Vulnerabilities
A-G	Air-to-Ground (A-G) Comm. Candidates	
1	HF A-G	- Antenna directionality open to natural and man-made interference - Wide variance in link quality, signal propagation performance, night / day, solar cycle, sun spots, solar particles, solar wind, nuclear upset, requires skilled operator or ALE (Automatic Link Establishment)
2a	VHF A-G: Use 112 to 118 MHz	- Interference from natural and man-made interference (e.g., FM radio) - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas
2b	VHF A-G: Improve VHF Efficiency	- Interference from natural and man-made interference (e.g., FM radio) - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas
2c	VHF A-G: Low Band (Ground-to-Air only)	- Interference from natural and man-made interference - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - Spectrum currently not categorized for aero mobile use - Ground transmit only, lack of return link unless paired with another band
3a	UHF A-G: Aviation Allocation	- Interference from natural and man-made interference - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - Spectrum currently not categorized for aero mobile use, however as digital cable/ fiber to the home increases, demand for broadcast TV will decrease likely freeing up this band
3b	UHF A-G: High Band (Ground-to-Air only)	- Interference from natural and man-made interference - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - Spectrum currently not categorized for aero mobile use - Ground transmit only, lack of return link unless paired with another band
3c	UHF A-G: Other	- Interference from natural and man-made interference - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - Spectrum currently not categorized for aero mobile use, however as digital cable/ fiber to the home increases, demand for broadcast TV will decrease likely freeing up this band
4	L-Band A-G	- Interference from natural and man-made interference - Interference with same band SATCOM - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - No broadband L-Band spectrum available unless future re-assignments take place - Mobile satellite allocations are a major part of this band area, and depending upon spectrum allocation will need technology for controlling beams to prevent interference (similar to Qualcomm's Ku band air-to-ground directional antenna approach)
5	S-Band A-G	- 4x more RF power required compared to a similar L-Band link making Power Amplifiers more difficult to build for wide bandwidths - SATCOM interference
6a	C-Band A-G: MLS band	- Potential interference with commercial devices [e.g., low Unlicensed National Information Infrastructure (U-NII) band intended for indoor use, than potentially could be carried onto the aircraft] - SATCOM interference
6b	C-Band A-G: Radar Alt.	- 16x more RF power required compared to a similar L-Band link making Power Amplifiers very difficult to build for wide bandwidths - Interference to and from Radar Altimeters
6c	C-Band A-G: AeroMACS	- Possibly PHY and MAC layer protocol vulnerabilities - Unidirectional authentication scheme, no provision for base station to subscriber authentication - Obstruction LOS issues
7	Optical A-G	- Environmental conditions attenuating or obscuring link: fog, rain, clouds, smoke, haze, bright lights (e.g., sun) - Difficulty establishing and maintaining link: Pointing accuracy under all dynamic conditions
8	Hybrid RF/Optical A-G	- For optical: Environmental conditions attenuating or obscuring link: fog, rain, clouds, smoke, haze, bright lights (e.g., sun) - Difficulty establishing and maintaining optical link: Pointing accuracy under all dynamic conditions
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)	- Environmental conditions: Signal fading in rain is significant (many dBs per mile), greater at higher bands - Ground broadcast only for enroute applications, lack of return link unless paired with another band
10	DTV VHF/UHF Network	- Use of commercial DTV assets - Ground broadcast only, lack of return link unless paired with another band

Figure 204 – Additional Vulnerabilities Specific to the A-G Technology Candidates (Part 1 of 2)

#	Communications Candidates	Candidate Specific Vulnerabilities
A-G	Air-to-Ground (A-G) Comm. Candidates	
11a	Cellular Network: Aircell	- Use of commercial DTV assets - Open to natural and man-made interference - Access, many non-aviation transmitters
11b	Cellular Network: LTE+	- Interference from natural and man-made interference - Omni antenna may be more easily interfered with than directional antennas / sky looking antennas - Use of Commercial LTE bands (750 MHz) are doubtful. Requires cooperation of mobile service providers. - Technical challenges for robust link and to avoid interference with ground users: antenna directionality, latency, access timing, Doppler (However there may be some unidirectional bands still available) - Access, many non-aviation transmitters
11c	Cellular Network: AWS	- Interference from natural and man-made interference - Directional antenna required - Need fixed site primary user lockout
12	LEO SATCOM Network (e.g., Iridium Next+)	- Slight signal fading in heavy rain - Satellite failures - Meteors / collisions with satellites - Coverage outages/holes - Long mean time to repair - Worldwide control and monitor facilities
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)	- Moderate to very significant signal fading in heavy rain - Potential loss of signal on ground (taxi, tarmac), especially in rain conditions - Satellite failures - Meteors / collisions with satellites - Solar storms - Long mean time to repair
14	MEO SATCOM Network (e.g. GlobalStar+)	- Slight signal fading in heavy rain - Potential loss of signal on ground (taxi, tarmac) - Satellite failures - Meteor, solar storms - Long mean time to repair - Coverage outages
15	VHF A-A Hopping for long range A-G Com.	- Hopping allows entities to maliciously modify or generate miss-information - Location of aircraft many not allow hopping link to close - Hopping latency - Number of aircraft equipped for hopping relay - Bandwidth to support many aircraft
16	UHF A-A Hopping for long range A-G Com.	- Hopping allows entities to maliciously modify or generate miss-information - Location of aircraft many not allow hopping link to close - Hopping latency - Number of aircraft equipped for hopping relay
17	L-Band A-A Hopping for long range A-G Comm.	- Hopping allows entities to maliciously modify or generate miss-information - Location of aircraft many not allow hopping link to close - Hopping latency - Number of aircraft equipped for hopping relay
18	X-Band	- Interference from natural and man-made interference - Interference with weather radar - Band is primarily designed as Mobile, Fixed, and Maritime; the Mobile bands are generally non-aeronautical
19	GEO + HEO SATCOM Network	- Moderate to very significant signal fading in heavy rain - Potential loss of signal on ground (taxi, tarmac), especially in rain conditions - Satellite failures - Meteors / collisions with satellites - Solar storms - Long mean time to repair - Satellite system tracking complexity - Low antenna beam angles

Figure 205 – Additional Vulnerabilities Specific to the A-G Technology Candidates (Part 2 of 2)

19.6.3 Vulnerabilities in the Communication Protocols

Communication protocols define the set of rules by which information is exchanged between two or more entities over a communication link or network. The set of rules includes how the data is represented, the signals used in communications (e.g., signals regarding how the connection will be established or how information is exchanged), the detection of errors, routing, acknowledgements, loss of information, and the security controls (e.g., access, authentication, encryption, etc.).

Communication protocols typically have multiple layers (a protocol stack) that can be developed to work together to enhance the overall communications security. The set of protocols are often defined in hierarchical layers according to the level of communication each protocol is responsible for (low, medium, or high). Typically, a protocol stack will have lower-level protocols that set the rules for the physical interaction between networking hardware devices and higher-level protocols that set the rules for user applications.

For example, the widely used Transmission Control Protocol/Internet Protocol (TCP/IP) network communications protocol has four layers that can work together to provide a more robust communications security than any individual layer. The four layers include the: 1) application layer, 2) transport layer, 3) network layer, and 4) data link layer, as described below [*reference: NIST (http://www.itl.nist.gov/lab/bulletns/bltnapr06.htm)*].

- The application layer sends and receives data for an application. Separate controls can be established for each application. While such an arrangement provides a high degree of control and flexibility for the security of the application, it may result in considerable resources to implement. The development of new application layer security controls can also create new vulnerabilities, and it may not be possible to develop the controls for some applications.
- The transport layer provides connection-oriented or connectionless services to transport application layer services across networks. Controls at this layer can protect data in a single communications session between hosts.
- The network layer routes packets across networks. Controls at this layer apply to all applications, rather than to specific applications. Applications do not have to be modified to use the controls, but this arrangement provides less control and flexibility for protecting specific applications than the transport and application layer controls.
- The data link layer handles communications on the physical network components. Controls at this level protect a specific physical link. Since each physical link must be secured separately, controls at this level are not feasible for protecting connections that involve several links.

The Aeronautical Telecommunication Network (ATN) has been specified by ICAO based on the Open Systems Interconnection (OSI) model which has been defined with seven layers including: 1) physical layer, 2) data link layer, 3) network layer, 4) transport layer, 5) session layer, 6) presentation layer, and 7) application layer.

The National Institute of Standards and Technology has developed a similar protocol standard called the Government Open Systems Interconnection Profile (GOSIP).

As data is prepared for transport through a networked communication system, it is passed from the highest to the lowest layer, with each layer adding more information. Security controls at a higher layer cannot provide full protection for the lower layers, because the lower layers add information to the communications after the higher-layer security controls have been applied. The lower-layer security controls are less flexible and granular than higher-layer controls. As a result, controls at the network layer are widely used to secure communications and to provide a more balanced solution than can be achieved through the application of the higher-layer and lower-layer security controls.

A basic objective of the A-G and A-A networks is to maintain robust and transparent, and likely in the future, secure connectivity among ground-based and aircraft-based nodes. This “mobility” is essentially a problem maintaining one or more paths between the aircraft and ground nodes with the required QOS to support the intended applications, and exchanging the information to enable the various applications over these paths. Basically, this is a connectivity and routing of information problem and in particular it is a route maintenance problem that the communication protocols must address. Route maintenance refers to the update of the routing database that is used to move data communications information (e.g., messages/packets) through the network on a hop-by-hop basis.

Protocols that use static routing are easier to maintain security but they cannot support mobility needs. This is because routes to and from aircraft to ground are inherently dynamic in that an aircraft may traverse multiple sub-networks and within each sub-network they traverse multiple ground stations, and thus the protocol must support some type of adaptive routing.

Adaptive routing may be centralized or distributed. A centralized approach to adaptive routing has the problem that the central control center where changes would be reported becomes a bottleneck, especially in a global environment. Even if enough capacity could be provided, there are associated timing considerations since a reported change in an aircraft’s location must be available to communicating ground systems in real time. There are also administrative considerations with centralized adaptive routing. These considerations include determining which administration [e.g., a particular Civil Aviation Authority (CAA), service provider, etc.] would operate the central control center and what are the liabilities associated with such an operation. Accordingly, since neither static routing nor centralized adaptive routing are appropriate for the future networked aeronautical communications. A distributed adaptive routing approach is necessary, and must be supported by the network protocols.

There are two general approaches to distributed adaptive routing: 1) link state routing, and 2) distance vector routing. Under link state routing, each change in the network topology (e.g., in the connectivity to/from an aircraft) is broadcast to every other node in the network. The main problem with this type of routing protocol approach is that the number of messages required to report changes in network topology becomes inordinately large. Because of this, the distance vector approach to distributed adaptive routing is believed to be the preferred protocol for future networked aeronautical communication systems.

The principle of distance vector routing protocol is that specific changes in connectivity are propagated (i.e., advertised) to affected routers throughout the network. An advertised route generically includes a measure of the cost and quality of service associated with the path(s).

Protocols that provide for acknowledgement, retransmission, sequencing, encryption, priority, and authentication are more robust. Commercial wide-band air/ground sub-networks can be used at least as a backup to the sub-networks reserved for use by aeronautical safety applications. In fact, the Air/Ground router could enforce the priority requirements by giving priority to air traffic safety communications traffic. This would be consistent with the overarching objective of ensuring the availability of safety applications since having multiple alternative paths increases availability.

One basic means for implementing an authentication protocol is using Public/Privates keys, whereby Public Key certificates are known ahead of time or exchanged when the connection is established via an OPEN exchange. A key agreement procedure is performed and subsequent exchanges are protected with a Message Authentication Code (MAC) protocol. The MAC protocol needs to be devised in a manner that provides protection from replay attacks.

The vulnerabilities in the protocols can be addressed by including many of the specific security controls identified in Section 19.8 (page 299).

[*Reference: "A Common Mobility Solution for ATN OSI and Internet Protocol Stacks," by Tom McParland (Basic Commerce and Industries)*].

19.7 Evaluation of Threats/Vulnerabilities (i.e., Risk Assessment)

Risk is the likelihood that a threat-source exploits a vulnerability that results in an adverse impact to the system.

The generic risk analysis for each vulnerability identified in Section 19.6 (not including specific additional vulnerabilities identified in Section 19.6.2) consists of evaluating the threats and security controls to determine the likelihood that vulnerabilities could be exploited and the potential impact should the vulnerabilities be exploited. The general risk assessment process as documented in NIST SP-800-30 (entitled, "Information Security Guide for Conducting Risk Assessments") is shown in Figure 206. Assessment of risk considers the threat sources, vulnerabilities, likelihood, and impact.

Figure 207 identifies the way that A-A and A-G NAS communication system vulnerabilities combine with the identified threats to create risks. Note that: a) Corruption of Information (deliberate or accidental) is characterized by "loss of integrity", b) repudiation is characterized by "denial of service", and c) availability/continuity is characterized by "loss of system availability."

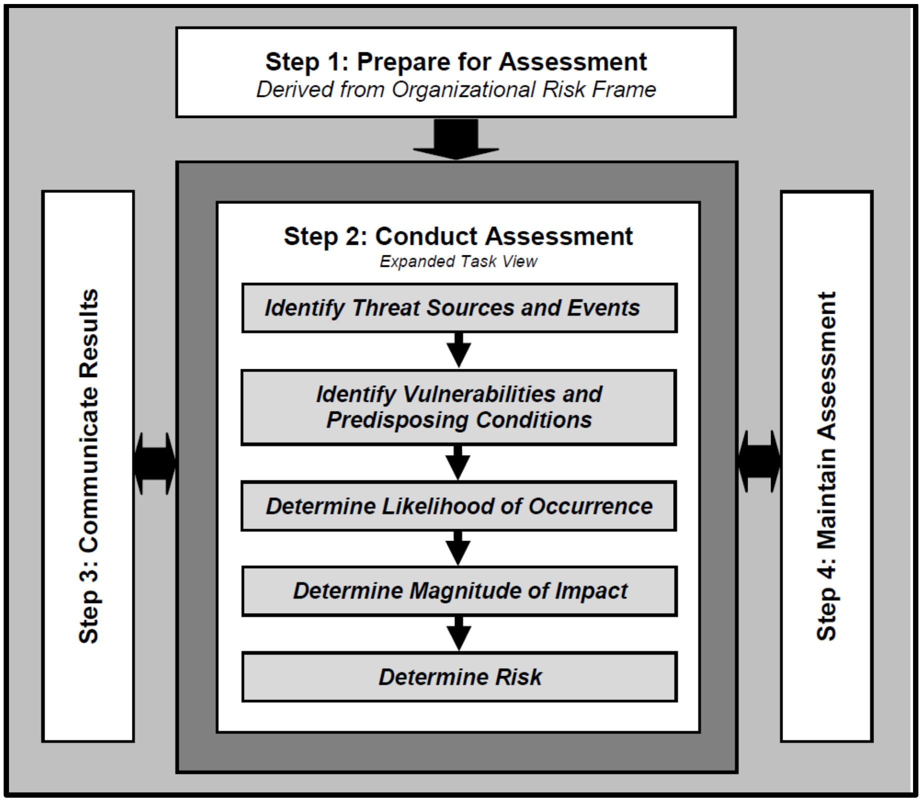


Figure 206 – General Risk Assessment Process

[Reference: NIST SP-800-30 (Rev. 1), "Information Security Guide for Conducting Risk Assessments," September 2012, Figure 5, page 23.]

Figure 207 – General Evaluation of Threats / Vulnerabilities to NAS Communications

Risk ID	Threat-source	Vulnerability	Risk Summary
R.01	IT System, Human	V.ACCESS.DISABLE	*Loss of system integrity*. Disablement or modification of security functions allow attackers access to the system and can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.
R.02	IT System, Human	V.ACCESS.EAVESDROP	*Loss of system confidentiality*. Eavesdropping on messages over the communications link violates protection of information from unauthorized disclosure.
R.03	IT System, Human	V.ACCESS.MASQUERADE	*Loss of system integrity*. Users masquerading as another type of user create deception amongst the user population and foster an environment of inaccurate information.
R.04	IT System, Human	V.ACCESS.TECHNICIAN	*Loss of system integrity*. Technicians masquerading as an end user create deception amongst the user population and foster an environment of inaccurate information.
R.05	IT System, Human	V.ACCESS.ABUSE	*Loss of system confidentiality*. Authorized users who gain unauthorized access to information violate protection of information from unauthorized disclosure.
R.06	IT System, Human	V.ACCESS.OTHER-SYSTEM	*Loss of system integrity*. Authorized users who gain unauthorized access to resources or information can lead to corruption of information; which can result in incorrect decision making and reduce the assurance of the system.
R.07	IT System, Comm. Link, Human	V.DENIAL.DISRUPT	*Loss of system availability*. An attacker can disrupt the A-A and/or A-G communication links and prevent the flow of information and thereby impact operations.
R.08	IT System, Comm. Link, Human	V.DENIAL.FLOOD	*Loss of system availability*. An attacker can flood the A-A and/or A-G communication links with injected messages and thereby reduce availability and negatively impact operational effectiveness.
R.09	Comm. Link, Human	V.DENIAL.JAM	*Loss of system availability*. An attacker can jam communications. This could reduce comm. availability and negatively impact operational effectiveness.
R.10	Comm. Link, Human	V.DENIAL.MALFORM	*Loss of system availability*. An attacker can inject malformed packets into the comm. links consuming processing cycles and exhausting resources, thereby reducing availability of system and sub-system components.
R.11	Comm. Link, Human	V.DENIAL.OTHER-SYSTEM	*Loss of system availability*. The NAS systems and/or sub-systems may become exhausted due to system error, non-malicious user actions, or DoS attacks against the A-A and/or A-G communication systems. This could reduce availability of system and sub-systems.
R.12	IT System, Human	V.ENTRY.ALTER	*Loss of system integrity*. An attacker my delay/inject/modify/re-direct/re-order/re-play or alter messages on A-A and/or A-G comm. links which can lead to corruption of information resulting in incorrect decision making.

Risk ID	Threat-source	Vulnerability	Risk Summary
R.13	IT System, Human	V.ENTRY.EAVESDROP	*Loss of system confidentiality*. An attacker is able to eavesdrop and interpret information transmitted over the comm. links of thereby defeating protection of information from unauthorized disclosure.
R.14	IT System, Human	V.ENTRY.IMPERSONATE	*Loss of system integrity*. An attacker is able to impersonate another user of the system due to inadequate authentication of the system.
R.15	IT System, Human	V.ENTRY.MALFORM	*Loss of system integrity*. An attacker is able to inject malformed messages into the comm. links. This action can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.
R.16	IT System, Human	V.ENTRY.SOFTWARE	*Loss of system integrity*. An authorized user is able to introduce unauthorized software in the system which may or may not be malicious. Unauthorized software installation undermines the software configuration process and reduces the assurance of the system.
R.17	IT System, Human	V.ENTRY.VULNERABILITIES	*Loss of system integrity*. Known and unknown vulnerabilities in the operating system and supporting utilities are exploited which can lead to corruption of information resulting in incorrect decision making.
R.18	IT System	V.FAILURE.DENIAL	*Loss of system availability*. Security configuration is lost during system failure and is unable to re-establish communications upon restart resulting in denial-of-service. The system is unable to process information, thus reducing availability and negatively impacting operational effectiveness.
R.19	IT System	V.FAILURE.DISABLE	*Loss of system integrity*. Security function is disabled upon system restart. Thus potentially allowing attackers access to the system and can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.
R.20	IT System	V.FAILURE.FALLBACK	*Loss of system integrity*. During a failure recovery, the system enables security credentials which have previously been compromised. Thus potentially allowing attackers access to the system and can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.
R.21	IT System	V.FAILURE.LOG	*Loss of system integrity*. System compromises security information by writing to unprotected log during system failure. Thus the information is vulnerable to improper modification.
R.22	IT System	V.OBSERVE.LOG-OVERKILL	*Loss of system integrity*. The system collects too much log information and an administrator is unable to identify the most serious problems. Thus potentially not detecting system or data integrity issues.
R.23	IT System, Human	V.OBSERVE.LOG-PROTECT	*Loss of system integrity*. The lack of a real-time independent reporting system can lead to a security compromise going undetected because an attacker is able to modify or destroy an alarm or log before they reach the technician. Thus potentially not detecting system or data integrity issues.

Risk ID	Threat-source	Vulnerability	Risk Summary
R.24	IT System, Human	V.OBSERVE.REPORT	*Loss of system integrity*. The lack of a real-time independent reporting system can lead to a security compromise going undetected due to poor reporting of security events. Thus potentially not detecting system or data integrity issues.
R.25	IT System, Human	V.OBSERVE.UNABLE	*Loss of system integrity*. The system is insensitive to certain events that may lead to a security compromise going undetected because the system is unable to detect the problem.
R.26	IT System, Human	V.OBSERVE.DISCLOSURE	*Loss of system confidentiality*. Security event records may be disclosed to unauthorized individuals thereby defeating protection of information from unauthorized disclosure.
R.27	Human	V.OPERATE.DELIBERATE	*Loss of system integrity*. The system design does not foster proper security implementation / management. If security mechanisms are not implemented properly, continued use of contaminated or corrupted data could result in inaccurate decision making and therefore loss of system integrity.
R.28	IT System, Human	V.OPERATE.NON-SECURITY	*Loss of system integrity*. A non-security function or process can be modified for the purpose of enabling an attack. If security mechanisms are not implemented properly and not able to detect the modification, continued use of contaminated or corrupted data could result in inaccurate decision making and therefore loss of system integrity.
R.29	IT System, Human	V.TRACEABLE.UNABLE	*Loss of system integrity*. Improper metrics capturing does not provide enough information to identify the source of a security breach. If a security breach is not resolved, continued use of contaminated or corrupted data could result in inaccurate decision making and therefore loss of system integrity.
R.30	IT System, Comm. Link	V.TRANSMISSION.CONTINUITY	*Loss of system availability*. Interruption of link continuity can affect the delivery of information and lead to loss of functionality. Loss of NAS A-A or A-G link availability negatively impacts system availability and its overall operational effectiveness.
R.31	IT System, Comm. Link	V.TRANSMISSION.QOS	*Loss of system availability*. Absence of QoS can affect delivery of information and lead to a loss of functionality. Loss of A-A and/or A-G link availability negatively impacts system availability and its overall operational effectiveness.

[Reference: Based upon risks identified in Table 4 of "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, by NASA Glenn Research Center.]

19.8 Methods to Mitigate Vulnerabilities / Security Controls

The goal of most security programs is to reduce risk. Risk mitigation is accomplished by decreasing the threat level by eliminating or intercepting the adversary before they attack, blocking vulnerabilities through enhanced security controls, or reducing the impact of the potential consequences should a threat be successful in exploiting a vulnerability. A good basic approach for mitigating risk is a strategy that leverages the appropriate combination of eliminating threats, blocking vulnerabilities, and reducing the adverse impact of successful attacks.

After information security objectives, needs, and ultimately requirements are identified, the selection of security controls to protect the organization operations (including mission, functions, image, or reputation), organizational assets, individuals, other organizations, or the Nation. Such protection can be achieved for communication and information systems with appropriate control of the information confidentiality, integrity (including data integrity, authentication, and data separation), and availability (including availability/ continuity of services, and non-repudiation).

In the context communication and information systems, security controls are safeguards and countermeasures used to achieve the security objectives/needs/requirements.

Security controls include the use of both technical and nontechnical methods.

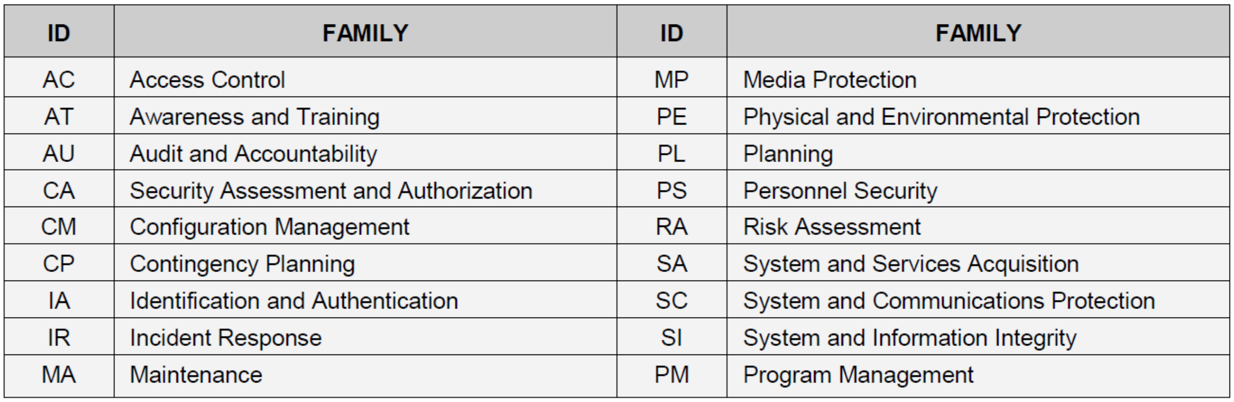
- Technical controls are safeguards that are incorporated primarily in computer hardware, software, or firmware. Examples of technical controls include: access control mechanisms/firewalls, identification and authentication mechanisms, encryption methods, and intrusion detection software.
- Non-technical controls are management and operational controls.
  - Management controls focus on processes that are performed by an organization to maintain information system security to an acceptable level of risk. Examples include security policies, configuration management, and contingency and recovery planning.
  - Operational controls focus on processes that are performed by people. Examples include personnel, physical, and environmental security measures like the use of identification badges and training employees and users in the proper operation of security systems.

Figure 208 lists the eighteen security control families identified in NIST Special-Publication 800-53 (draft Rev. 4). Each family contains security controls related to the general security topic of the family. A two-character identifier uniquely identifies security control families, for example, AC (Access Control) and SI (System and Information Integrity). Security controls may involve aspects of policy, oversight, supervision, manual processes, actions by individuals, or automated mechanisms implemented by information systems/devices. A detailed description of the controls associated with each of these families can be found in Appendix F of NIST SP-800-53.

The security controls listed in publication NIST SP-800-53 represent the state-of-the-practice safeguards and countermeasures for federal information systems and organizations. The security controls will be reviewed and revised periodically to reflect:

- Experience gained from using the controls;
- New federal legislation, Executive Orders, directives, regulations, or policies;
- Changing security requirements;
- Emerging threats, vulnerabilities, and attack methods; and
- Availability of new technologies.

Updates to the security controls are expected during the time horizon and implementation of the long range NAS A-A and A-G communication systems that are the subject of this study.



ID	FAMILY	ID	FAMILY
AC	Access Control	MP	Media Protection
AT	Awareness and Training	PE	Physical and Environmental Protection
AU	Audit and Accountability	PL	Planning
CA	Security Assessment and Authorization	PS	Personnel Security
CM	Configuration Management	RA	Risk Assessment
CP	Contingency Planning	SA	System and Services Acquisition
IA	Identification and Authentication	SC	System and Communications Protection
IR	Incident Response	SI	System and Information Integrity
MA	Maintenance	PM	Program Management

Figure 208 – Eighteen Security Control Families

[Reference: NIST SP-800-53 (draft Rev. 4), "Security and Privacy Controls for Federal Information Systems and Organizations," page 9.]

For the purposes of this evaluation, given that the Future A-A and A-G communication system are still very early in the candidate identification and evaluation phase, a list of applicable information system security controls that should be considered for future A-A and A-G systems, especially networked communication system. By way of example, basic Account Management functionality is an inherent security control found in nearly any modern information system that is anticipated be deployed for use in a generic NAS communication system. Figure 209 (page 302) documents the inherent security controls envisioned for the future NAS networked communications computing environment.

Figure 210 (page 308) correlates the risks identified in Figure 207 (page 297) with relevant IT security controls documented in Figure 209 and with other mitigating factors.

Figure 209 – Security Controls Envisioned for Comm. Environment

Family	Class	Control	Title	Description
Access Control	Technical	AC-2	Account Management	The organization manages information system accounts, including: a. Identifying account types (i.e., individual, group, system, application, guest/anonymous, and temporary); b. Establishing conditions for group membership; c. Identifying authorized users of the information system and specifying access privileges; d. Requiring appropriate approvals for requests to establish accounts; e. Establishing, activating, modifying, disabling, and removing accounts; f. Specifically authorizing and monitoring the use of guest/anonymous and temporary accounts; g. Notifying account managers when temporary accounts are no longer required and when information system users are terminated, transferred, or information system usage or need-to-know/need-to-share changes; h. Deactivating: (i) temporary accounts that are no longer required; and (ii) accounts of terminated or transferred users; i. Granting access to the system based on: (i) a valid access authorization; (ii) intended system usage; and (iii) other attributes as required by the organization or associated missions/business functions; and j. Reviewing accounts at a defined frequency. (2) The information system automatically terminates temporary and emergency accounts after a defined time period. (3) The information system automatically disables inactive accounts after a defined time period.
	Technical	AC-3	Access Enforcement	The information system enforces approved authorizations for logical access to the system in accordance with applicable policy.
	Technical	AC-7	Unsuccessful Login Attempts	The information system: a. Enforces a limit on the consecutive invalid login attempts by a user during a defined time period; and b. Automatically locks the account/node for a defined time period; locks the account/node until released by an administrator; delays next login prompt according to defined delay algorithm when the maximum number of unsuccessful attempts is exceeded. The control applies regardless of whether the login occurs via a local or network connection.

Family	***Class***	***Control***	***Title***	***Description***
Awareness and Training	Management	AT-1	Security Awareness and Training Policy and Procedures	The organization develops, documents, disseminates, and maintains a security awareness and training policy that addresses purpose, scope, roles, responsibilities, management commitment, coordination among organizational entities, and compliance.
	Operational	AT-2	Security Awareness Training	The organization provides security awareness training to information system users.
Audit and Accountability	Technical	AU-7	Audit Reduction and Report Generation	The information system provides an audit reduction & report generation capability. a. The information system provides the capability to automatically process audit records for events of interest based on selectable event criteria.
	Technical	AU-9	Protection of Audit Information	The information system protects audit information and audit tools from unauthorized access, modification, and deletion.
	Technical	AU-12	Audit Generation	The information system: a. Provides audit record generation capability for the list of auditable events defined in AU-2 at the specified information system components; b. Allows designated organizational personnel to select which auditable events are to be audited by specific components of the system; and c. Generates audit records for the list of audited events defined in AU-2 with the content as defined in AU-3.
Security Assessment and Authorization	Operational	CA-2	Security Assessments	The organization assesses the security controls in the information system and its environment of operation.
	Operational	CA-5	Plan of Action and Milestones	The organization develops and updates a plan of action and milestones for the information system to document the organization’s planned remedial actions to correct weaknesses or deficiencies noted during the assessment of the security controls and to reduce or eliminate known vulnerabilities in the system.
	Operational	CA-7	Continuous Monitoring	The organization develops a continuous security monitoring strategy.
Configuration Management	Operational	CM-3	Configuration Change Control	The organization: a) Determines the types of changes to the information system that are configuration-controlled; b) Reviews proposed changes to the information system with explicit consideration for security impact analyses; and c) Implements approved configuration-controlled changes;

Family	***Class***	***Control***	***Title***	***Description***
Contingency Planning	Operational	CP-2	Contingency Plan	The organization develops a contingency plan for the information system.
	Operational	CP-3	Contingency Training	The organization provides contingency training to information system users consistent with assigned roles and responsibilities.
Identification and Authentication	Technical	IA-2	Identification and Authentication	The information system uniquely identifies and authenticates organizational users (or processes acting on behalf of organizational users).
	Technical	IA-5	Authenticator Management	The organization manages information system authenticators for users and devices by: a. Verifying, as part of the initial authenticator distribution, the identity of the individual and/or device receiving the authenticator; b. Establishing initial authenticator content for authenticators defined by the organization; c. Ensuring that authenticators have sufficient strength of mechanism for their intended use;
	Technical	IA-5	Authenticator Management	(continued) d. Establishing and implementing administrative procedures for initial authenticator distribution, for lost/compromised or damaged authenticators, and for revoking authenticators; e. Changing default content of authenticators upon information system installation; f. Establishing minimum and maximum lifetime restrictions and reuse conditions for authenticators (if appropriate); g. Changing/refreshing authenticators per defined time period; h. Protecting authenticator content from unauthorized disclosure and modification; and i. Requiring users to take, and having devices implement, specific measures to safeguard authenticators.
	Technical	IA-6	Authenticator Feedback	The information system obscures feedback of authentication information during the authentication process to protect the information from possible exploitation/use by unauthorized individuals.
	Technical	IA-7	Cryptographic Module Authentication	The information system implements mechanisms for authentication to a cryptographic module as to authenticate access and to verify authorizations to assume the roles and perform services.
	Technical	IA-11	Re-authentication	Requires users and devices to re-authenticate is specified situations including: (i) when security categories of information systems change; (ii), when the execution of privileged functions occurs; (iii) after a fixed period of time; and (iv) periodically.

Family	***Class***	***Control***	***Title***	***Description***
Incident Response	Management	IR-1	Incident Response Policy and Procedures	The organization: a. Develops, documents, and disseminates incident response policy and procedures; and b. Reviews and updates incident response policy and procedures.
	Operational	IR-2	Incident Response Training	The organization provides incident response training to information system users consistent with assigned roles and responsibilities.
	Operational	IR-3	Incident Response Testing	The organization tests the incident response capability for the information system.
	Operational	IR-4	Incident Handling	The organization: a. Implements an incident handling capability for security incidents; b. Coordinates incident handling activities with contingency planning activities; and c. Incorporates lessons learned from ongoing incident handling activities into incident response procedures, training, and testing/exercises, and implements the resulting changes accordingly.
	Operational	IR-5 and IR-6	Incident Monitoring and Reporting	The organization tracks, documents, and reports information system security incidents.
	Management	IR-8	Incident Response Plan	The organization develops and incident response plan.
Maintenance	Operational	MA-2	Controlled Maintenance	The organization: a. ensures maintenance and repairs on information system components in accordance with manufacturer or vendor specifications and/or organizational requirements; b. Approves and monitors all maintenance activities; and c. Checks all potentially impacted security controls to verify that the controls are still functioning properly following maintenance or repair actions.
	Operational	MA-6	Timely Maintenance	The organization obtains maintenance support and/or spare parts within appropriate time period of failure.
Media Protection	Operational	MP-2	Media Access	The organization restricts access to defined personnel or roles
Physical and Environmental Protection	Management	PE-1	Physical and Environmental Protection Policy and Procedures	The organization develops, documents, disseminates, and reviews/ updates physical and environmental protection policy.
	Operational	PE-4	Access Control for Transmission	The organization controls physical access to transmission system.
	Operational	PE-9	Power Equipment and Cabling	The organization protects power equipment and power cabling for the information system from damage and destruction
	Technical	PE-11	Emergency Power	The organization provides a short-term uninterruptible power supply.

Family	***Class***	***Control***	***Title***	***Description***
Planning	Management	PL-7	Security Concept of Operations	The organization develops a security Concept of Operations (ConOps) for the information system.
	Management	PL-8	Information Security Architecture	The organization develops an information security architecture for the information system, reviews and updates, and ensures information security updates are reflected in the ConOps.
Personnel Security	Management	PS-1	Personnel Security Policy and Procedures	The organization develops a personnel security policy that addresses purpose scope, roles, and responsibilities
	Operational	PS-3	Personnel Screening	Screens individuals prior to authorizing access to the information system (e.g., Air Traffic Controller).
Risk Assessment	Management	RA-1	Risk Assessment Policy and Procedures	The organization develops, documents, and reviews/updates risk assessment policy and procedures.
	Operational	RA-2	Security Categorization	The organization: categorizes information and the information system in accordance with applicable federal laws, Executive Orders, directives, policies, regulations, standards, and guidance.
	Operational	RA-3	Risk Assessment	The organization conducts, documents, and updates risk assessment.
System and Services Acquisition	Operational	SA-4	Acquisition Process	The organization includes security requirements, descriptions, and criteria, explicitly or by reference, in the acquisition contract for the information system.
System and Communications Protection	Technical	SC-2	Application Partitioning	The information system separates user functionality (including user interface services) from information system management functionality.
		SC-3	Security Function Isolation	The information system isolates security functions from non-security functions.
	Technical	SC-6	Resource Availability	The information system protects the availability of resources by allocation, to prevent lower-priority processes from delaying or interfering with higher-priority processes.
	Technical	SC-8	Transmission Integrity	The information system protects the integrity of the transmitted information.
	Operational	SC-12	Cryptographic Key Establishment and Management	The organization establishes and manages cryptographic keys for required cryptography employed within the information system.
	Technical	SC-13	Cryptographic Protection	The information system implements crypto in accordance with applicable federal laws, Executive Orders, directives, policies, regulations, and standards.
	Operational	SC-17	Public Key Infrastructure Certificates	The organization issues public key certificates per policy.
	Technical	SC-23	Session Authenticity	The information system protects the authenticity of communications sessions.

Family	**Class**	**Control**	**Title**	**Description**
System and Information Integrity	Operational	SI-2	Flaw Remediation	The organization identifies, reports, and corrects information system flaws.
	Technical	SI-6	Security Function Verification	The information system verifies the correct operation of the security functions.
	Technical	SI-16	Memory Protection	The information system implements security safeguards to protect its memory from unauthorized code execution.
Program Management	Management	N/A	N/A	N/A

[Reference: NIST SP-800-53 (draft Rev. 4) and security controls identified in Table 5 of "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, by NASA Glenn Research Center.]

Figure 210 – Correlation of Risks and Security Controls for NAS Communications

Risk ID	Risk Summary	Correlation of Security Controls
R.01	*Loss of system integrity*. Disablement or modification of security functions allow attackers access to the system and can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.	**AC-2** [Account Management] **AC-3** [Access Enforcement] **AC-7** [Unsuccessful Login Attempts] **SC-2** [Application Partitioning] **SC-3** [Security Function Isolation]
R.02	*Loss of system confidentiality*. Eavesdropping on messages over the communications link violates protection of information from unauthorized disclosure.	**SC-13** [Cryptographic Protection] **SC-17** [Public Key Certificates]
R.03	*Loss of system integrity*. Users masquerading as another type of user create deception amongst the user population and foster an environment of inaccurate information.	**IA-2** [Identification and Authentication (Org. Users)] **IA-5** [Authenticator Management] **AC-3** [Access Enforcement]
R.04	*Loss of system integrity*. Technicians masquerading as an end user create deception amongst the user population and foster an environment of inaccurate information.	**IA-2** [Identification and Authentication (Org. Users)] **IA-5** [Authenticator Management] **AC-3** [Access Enforcement]
R.05	*Loss of system confidentiality*. Authorized users who gain unauthorized access to information violate protection of information from unauthorized disclosure.	**AC-2** [Account Management] **AC-3** [Access Enforcement] **AC-7** [Unsuccessful Login Attempts] **IA-6** [Authenticator Feedback]
R.06	*Loss of system integrity*. Authorized users who gain unauthorized access to resources or information can lead to corruption of information; which can result in incorrect decision making and reduce the assurance of the system.	**IA-2** [Identification and Authentication (Org. Users)] **IA-5** [Authenticator Management] **AC-3** [Access Enforcement]
R.07	*Loss of system availability*. An attacker can disrupt the A-A and/or A-G communication links and prevent the flow of information and thereby impact operations.	None.
R.08	*Loss of system availability*. An attacker can flood the A-A and/or A-G communication links with injected messages and thereby reduce availability and negatively impact operational effectiveness.	None.
R.09	*Loss of system availability*. An attacker can jam communications. This could reduce comm. availability and negatively impact operational effectiveness.	None.
R.10	*Loss of system availability*. An attacker can inject malformed packets into the comm. links consuming processing cycles and exhausting resources, thereby reducing availability of system and sub-system components.	**IA-2** [Identification and Authentication (Org. Users)] **AC-3** [Access Enforcement]
R.11	*Loss of system availability*. The NAS systems and/or sub-systems may become exhausted due to system error, non-malicious user actions, or DoS attacks against the A-A and/or A-G communication systems. This could reduce availability of system and sub-systems.	**SC-3** [Security Function Isolation] **SC-6** [Resource Availability]
R.12	*Loss of system integrity*. An attacker my delay/inject/modify/re-direct/re-order/re-play or alter messages on A-A and/or A-G comm. links which can lead to corruption of information resulting in incorrect decision making.	**SC-8** [Transmission Integrity] **SC-13** [Cryptographic Protection] **SC-23** [Session Authenticity]
R.13	*Loss of system confidentiality*. An attacker is able to eavesdrop and interpret information transmitted over the comm. links of thereby defeating protection of information from unauthorized disclosure.	**SC-13** [Cryptographic Protection]

Risk ID	Risk Summary	Correlation of Security Controls
R.14	*Loss of system integrity*. An attacker is able to impersonate another user of the system due to inadequate authentication of the system.	**AC-3** [Access Enforcement] **AU-9** [Protection of Audit Information] **IA-2 (8)** [Identification and Authentication (Org. Users)] **IA-6** [Authenticator Feedback]
R.15	*Loss of system integrity*. An attacker is able to inject malformed messages into the comm. links. This action can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.	**SC-8** [Transmission Integrity] **SC-12** [Cryptographic Key Establishment and Management] **SC-13** [Cryptographic Protection] **SC-23** [Session Authenticity]
R.16	*Loss of system integrity*. An authorized user is able to introduce unauthorized software in the system which may or may not be malicious. Unauthorized software installation undermines the software configuration process and reduces the assurance of the system.	**MA-2** [Controlled Maintenance] **MP-2** [Media Access]
R.17	*Loss of system integrity*. Known and unknown vulnerabilities in the operating system and supporting utilities are exploited which can lead to corruption of information resulting in incorrect decision making.	**AC-3** [Access Enforcement] **AC-7** [Unsuccessful Login Attempts] **AU-7** [Audit Reduction and Report Generation] **IA-2** [Identification and Authentication (Org. Users)] **IA-6** [Authenticator Feedback]
R.18	*Loss of system availability*. Security configuration is lost during system failure and is unable to re-establish communications upon restart resulting in denial-of-service. The system is unable to process information, thus reducing availability and negatively impacting operational effectiveness.	**IA-11** [Re-authentication] **CM-3** [Configuration Change Control] **SI-2** [Flaw Remediation] **SI-6** [Security Function Verification]
R.19	*Loss of system integrity*. Security function is disabled upon system restart. Thus potentially allowing attackers access to the system and can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.	**SC-2** [Application Partitioning] **SC-3** [Security Function Isolation] **SC-6** [Resource Availability] **SI-6** [Security Function Verification] **SI-16** [Memory Protection]
R.20	*Loss of system integrity*. During a failure recovery, the system enables security credentials which have previously been compromised. Thus potentially allowing attackers access to the system and can lead to corruption of information; which can result in incorrect decision making and eventually lead to loss of confidentiality and loss of availability.	**IA-2** [Identification and Authentication] **SC-3** [Security Function Isolation] **SC-6** [Resource Availability] **SI-6** [Security Function Verification] **SI-16** [Memory Protection]
R.21	*Loss of system integrity*. System compromises security information by writing to unprotected log during system failure. Thus the information is vulnerable to improper modification.	**AU-9** [Protection of Audit Information] **SI-6** [Security Function Verification] **SI-16** [Memory Protection] **PL-7** [Security Concept of Operations]
R.22	*Loss of system integrity*. The system collects too much log information and an administrator is unable to identify the most serious problems. Thus potentially not detecting system or data integrity issues.	**AU-7** [Audit Reduction and Report Generation] **AU-12** [Audit Generation]
R.23	*Loss of system integrity*. The lack of a real-time independent reporting system can lead to a security compromise going undetected because an attacker is able to modify or destroy an alarm or log before they reach the technician. Thus potentially not detecting system or data integrity issues.	**AU-9** [Protection of Audit Information]
R.24	*Loss of system integrity*. The lack of a real-time independent reporting system can lead to a security compromise going undetected due to poor reporting of security events. Thus potentially not detecting system or data integrity issues.	**AU-7** [Audit Reduction and Report Generation]

Risk ID	Risk Summary	Correlation of Security Controls
R.25	*Loss of system integrity*. The system is insensitive to certain events that may lead to a security compromise going undetected because the system is unable to detect the problem.	**PL-7** [Security Concept of Operations] **PL-8** [Information Security Architecture]
R.26	*Loss of system confidentiality*. Security event records may be disclosed to unauthorized individuals thereby defeating protection of information from unauthorized disclosure.	**AC-3** [Access Enforcement] **AU-9** [Protection of Audit Information]
R.27	*Loss of system integrity*. The system design does not foster proper security implementation / management. If security mechanisms are not implemented properly, continued use of contaminated or corrupted data could result in inaccurate decision making and therefore loss of system integrity.	**AC-3** [Access Enforcement] **SC-8** [Transmission Integrity] **SC-12** [Cryptographic Key Establishment and Management] **SI-2** [Flaw Remediation] **SI-6** [Security Function Verification]
R.28	*Loss of system integrity*. A non-security function or process can be modified for the purpose of enabling an attack. If security mechanisms are not implemented properly and not able to detect the modification, continued use of contaminated or corrupted data could result in inaccurate decision making and therefore loss of system integrity.	**MA-2** [Controlled Maintenance] **MP-2** [Media Access]
R.29	*Loss of system integrity*. Improper metrics capturing does not provide enough information to identify the source of a security breach. If a security breach is not resolved, continued use of contaminated or corrupted data could result in inaccurate decision making and therefore loss of system integrity.	**PL-7** [Security Concept of Operations] **IR-3** [Incident Response Testing]
R.30	*Loss of system availability*. Interruption of link continuity can affect the delivery of information and lead to loss of functionality. Loss of NAS A-A or A-G link availability negatively impacts system availability and its overall operational effectiveness.	**PL-8** [Information Security Architecture]
R.31	*Loss of system availability*. Absence of QoS can affect delivery of information and lead to a loss of functionality. Loss of A-A and/or A-G link availability negatively impacts system availability and its overall operational effectiveness.	**PL-7** [Security Concept of Operations] **PL-8** [Information Security Architecture]

[Reference: Based upon correlation of Risks/Controls identified in Table 6 of "UAS Integration in the NAS CNPC Architecture, Risk Assessment Report," Version 1.0, dated 01/16/2013, by NASA Glenn Research Center.]

19.9 NAS High Level Information System Security Objectives

The following set of high level security objectives as documented in ARINC Report 811 are applicable to future A-A and A-G communication systems.

- Aircraft information systems should use common security controls.
- The overall life-cycle cost of aircraft system security controls should be minimized.
- Aircraft information systems should employ multiple security controls to mitigate each significant threat.
- Development, operation, and maintenance of security controls for aircraft information systems should fit within the existing aircraft lifecycle.
- Security solutions for new systems should require as few changes as possible to existing systems.
- Security controls for aircraft information systems should be flexible in order to permit a variety of different operational policies and procedures.
- Aircraft information systems should provide effective operation to users performing authorized actions.
- Aircraft information systems should accommodate regular adoption of new security controls and technologies.
- Security controls for aircraft systems should require minimal administrative and operational overhead.
- Security controls for aircraft information systems should not inhibit airline mission accomplishment.
- Security controls for aircraft information systems should be based on open standards.
- Security controls for aircraft information systems should protect airlines, manufacturers, and system suppliers from threats that may affect their commercial image.
- Security controls for aircraft information systems should not compromise the safety of the aircraft.
- Security controls for aircraft information systems should mitigate the risks to an acceptable level.

[Reference: ARINC Report 811, developed by AEEC and entitled "Commercial Aircraft Information Security Concepts of Operation and Process Framework" (December 2005), Section 3.8, Table 1.]

19.10 Assessment Conclusion

While this section has identified and evaluated the threats, vulnerabilities, and resulting risks of generic NAS A-A and A-G ATM-relevant communications, especially in the more highly networked envisioned future ATM systems, it is not envisioned that all of the mitigations and controls identified will need to be implemented. Instead the implementation of the mitigations needs to consider the full operational environment including at least the intended operation(s), likelihood of the threats, operational mitigations, operational constraints, and the additional costs and effectiveness associated with the security controls.

There are several activities underway trying to address the aviation security challenges for the NAS elements, including the A-A and A-G communication systems. Finding security solutions that will be viable for all stakeholders will be a challenge. Additional research and development into aviation security issues and mitigations that take into account the full set of stakeholder issues is warranted.

The successful implementation of NAS communications / information security will require coordination and collaboration between traditional aeronautical stakeholders (e.g., airlines, aircraft manufacturers, avionics suppliers, ground systems suppliers, aeronautical service providers, FAA/civil aviation authorities, military aviation authorities) and information security and information technology experts.

Understanding of the specific threats, operational environment, and operational constraints is essential to identifying and implementing appropriate A-A and A-G communication security controls. Simply applying controls used by corporate information systems may not be appropriate or sufficient for NAS communication and information systems.

20 PHASE 2 INTERIM STUDY FINDINGS

The section of the report summarizes the interim study findings and provides a conclusion to the second phase of the study.

20.1 Summary of Phase 2 Interim Study Findings

1. While the focus of this study is on the long range future A-A and A-G data communication technology candidates (including their relevant infrastructure and architectural elements needed to address the NAS communication needs for NextGen and beyond), it is important to also consider the infrastructure and architecture of other functional elements of the NAS such that the overall NAS infrastructure and architecture can be optimized. Thus, this report has documented at a high level relevant other areas of the NAS infrastructure, especially the CNS infrastructure, since integration with or leveraging other infrastructure elements might yield significant cost savings.
2. Today's A-A and A-G communication systems are largely implemented using federated systems.
3. As NAS communication and information systems become more networked, there is the potential for increased cyber-attacks, similar to those experienced by corporate communication and information systems.
4. Understanding of the specific threats and operational constraints is key to identifying and implementing appropriate A-A and A-G communication systems security mitigations and controls. Simply applying information security controls used by the computer industry may not be appropriate or sufficient for NAS information and communication systems.
5. The successful implementation of NAS communications information security will require coordination and collaboration between traditional aeronautical stakeholders (e.g., airlines, aircraft manufacturers, avionics suppliers, ground systems suppliers, aeronautical service providers, FAA/civil aviation authorities, military aviation authorities) and information security and information technology experts.
6. There are several activities underway trying to address the aviation / security challenges for the NAS elements, including the A-A and A-G communication systems. Finding security solutions that will be viable for all stakeholders will be a challenge. Additional research and development into aviation security issues and mitigations that take into account the full set of stakeholder issues and holistically address the NAS security challenges is needed.

20.2 Interim Study Conclusion

This concludes Phase 2 of the study (presented in Sections 16 to 20 of this report) which was originally documented in the second in a series of five interim reports that were completed during the execution of this study to identify and evaluate air-to-air and air-to-ground candidates for meeting the long-term evolving needs of the National Airspace System during the modernization time horizon of 50 years. Subsequent sections of this document describe the results from phases 3 through 5 of the study.

Phase 3 of the study is documented in Sections 21 to 24. These sections describe a comparative cost analysis of the implementation, operation, and maintenance costs for the communications candidates.

Phase 4 of the study is documented in Sections 25 to 28. These sections: a) identify, describe, and prioritize a set of long-term ATM applications including identifying which applications could be supported by the communications candidates, and b) provide use case analyses for three of the highest priority applications including Delegated Interval / Interval Management, Delegated Separations, and Airborne Self-Separation.

Phase 5 of the study is documented in Sections 29 to 32. These sections identify criteria for prioritizing the communication candidates and describe the use of the criteria to prioritize the candidates from most promising to least promising.

21 COST ESTIMATION METHODOLOGY AND BENCHMARKS

This section of the report describes the cost estimation methodology that was used to estimate the costs for implementing, operating, and maintaining each of the various A-A and A-G wireless communication candidates, as well as various integrations for potential use in the NAS.

This section includes:

- An overview of four common cost estimation methods (Section 21.1)
- The cost estimation method used for the cost estimates in this report (Section 21.2)
- Benchmarks used as basis for parametric cost estimates:
  - Airborne System Cost Benchmarks (Section 21.3)
  - Ground System Cost Benchmarks (Section 21.4)
  - Satellite System Cost Benchmarks (Section 21.5)

21.1 Overview of Four Common Cost Estimation Methodologies

[Reference: Cost Estimating Methodologies, Teaching Note, by Tomeka S. Williams and Ellen Barber, Defense Acquisition University, February 2011, pages B-13 to B-24.]

There are four common analytical cost estimation methods commonly used to develop cost estimation for large acquisition programs. The four methods commonly used include: 1) Analogy; 2) Parametric (or Statistical); 3) Engineering (or Bottoms Up); and 4) Extrapolation of Actual Costs methods. Each of these cost estimation methods are described in the subsections below. Each of these common cost estimation methods is appropriate for different phases of system acquisition cycle as is illustrated in Figure 136.

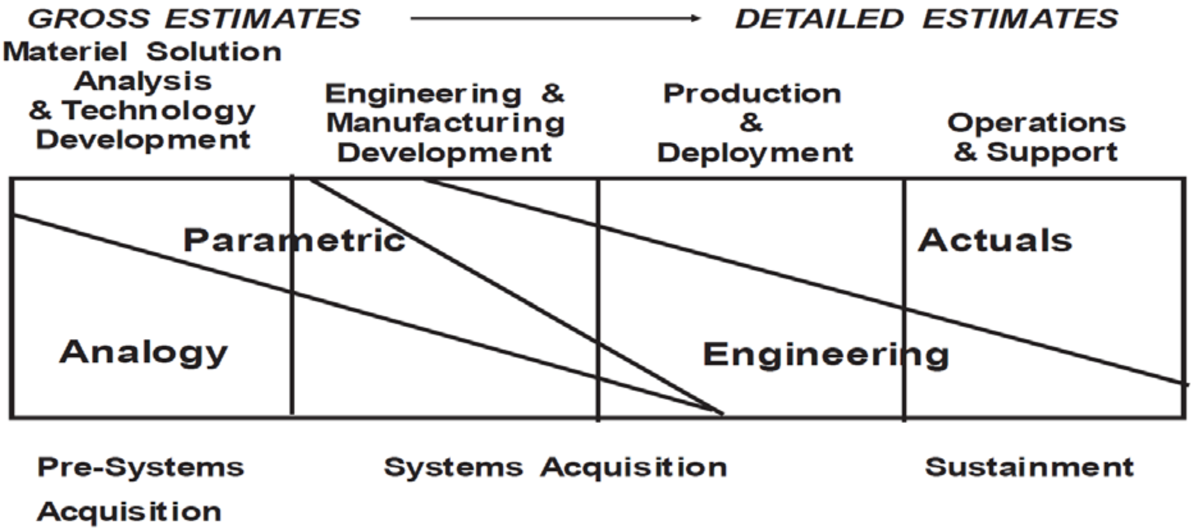


Figure 211 – Cost Estimating Methods Appropriate to Acquisition Phases

[Reference: Cost Estimating Methodologies, Teaching Note, by Tomeka S. Williams and Ellen Barber, Defense Acquisition University, February 2011, page B-14.]

21.1.1 Analogy Cost Estimation Method

The analogy method compares a proposed future system with a similar system in which the form, fit, and function are alike. The analogous system should be acquired in the recent past, for which there is accurate cost and technical data. There must be a reasonable and logical correlation between the proposed and “historical” systems identified by the cost estimator. This subjective evaluation of the differences between the new system of interest and the historical system is documented by the estimator. The analogy method is typically performed in the early stages of a development (or potential development). This is early in the life of a potential acquisition program when there may be a limited number of historical data points and the cost estimator may be dealing with technology that experiences rapid change. The analogy method is also a very common technique used for cross checking more detailed estimates (e.g., provides a sanity check).

With new and emerging technologies, finding an analogous system that is “similar” in form, fit, function, implementation technologies, etc., is often problematic.

Because of this, the basic analogy method is often improved by utilizing a variety of adjustment factors derived from the physical or performance differences between the system (or systems) used as the basis of estimate. Such factors may include complexity, inflation, performance factors, etc.

Estimating by analogy has many advantages. It is reasonably fast and inexpensive to generate such an estimate and easy to change. However, an estimate produced by analogy typically includes a high degree of cost risk because it is based on a single historical data point and tends to require subjective judgment as to what system is analogous and the extent of the similarities. Estimating costs through the use of the parametric cost estimation method is one way to address some of this cost risk.

21.1.2 Parametric Cost Estimation Method

The parametric method uses statistical relationships between historical cost and other factors to estimate costs for the new system. The factors may include one or more system performance or design characteristics (e.g., complexity, communications quality of service, bandwidth, coverage volume, etc.). Like estimating by analogy, the parametric method is most commonly performed during the initial phases of system development. Estimating cost using parametrics is a way to show how various factors influence cost.

A critical consideration in parametric cost estimating is the similarity of the systems in the underlying database used as benchmarks, both to each other and to the system which is being estimated. A good benchmark database must be timely and accurate, containing the latest available data that can readily be used to parametrically estimate the system of interest.

Estimating by the parametric method has many advantages over other estimating methods. Because the cost estimates are based upon more than a single data point, estimating by parametrics is less risky than estimating by analogy. A major benefit of applying the parametric method is that one can estimate the costs of future systems that are similar to the benchmarks but different in a number of areas that can significantly affect the cost with the use of appropriate cost sensitivity factors. The biggest downside of estimating by parametrics is that such a technique is constrained by the amount and quality of the data and the accuracy of the predicted cost sensitivity factors.

21.1.3 Bottoms-up (or Engineering) Cost Estimation Method

The "bottoms-up" (or engineering) method of cost estimation is the most detailed of all the techniques and the most costly to implement. It reflects a detailed build-up of labor, material, and overhead costs associated with the costs for the elements of the system being estimated. Estimating using the “bottom-up” method is typically performed when the system design is firm. Such a method is not appropriate for the current stage of estimating the costs associated with the A-A and A-G candidates, as many of the candidates are very early in the conceptual stages of development.

21.1.4 Actual Cost Estimation Method

The actual cost method of cost estimation is one that leverages the real development, deployment, and operation and maintenance costs of a current very similar program. It reflects costs for the development, deployment, and operation & maintenance of real systems. This may be based upon preferably very mature system costs or an early stage of low rate initial production, deployment, and operation. Estimating using actual costs is essentially an extrapolation of current system costs that is done when the system is fairly mature. Obviously, such a method is not appropriate for the current stage of estimating the costs associated with the A-A and A-G candidates, especially with potential implementation decades in the future.

21.2 Cost Estimation Methodology Used

The parametric cost estimation methodology has been used to estimate the costs associated with the various communication candidates. The cost estimation methodology that was applied identified and used relationships between historical costs associated with a number of relevant benchmark CNS systems that are in use today, the characteristics of the various alternatives that influence costs, and predictions for how costs will change over time.

A critical consideration when using the parametric cost estimation is the similarity of the systems in the underlying benchmark database to the systems for which cost is being estimated. Our team has identified a number of good benchmark systems that are we believe are appropriate for use in estimating the costs (or relative costs) of future candidate systems with appropriate cost adjustment factors applied.

21.3 Benchmarks for Airborne Systems

Information provided in this section was considered as part of the benchmark database for the parametric cost estimation method used for estimating the costs of airborne systems associated with the A-A and A-G future communications candidates.

21.3.1 Benchmark: HF, VHF, and SATCOM Avionics Catalog Equipment 2013 List Prices

Rockwell Collins is one of several suppliers who provide avionics equipment to today’s civil, military, and government aircraft. The aircraft include a variety of fixed-wing and rotary wing aircraft, including both manned and unmanned aircraft, conducting a wide variety of missions. Missions include, for example, large civil air transport passenger and cargo aircraft (e.g., large passenger aircraft including those from Airbus and Boeing), Business and Regional passenger and cargo aircraft (e.g., medium sized passenger aircraft from Bombardier, Embraer, Saab), Department of Defense (e.g., tactical aircraft like fighters, cargo aircraft, helicopters, UAVs), and government aircraft (e.g., FAA flight inspection vehicles, NASA space vehicles).

Catalogs of Rockwell Collins 2013 avionics equipment prices were reviewed by the authors of this document, including, for example:

- Commercial Systems Air Transport 2013 Price Book, Catalog Number 147-0132-009, Rockwell Collins, January 1, 2013.
- Commercial Systems Business and Regional 2013 Price Book, Catalog Number 147-0131-009, Rockwell Collins, January 1, 2013.

Sometimes, discounted prices are extended to original equipment purchasers (e.g., airline operators, original aircraft equipment manufacturers) depending upon a number of factors. Depending upon the aircraft and desired level of availability for the communications function, installations that include single, dual, and triple redundancy of equipment are common.

21.3.2 Benchmark: ADS-B Aircraft Equipment and Installation Costs

ADS-B Estimated Aircraft Equipment and Installation Costs per the FAA *[reference: http://www.aviationtoday.com/av/issue/cover/16804.html]* are as follows:

- $4,328 to $17,283 for GA aircraft
- $12,906 to $463,706 for turboprops; and
- $3,862 to $135,736 for turbojet aircraft

21.3.3 Benchmark: Aircraft Out of Service Costs

Taking aircraft out of service to perform system upgrades on in-service aircraft can be very expensive. For example, it has been estimated that aircraft out of service costs are on the order of:

- $100,000 per day for Air Transport aircraft
- $50,000 per day for Business and Regional aircraft
- $8,696 per day for Air Taxi
- $920 per day for General Aviation business aircraft
- $20 per day for General Aviation personal aircraft

Note that this study has not attempted to estimate the out of service cost for aircraft, which in many cases can far exceed the cost of the avionics equipment or its installation, if the aircraft was taken out of service solely for the Communication Systems upgrades that are the purpose of this study. However, the out of service cost may be essentially neglected if the aircraft is being taken out of service for other reasons (e.g., a periodic C or D check, where C check is light maintenance and D check is heavy maintenance); whereby, the incremental cost of performing an avionics upgrade may not extend the out of service time. Often the pacing items are any repairs of structural fatigue or engine maintenance.

[Reference: "Viewing NAS Evolution from the Perspective of Required Changes to Aircraft Avionics," by Ken V. Hollinger and Marc Narkus-Kramer, The MITRE Corporation, Center for Advanced Aviation System Development (CAASD), American Institute of Aeronautics and Astronautics, April 2007.]

21.3.4 Benchmark: Aircraft Avionics Maintenance Costs

Part of Rockwell Collins Company is an entity that provides avionics services and asset management known as "Dispatch^{SM} 100." This entity is part of Rockwell Collins' Integrated Service Solutions (ISS) business. Services include aircraft avionics maintenance services that include guaranteed spares availability, systems configuration updates, technical repairs and performance monitoring on our comprehensive suite of communications, surveillance, displays, and pilot controls systems.

While detailed costs for these services are not included in this report, benchmark information regarding the fixed fee performance contracts (see Figure 212) for aircraft maintenance was leveraged in the model for operations and maintenance described in Section 22.3.3. It has been estimated by an International & Services Solution strategist working for Rockwell Collins that the year over year maintenance cost as a percentage of sell price of avionics equipment is about 7%. This estimate was based upon the worldwide Air Transport aircraft fleet.

[Reference: Personal communications with Lenora Gehrls, Rockwell Collins, December 11, 2013.]

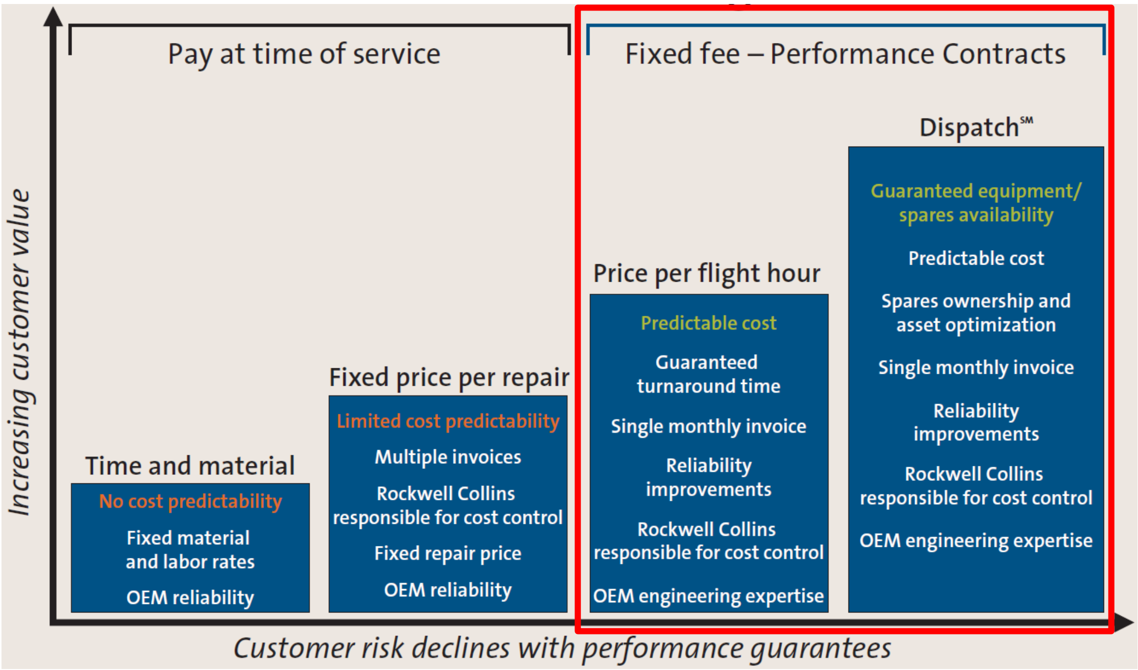


Figure 212 – Aircraft Maintenance

[Reference: Global Asset Management brochure #147-1264-002, Rockwell Collins, 2012, page 2.]

21.3.5 Benchmark: Number of Aircraft

Benchmark information regarding the number and types of aircraft in this section was utilized in the aircraft equipage models (see Section 22.3.4) used for cost estimation.

21.3.5.1 Number of Aircraft – ACAS Data Source

The quantify of active aircraft in the United States and the world, where aircraft include commercial aircraft, military transports, and business jets, from the AirCraft Analytical System (ACAS) November 2013 dataset that is updated monthly is provided in Figure 213.

Aircraft Type	**Quantity**
Active Commercial, Military Transport, and Business Jet Aircraft	67,781 (worldwide) 27,282 (United States)
Passenger Aircraft	23,994 (worldwide) 6,050 (United States)
Freighter Aircraft	3,230 (worldwide) 1,527 (United States)

Figure 213 – Number of Aircraft (2013)

[Reference: AirCraft Analytical System (ACAS) Dataset, November 2013.]

21.3.5.2 Number of Aircraft – 2013 Data Source

The quantity of active commercial aircraft, business, and regional aircraft in the United States is provided in Figure 214.

Aircraft Type	**Quantity**
Air Transport	4,811 (United States)
Business Aircraft	14,513 (United States)
Regional Aircraft	2,599 (United States)

Figure 214 – Number of Active ATS and BRS Aircraft in the United States (2013)

[Reference: Personal communications with Leorna Gehrls, Rockwell Collins, December 12, 2013.]

21.3.5.3 Number of Aircraft – FAA Administrator's Fact Book

According to the 2012 FAA Administrator's Fact Book, the NAS infrastructure contains:

- 18,023 commercial aircraft (CY 2011 data)
- 223,400 general aviation aircraft (CY 2010 data)

[Reference: FAA Administrator's Fact Book, June 2012]

21.3.5.4 Number of US Military Aircraft – Global Firepower

Figure 215 indicates the number of active aircraft, including both fixed-wing and rotary-wing aircraft of all types included UAVs, transports, gunships, etc. in the United States Military as of 2012 according to Global Firepower.

Aircraft (not-including Helicopters)	**Helicopters**
15,293	6,665

Figure 215 – Number of United States Military Aircraft of all Types (2012)

[Reference: http://www.globalfirepower.com/country-military-strength-detail.asp?country_id=United-States-of-America, December 14, 2012.]

Another source, Wikipedia, has provided a listing of the number and type of United States Military aircraft in each of the service branches. This information was summarized and is provided in Figure 216.

Service Branch	Fixed Wing and VTOL Aircraft	Helicopters	Large UAVs
Air Force	4688	92	306
Army	183	4870	20
Navy	1918	803	0
Marines	584	570	28
Coast Guard	89	142	0

Figure 216 – Number of United States Military Aircraft by Service Branch (2013)

[Reference: http://en.wikipedia.org/wiki/List_of_active_United_States_military_aircraft, November 26, 2013.]

21.3.5.5 Number of Aircraft – Google / GAMA Source

The number of aircraft and helicopters worldwide (as of 2003) was estimated as provided in Figure 217.

Aircraft Type	Worldwide Quantity [2003 Estimate]
General Aviation	312,000 (211,190 in US)
Passenger Aircraft	17,770
Military Aircraft	89,129
Civil Helicopters	26,500
Military Helicopters	29,700

Figure 217 – Number of Aircraft (2003)

[Reference: http://answers.google.com/answers/threadview/id/584144.html.]

According to the General Aviation Manufacturers Association (GAMA) as provided in the reference cited in Figure 217, there were (circa 2003) approximately 312,000 active general aviation aircraft worldwide and of these, approximately 211,190 were in the United States. General aviation (GA) is defined as all aviation other than scheduled commercial airlines and military aviation, and includes helicopters, single-engine piston-powered airplanes, multi-engine turboprops, and intercontinental business jets.

21.4 Benchmarks: Applicable to Ground Systems

Information provided in this section was considered as part of the benchmark database for the parametric cost estimation method used for estimating the costs of ground systems associated with the A-A and A-G future communications candidates.

21.4.1 Benchmark: ITT ADS-B System

[Reference: http://www.exelisinc.com/solutions/ADS-B/Pages/default.aspx]

The FAA awarded ITT an 18 year $1.86B contract to build, own, maintain, and manage through 2025 a network of 794 ADS-B transmit/receive ground stations, many installed on AT&T cellphone towers (i.e., AT&T is a contract partner to ITT). The FAA will pay “subscription charges” to ITT, just as the agency today buys telecom services from telecommunications companies.

- 794 ADS-B ground stations
- 3 data control stations at AT&T Data Hosting Centers for message processing
- 2 Network Operations Centers (NOC) (Primary in Herndon, VA and a backup in Middleton, NJ)
- 271 service delivery points: ADS-B data will be delivered to the FAA at 271 service delivery points located at the FAA Air Traffic Control Facilities (including towers, TRACONs, and En-route Centers)

The FAA’s annual expenditures to ITT for ADS-B services will be $100M ($0.1B)/year after the system is deployed.

21.4.2 Benchmark: FAA FY2014 Budget Applicable to Numerous Ground Systems

[Reference: Federal Aviation Administration FY2014 President’s Budget Submission]

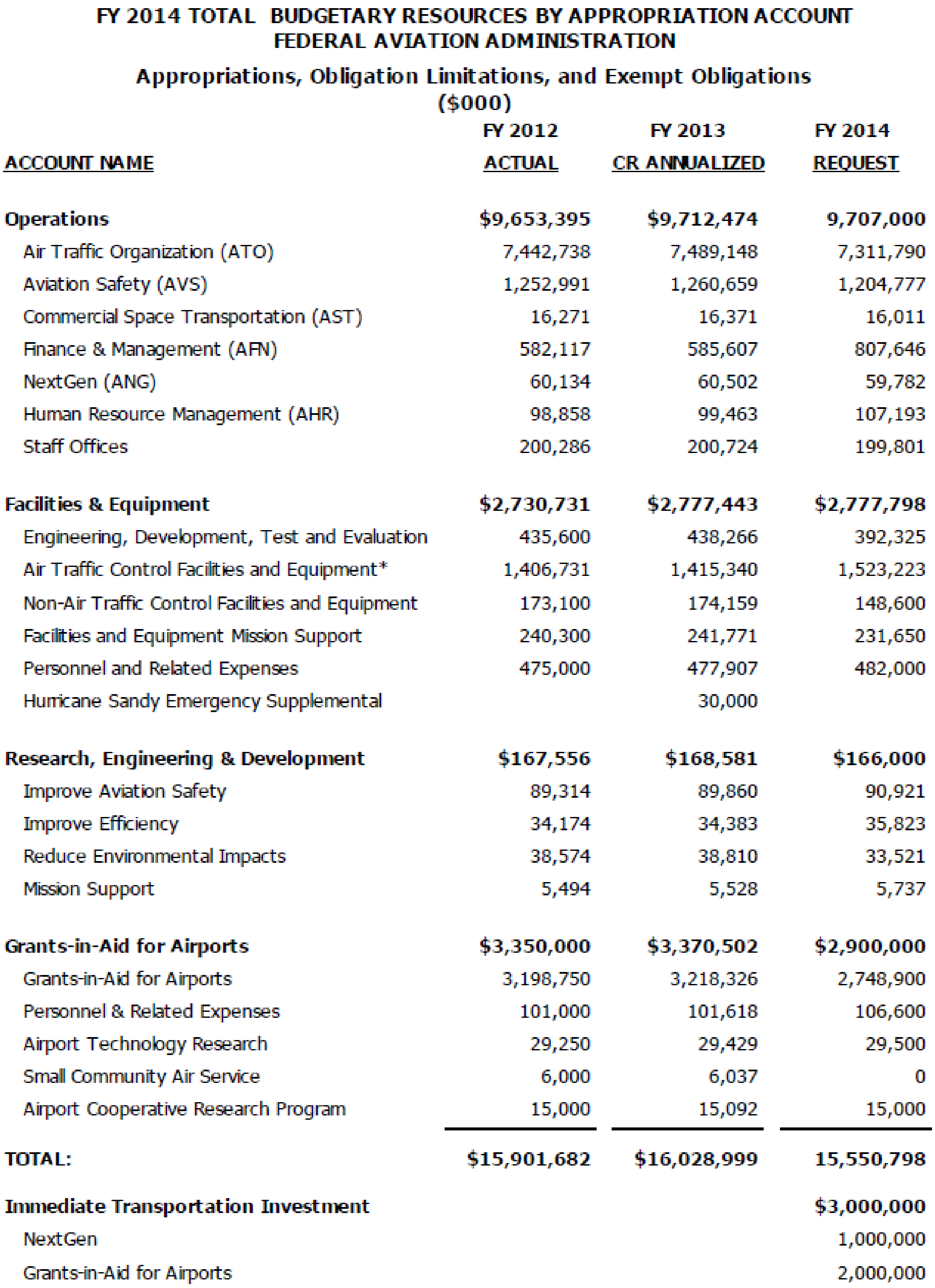
The FAA’s FY 2014 total budget request was $15.6 billion as allocated into the following accounts:

- $9.7 billion was for operations
- $2.8 billion for facilities and equipment (F&E)
- $166 million for research, engineering, and development (RE&D)
- $2.9 billion for grants-in-aid for airports
- $12 million for the Joint Planning and Development Office (JPDO)

In addition to the FAA $15.6 budget request, an additional $3 billion for Immediate Transportation Investment for aviation consisting of:

- $1 billion in NextGen efforts
  - NextGen is not a single program. It encompasses many programs, systems, and procedures, at different levels of maturity. Some are being deployed now, some are in development and nearing deployment, and still more are being defined as the technology necessary for them becomes available.
  - NextGen allocation: $928.1 million for F&E, $61.4 million for RE&D, and $12.6 million for operations.
- $2 billion for Airport Improvement Program

The FAA’s FY2012 to FY2014 budget appropriations are summarized in Figure 218.



FY 2014 TOTAL BUDGETARY RESOURCES BY APPROPRIATION ACCOUNT
FEDERAL AVIATION ADMINISTRATION

Appropriations, Obligation Limitations, and Exempt Obligations
($000)

ACCOUNT NAME	FY 2012 ACTUAL	FY 2013 CR ANNUALIZED	FY 2014 REQUEST
Operations	**$9,653,395**	**$9,712,474**	**9,707,000**
Air Traffic Organization (ATO)	7,442,738	7,489,148	7,311,790
Aviation Safety (AVS)	1,252,991	1,260,659	1,204,777
Commercial Space Transportation (AST)	16,271	16,371	16,011
Finance & Management (AFN)	582,117	585,607	807,646
NextGen (ANG)	60,134	60,502	59,782
Human Resource Management (AHR)	98,858	99,463	107,193
Staff Offices	200,286	200,724	199,801
Facilities & Equipment	**$2,730,731**	**$2,777,443**	**$2,777,798**
Engineering, Development, Test and Evaluation	435,600	438,266	392,325
Air Traffic Control Facilities and Equipment*	1,406,731	1,415,340	1,523,223
Non-Air Traffic Control Facilities and Equipment	173,100	174,159	148,600
Facilities and Equipment Mission Support	240,300	241,771	231,650
Personnel and Related Expenses	475,000	477,907	482,000
Hurricane Sandy Emergency Supplemental		30,000	
Research, Engineering & Development	**$167,556**	**$168,581**	**$166,000**
Improve Aviation Safety	89,314	89,860	90,921
Improve Efficiency	34,174	34,383	35,823
Reduce Environmental Impacts	38,574	38,810	33,521
Mission Support	5,494	5,528	5,737
Grants-in-Aid for Airports	**$3,350,000**	**$3,370,502**	**$2,900,000**
Grants-in-Aid for Airports	3,198,750	3,218,326	2,748,900
Personnel & Related Expenses	101,000	101,618	106,600
Airport Technology Research	29,250	29,429	29,500
Small Community Air Service	6,000	6,037	0
Airport Cooperative Research Program	15,000	15,092	15,000
TOTAL:	**$15,901,682**	**$16,028,999**	**15,550,798**
Immediate Transportation Investment			**$3,000,000**
NextGen			1,000,000
Grants-in-Aid for Airports			2,000,000

Figure 218 – FAA FY2012, FY2013, and FY2014 Budgets

[Reference: Federal Aviation Administration FY2014 President’s Budget Submission, Exhibit II-2.]

The Air Traffic Control Facilities and Equipment (F&E) program (activity 2 under the F&E account as presented in Figure 218) is requesting $1,523,223,500 for FY 2014, which is an increase of $116,492,500 above the actual FY 2012 level. This funding is intended for the FY 2014 efforts on the following programs:

- $523,875,200 is requested for NextGen technologies, tools, and systems;
- $999,348,300 is requested for legacy systems, buildings, infrastructure, and sustaining a safety infrastructure adequate for ATC services in the NAS.

This ATC F&E funding is targeted for modernization of air traffic control facilities, systems, and equipment. It will support FY 2014 infrastructure upgrades, system replacements, and technology refresh at manned and unmanned facilities to sustain equipment including:

- Ground-based radar
- Communications
- Automation
- Navigation
- Landing
- Other ATC systems and support equipment

In the FAA's FY2014 budget [per the reference provided at the beginning of this subsection, where page numbers refer to the specific page in the referenced budget request]:

- $5.5M has been allocated to maintaining Air/Ground Communications Infrastructure [page 275]
- $20.25M for Next Generation Very High Frequency Air/Ground Communications System (NEXCOM) [page 275]
- $11M for Alaskan Satellite Telecommunications Infrastructure [page 276]
- $115.45M for the Data Communications (Data Comm) program [page 303]
- $2.5M for VHF and HF Radio Equipment to continue funding the Very High Frequency (VHF) and national High Frequency (HF) radio network modernization efforts. Existing regional networks will continue to operate in the 25 kHz mode until all antiquated infrastructure equipment has been replaced with 12.5 kHz equipment in accordance with the National Telecommunications and Information Administration (NTIA). [page 265]
- $177.01M for paying for Automatic Dependent Surveillance-Broadcast (ADS-B) subscription services. [page 91]
- $8.3M for VOR with DME equipment whereby: a) $2.5M is requested for procurement of two VOR/DME Doppler Electronic Antenna Kits, 10 VOR/DME Hardware Antenna Kits, and to complete an on-going project to dopplerize a conventional VOR; and b) $5.8M is requested to fund a collaborative effort to manage the transition from a legacy network of VORs to a Minimum Operating Network (MON) by a target date of 2020. [Page 206]

- $4.0M for Distance Measurement Equipment (DME) is requested for: a) engineering and technical services/support ($330,000); b) procurement of 35 DME systems ($2,870,000), and c) completion of 35 establish/replacement DME projects ($800,000). [Page 219]
- $7.0M for Instrument Landing Systems (ILS) to support: a) engineering and technical services support, b) procurement of five ILS systems, c) completion of ILS replacement projects, and d) to begin three new ILS replacement projects. [Page 209]

21.4.3 Benchmark: Ground Cellular Networks

The benchmark information about ground cellular network costs provided in the subsections below was obtained from the following references.

[References:

AT&T, Sprint, and Verizon:

1. *http://www.forbes.com/sites/greatspeculations/2013/04/05/att-binges-on-lte-buildout-chasing-verizon/*
2. *http://dailycaller.com/2012/11/09/verizon-wireless-to-finish-network-upgrades-by-mid-2013/*
3. *http://www.forbes.com/sites/greatspeculations/2013/10/21/att-looks-to-free-up-cash-with-tower-sales-for-lte-upgrades-and-european-investments/*

Sprint:

4. *http://www.bloomberg.com/news/2013-06-26/sprint-sets-sights-on-verizon-at-t-as-deal-fight-recedes.html*

Verizon:

5. *http://gigaom.com/2009/10/05/verizon-spearheads-effort-to-pour-1-3b-into-lte/]*

While there are a number of references for cellular networks, there is minimal publically available information that provides a solid baseline relevant to cellular network costs in terms of the allocation among equipment, deployment, and operation & maintenance costs. The cost information that is publically available for cellular networks is difficult to interpret the scope of exactly what is covered by the cost expenditures with the mix of infrastructure, upgrades, towers, and purchase of spectrum. Nevertheless, the information contained in the following sections has been captured to support providing a basis of estimate for the candidate systems cost estimates.

21.4.3.1 Verizon LTE

LTE, or Long Term Evolution, is the next generation of high-speed data cellular networks. Verizon Wireless possesses the largest LTE network in the country.

The initial build of Verizon 4G Long Term Evolution (LTE) has been estimated at $1.3 Billion. It was initially launched in 30 markets (by 2010) and at the time of this writing (2013) has already covered ~170 million Americans in ~500 markets.

21.4.3.2 Sprint WiMAX

The initial LTE build to provide service to 123 million population by 2012 and 250 million population by 2013 has been identified to cost of $4-5B. Three frequency bands are being used including 800, 1.9, and 2.5 GHz with ~22,000 cell sites. Sprint is purchasing the Advanced Wireless Services (AWS) spectrum licenses at a cost of $3.6B.

21.4.3.3 AT&T LTE

As reported on the daily caller web site, AT&T planned to invest $22 billion dollars a year in its network over the next three years, including $14 billion in upgrades for both its wire-line and wireless networks.

As reported on the referenced Forbes web site (October 21, 2013):

- AT&T is in the midst of an LTE deployment phase that will cause capital spending to surge up to $21 billion this year and likely remain over $20 billion in the next two years as well.
- U.S. wireless carrier is looking to sell around 10,000 cell towers to Crown Castle International in a deal that could be worth as much as $5 billion, according to Bloomberg.
- Last year, Crown Castle International bought 7,200 cell towers from T-Mobile at around $2.4 billion.

21.4.4 Benchmark: HF Ground Systems

Rockwell Collins has a Government Systems division that has developed and deployed equipment for HF ground stations sited in the United States. While the details of the benchmark estimate will not be provided in this report, the approximate cost for the equipment at the site is ~$500K, without the non-recurring design costs.

[Reference: Personal communications with Manny Rivera, Rockwell Collins, December 9, 2013.]

21.5 Benchmarks: Applicable to Satellite Systems

Information provided in this section was considered as part of the benchmark database for the parametric cost estimation method used for estimating the costs of satellite systems associated with the A-A and A-G future communications candidates.

21.5.1 Benchmark: SATCOM Iridium Next

[References:

1. *Revolutionizing Air Travel Through Aireon's Global Space-based ADS-B Surveillance, Om P. Gupta (Aireon LLC), iCNS conference, April 24, 2013*
2. *http://en.wikipedia.org/wiki/Iridium_satellite_constellation]*

The section benchmarks the satellite build and deployment costs associated with Iridium NEXT satellite constellation. Figure 219 and Figure 220 provide an overview of the Iridium communications and costs for the satellite constellation upgrade, respectively. A summary of the satellite build and launch costs is as follows:

~$3B to upgrade the Iridium constellation (Iridium Next) includes:

- Satellite Equipment Build Costs:
  - $2.9B: Build of 81 new satellites (contracted with Thales Alenia Space)
  - Retain Low Earth Orbit (LEO) architecture, with 66 operational satellites, 6 in-orbit spares, and 9 ground spares
- Satellite Launch Costs:
  - Deployment between 2015 and 2017

  - $492M (contracted with SpaceX) to launch tens of Iridium NEXT satellites using SpaceX Falcon 9 rockets as the primary launch vehicle (7 launches of 10 satellites each) plus two satellites on a single launch of an ISC Kosmotras Dnepr rocket.

2012: Revenue $384M, Net of $65M (Thus, $319M/year operations and maintenance for current Iridium constellation)

- Customers:
  - Serving 611,000 customers
  - Anchor U.S. DoD customer represents 20% of revenue

Iridium Communications Overview

- Serving 611,000 customers
- Land-based handset, maritime, aviation, machine-to-machine (M2M) and government markets
- Anchor U.S. DoD customer represents 20% of revenue(1)
- 2012 net income of $65 million
  - Revenue of $384 million
  - Operational EBITDA (OEBITDA) of $206 million
- 2008-2012 service revenue and OEBITDA CAGRs of 10% and 17%

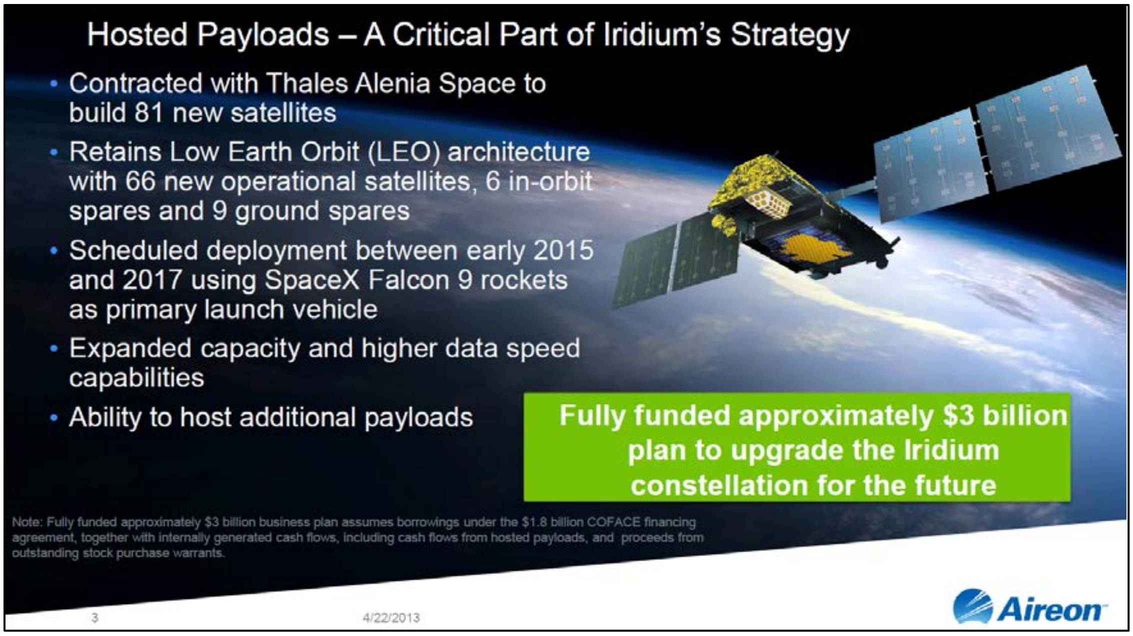
A vital, global communications provider of mobile voice and data services via 66 in-orbit satellites

(1) For the LTM period ended 12/31/12. Includes direct and indirect DoD revenue and revenue from certain other governmental entities through the DoD gateway.

2 4/22/2013 Aireon

Figure 219 – Iridium Communications Overview

[Reference: Revolutionizing Air Travel Through Aireon's Global Space-based ADS-B Surveillance, Om P. Gupta (Aireon LLC), iCNS Conference presentation, April 24, 2013, page 2.]



Hosted Payloads – A Critical Part of Iridium's Strategy

- Contracted with Thales Alenia Space to build 81 new satellites
- Retains Low Earth Orbit (LEO) architecture with 66 new operational satellites, 6 in-orbit spares and 9 ground spares
- Scheduled deployment between early 2015 and 2017 using SpaceX Falcon 9 rockets as primary launch vehicle
- Expanded capacity and higher data speed capabilities
- Ability to host additional payloads

Fully funded approximately $3 billion plan to upgrade the Iridium constellation for the future

Note: Fully funded approximately $3 billion business plan assumes borrowings under the $1.8 billion COFACE financing agreement, together with internally generated cash flows, including cash flows from hosted payloads, and proceeds from outstanding stock purchase warrants.

3 4/22/2013 Aireon

Figure 220 – Iridium NEXT Costs

[Reference: Revolutionizing Air Travel Through Aireon's Global Space-based ADS-B Surveillance, Om P. Gupta (Aireon LLC), iCNS Conference presentation, April 24, 2013, page 3.]

21.5.2 Benchmark: SATCOM Inmarsat Global Xpress

[Reference: http://www.inmarsat.com/career/corporate-compliance-officer/]

According to reference above, the costs and other relevant information associated with Inmarsat Global Xpress satellite constellation is given below. Inmarsat's Global Xpress will be the first worldwide Ka-band mobile satellite system.

- Three Inmarsat-5 (I-5) needed for global coverage are being launched on Proton rockets by International Launch Services from the Baikonur Cosmodrome in Kazakhstan.
- Each I-5 satellite is expected to have a commercial life of 15 years
- Procuring 4, I-5 satellites from Boeing, to be delivered by 2016
- Constellation plan: 3 satellites to provide global coverage and a 4th satellite is being built as a spare. Inmarsat is considering the business case to potentially launch the 4th satellite into the constellation to increase capacity and enhance network coverage.
- Cost $1.2B Inmarsat Next Generation of Satellites and Services: This includes 4.5 years cost of building four I-5 satellites (3 in-orbit and 1 spare), ground network, product development, launch services (for 3 satellites), and insurance. It does not include operation and maintenance.

21.5.3 Benchmark: SATCOM European Space Agency ANTARES Studies

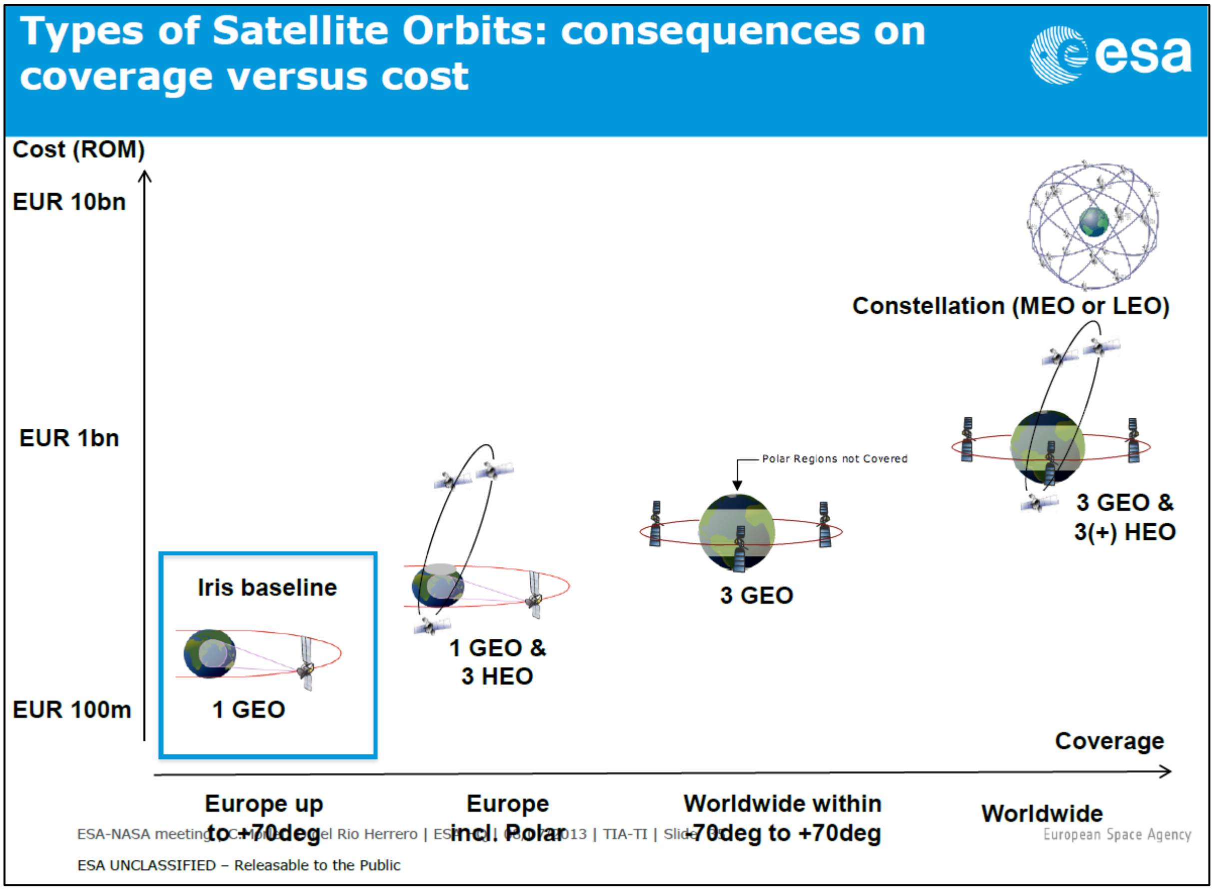
ANTARES (AeroNauTicAl REsources Satellite-based) is a study to conceptually design a new Satellite Communication System that supports future Air Traffic Management communications within European airspace. The ANTARES study that is part of the Iris program, which is a program created to study satellite-based solutions within the Single European Sky ATM Research (SESAR) program.

Within the Iris Program, ANTARES is a two-year study that focuses on the development of a new, ATM purpose-built, satellite-based communication system including low-cost user terminals and a new satellite communication standard. The ANTARES satellite-based communications system is being specifically designed to meet the operational, commercial and service requirements associated with the air-ground communications for ATM.

Additional information regarding the ANTARES and Iris programs can be found on the following ESA web site: http://telecom.esa.int/iris.

21.5.3.1 SATCOM: Initial Development and Deployment Cost Estimate

The European Space Agency (ESA) as part of future communications ANTARES system studies evaluated several types of satellite configurations. Figure 221 presents a summary of the estimated order of magnitude initial development and deployment costs (not including operations and maintenance/replenishment costs) associated with 4 different SATCOM configurations including: 1) a single GEO satellite covering Europe up to +70 degrees, 2) a single GEO with three HEO satellites to cover all of Europe including polar regions, 3) three GEO satellites that would provide worldwide coverage within +/- 70 degrees (i.e., does not include polar regions), and 4) three GEO with three HEO satellites that would provide worldwide coverage including polar regions. At the time of this writing, the approximate conversion is that 1 Euro (€) is approximately 1.3 dollars ($).



Types of Satellite Orbits: consequences on coverage versus cost

ESA UNCLASSIFIED – Releasable to the Public

Figure 221 – Estimated Costs for Various Satellite Systems

[Reference: Presentation: ESA-NASA Meeting on CNS/ATM, Catherine Morlet and O.del Rio Herrero, European Space Agency Head Quarters, July 8, 2013, slide 35.]

21.5.3.2 SATCOM: Ground-Earth Stations (GES)

[Reference: Personal communications with Catherine Morlet from the European Space Agency, November 26, 2013.]

The ROM cost estimate for Satellite ground-earth stations (GES) is 8M€ (~$10.9M) per year assuming an integrated ground segment, which is the most favorable case where all functions are centralized in one site. This cost estimate includes:

a. Hosting (use of existing infrastructure)
b. Electrical power
c. Property leases
d. License costs (if applicable)
e. Maintenance personnel
f. Equipment maintenance (maintenance contracts, consumables, and repairs)

21.5.3.3 SATCOM: Satellite Owner and Operator Sites

[Reference: Personal communications with Catherine Morlet from the European Space Agency, November 26, 2013.]

The ROM cost estimate for the Satellite Owner and Satellite Operator sites is 0.5M€ to 1M€ (~$0.65M to $1.3M) per year depending upon assumptions. This cost estimate includes:

a. Regulatory activities
b. Management and coordination of frequency spectrum
c. Preparation and attendance at ORM meetings
d. Maintenance of Satellite Operations Center (SOC) / Satellite Communications Center (SCC) infrastructure
e. In orbit testing
f. Station keeping
g. Close approach monitoring
h. Payload and eclipse operations, including solstice operations
i. Contingency training and rehearsal
j. Anomaly investigation and resolution
k. Lifetime analysis
l. Reporting

21.5.3.4 SATCOM: Network Operations Center (NOC)

[Reference: Personal communications with Catherine Morlet from the European Space Agency, November 26, 2013.]

The ROM cost estimate for the SATCOM NOC sites is 0.45M€ ($0.6M) per year. This cost estimate includes:

a. Network Management Center maintenance and operations, service delivery personnel
b. Network Control Center maintenance and operations

21.5.4 Benchmark: SATNAV GPS Development and Annual Operating & Maintenance Costs

[References: http://nation.time.com/2012/05/21/how-much-does-gps-cost/ and http://timemilitary.files.wordpress.com/2012/05/screen-shot-2012-05-21-at-11-51-31-am.png]

According to a 2012 congressional report cited by the references given above, the GPS constellation of 24 satellites plus spares cost:

- $12B: Cost to develop and deploy. The first GPS satellite was launched in 1974.
- $750M: The current estimated annual operating and maintenance costs of GPS Satellite System. This is over $2M/day.

21.5.5 Benchmark: SATNAV GPS III Cost Estimates

[Reference: Lower Cost Solutions for Providing GPS Capability, Report to Congressional Committees, United States Air Force, April 2013.]

According to the April 2013 congressional report cited in the reference above, the GPS III constellation of 30 satellites plus spares is estimated to cost:

- $25B: Estimated procurement cost for a GPS III 30-satellite constellation, not including 2 development units
- Launching satellites two at a time (dual launch) could reduce the cost by $3B (reduction of $80M per pair of GPS satellites)

[Reference: Defense Acquisitions, Assessments of Selected Programs, US Government Accountability Office (GAO) Report to Congressional Committees, March 2013.]

According to the March 2013 congressional report cited in the reference above, the GPS III program is estimated to cost:

- $2.71B: Research and development cost
- $1.53B: Procurement cost
- $4.34B: Total program cost
- $0.53B: Program unit cost

21.5.6 Benchmark: SATNAV GPS III Ground Control Segment Estimates

[Reference: Defense Acquisitions, Assessments of Selected Programs, US Government Accountability Office (GAO) Report to Congressional Committees, March 2013.]

According to the March 2013 congressional report cited in the reference above, the GPS III Next Generation Operational Ground Control System that will replace the current ground control system for all legacy and new GPS satellites is estimated to cost:

- $3.69B: Research and development cost
- N/A: Procurement cost
- $3.69B: Total program cost

21.5.7 Benchmark: SATNAV FAA Annual Operation and Maintenance for WAAS

[Reference: Federal Aviation Administration FY2014 President's Budget Submission]

The FAA's FY 2014 included paying for satellite leases/subscription services for the WAAS satellites as follows:

- $36.5M for the Wide Area Augmentation Systems (WAAS) for paying satellite leases/subscription services [page 91 of referenced FAA FY2014 budget].

22 COST MODEL

This section describes the cost model and assumptions used for estimating the total system costs for each of the various A-A and A-G communication candidates, as well as the various integrations of those candidates that are provided in Section 23.

The cost model in this section includes a description of the:

- Total system cost model and its four components (Section 22.1)
- Significant cost model assumptions (Section 22.2)
- Airborne cost models (Section 22.3)
- Ground cost models (Section 22.4)
- Satellite cost models (Section 22.5)

22.1 Total System Cost Model Overview

The cost model used in this report for the purposes of estimating the various future communications candidates and their integrations is formulated based upon summing the costs from four components as depicted in Figure 222. The four components of the total system cost include: 1) Technology Maturation and Standards Costs, 2) Equipment Costs, 3) Deployment Costs, and 4) Operation and Maintenance Costs. Each of these four components to the Total System Cost is described in the sub-sections below.

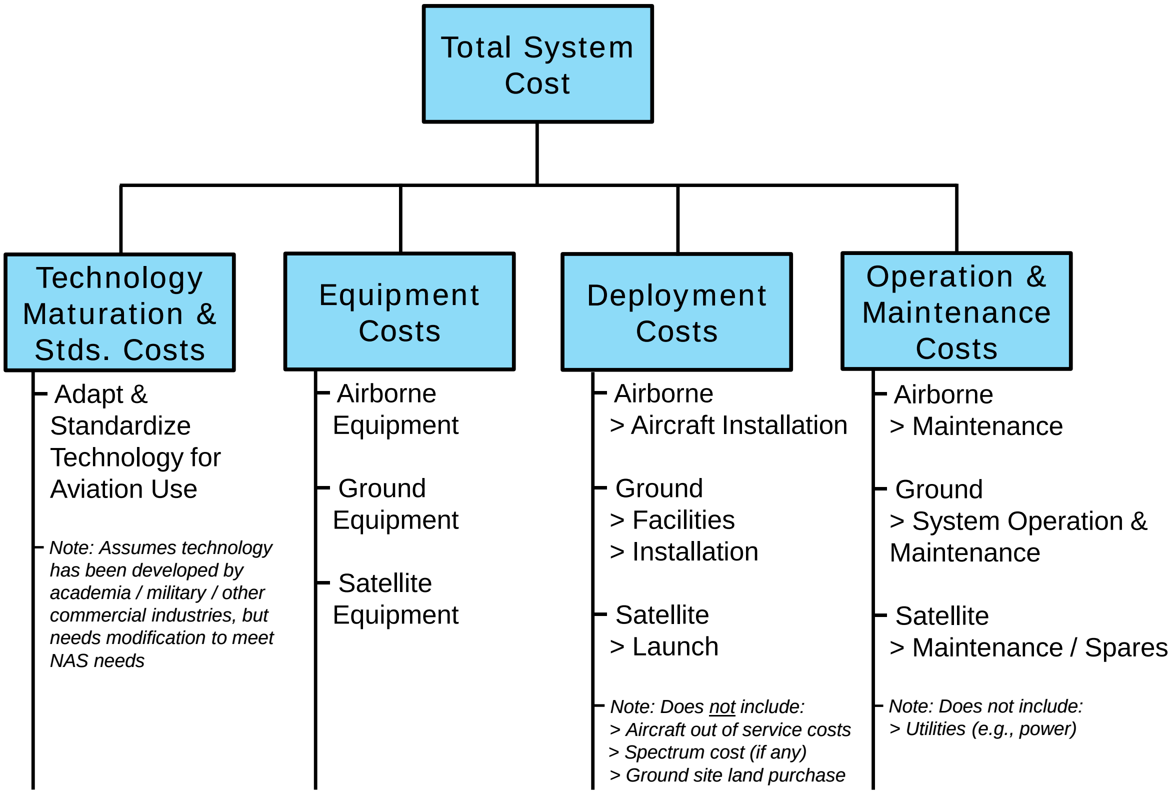


Figure 222 – Total System Cost Model

22.1.1 Technology Maturation and Standards Costs

The technology maturation and standards costs are an estimate of the incremental costs that need to be borne by the aviation community to adapt and standardize a given technology candidate to meet the needs of the NAS assuming that the technology has been matured by other entities (e.g., academia, military, government, or other commercial industry) for non-civil aviation use.

This approach was chosen so as not to fully burden immature technology candidates with the full R&D expenditures required to mature a technology candidate from its current technology readiness level to the level needed for incorporation in the NAS. Instead, the cost model has only burdened a currently immature technology candidate with the incremental costs that would need to be paid by the NAS stakeholders to incorporate a technology that has been matured to support other commercial industries.

22.1.2 Equipment Costs

Equipment costs include all the costs associated with designing, developing, manufacturing equipment and having the equipment approved or certified for use in the NAS. The cost estimates have incorporated the non-recurring costs (e.g., design, development, and certification/approval) into the cost of the equipment.

For the airborne equipment costs associated with NAS communication candidates, it includes the cost of "certified" communications avionics equipment and antennas. It does <u>not</u> include the costs for modifying downstream equipment (e.g., FMS, displays/human machine interfaces, and decision support equipment) for utilizing or displaying the information communicated to support a wide variety of applications. For ground equipment costs, it includes the cost of ground communication equipment. For satellite costs, it includes the cost of the satellites.

22.1.3 Deployment Costs

Deployment costs include the cost of taking the equipment and installing it in a deployed state. For airborne deployment costs, the cost estimates include installation of the equipment on the aircraft, but have <u>not</u> included any lost revenue or lost opportunity costs for taking aircraft out of service to perform the installations. See assumptions given in Section 22.2 (page 335).

For ground system deployment costs, the cost estimates include the cost of building the facilities and installing the equipment on site. It does <u>not</u> include the cost of purchasing the land for the ground facilities.

For satellite system deployment costs, the cost estimates include the cost to launch the satellites into their desired orbits.

The deployment costs have <u>not</u> attempted to estimate any potential costs associated with acquiring the spectrum allocation.

22.1.4 Operation and Maintenance Costs

The operation and maintenance costs include the costs associated with using the system in a manner that supports providing the intended function of the system (i.e., operational use of the system) and maintaining the equipment to be able to continue to perform its intended function. The maintenance costs include both preventative maintenance (where equipment is maintained before it breaks down) and corrective maintenance (where equipment is repaired or replaced after it breaks down).

22.2 Cost Model Assumptions

A number of assumptions have been made in the cost model as are identified in this section.

- The costs of each system have been normalized to today's (2013) costs, even though the system may not be technically realizable for many years because technology needs to mature.
- It has been assumed that the total cost of maturing currently immature candidates will not be solely burdened on the air transportation system users (i.e., other entities will also mature currently immature candidate technologies).
- For the purposes of cost comparison, it has been assumed that the useful life of the system is 25 years, whereby the life of the airborne systems, ground stations, and satellite systems is as follows:
  - Airborne Systems: 25 year life. For the purposes of comparison, it is assumed that each candidate will require one installation of new avionics communications equipment (e.g., radio, antenna, and communication management unit) for all candidates. Any interim updates or repairs costs are estimated as part of the operation and maintenance costs.
  - Ground Stations: 25 year life. It is assumed that each candidate will require one installation of new ground communications equipment, and any interim updates are estimated as part of the operation and maintenance costs.
  - Satellite Systems: There are different assumptions based upon whether the system is a LEO, MEO, GEO, or GEO + HEO.
    - LEO satellite systems are assumed to have a useful life of 6.25 years. Thus, it is assumed that the entire LEO satellite constellation needs to be built and deployed 4 times during the 25 year system life comparison [i.e., once at initial deployment, and then again after 6.25 years, 12.5 years, and 18.75 years].
    - MEO satellite systems are assumed to have a useful life of 8.33 years. It is assumed that the MEO satellite constellation needs to be built and deployed 3 times during the 25 year system life comparison [i.e., once at initial deployment, and then again after 8.33 years and 16.67 years].
    - GEO satellite systems are assumed to have a useful life of 12.5 years. It is assumed that the GEO satellite constellation needs to be built and deployed 2 times during the 25 year system life comparison [i.e., once at initial deployment, and then again after 12.5 years].
    - GEO + HEO satellite systems are assumed to have a useful life of 12.5 years. It is assumed that the GEO + HEO satellite constellation needs to be built and deployed 2 times during the 25 year system life comparison [i.e., once at initial deployment, and then again after 12.5 years]. While the GEO satellite is likely to last at least 12.5 years, the HEO satellite will typically not. The cost estimate has compensated for this by including additional spares and higher operations and maintenance costs for additional intermediate launches of the HEO satellites to maintain the constellation.

- For the purposes of cost comparisons presented in this report, the cost of inflation has been assumed to be equivalent to the time value of money.
  - This assumption has been made to simply the model and to not obscure the predicted costs with the compounding effects of inflation over multiple decades.
- No cost burden has been estimated for lost revenue or lost opportunity when taking equipment (e.g., aircraft, ground systems) out of service to upgrade with the new technology.
  - It is recognized that taking an aircraft out of service (e.g., to upgrade the communication systems), especially on aircraft that perform commercial operations like those for the airlines, can result in substantial lost revenue costs. However, if scheduled appropriately where the aircraft is already out of service (e.g., during a periodic maintenance checks, like a C-check or D-check were the aircraft is already out of service), then the incremental out of service cost for the communications technology upgrade may be negligible. For the purposes of the modeling herein, lost revenue or lost opportunity costs have not been estimated.
- No costs have been estimated to account for any potential costs associated with acquiring the spectrum allocation. Historically, the FAA has not paid for any spectrum allocation; although, the FAA and others have incurred costs of national and international spectrum management [e.g., support for International Telecommunication Union (ITU), World Radio Conferences (WRC), NTIA, and FCC spectrum management activities].
- For the purposes of the initial cost comparisons, it is assumed that avionics are developed to Level C software and hardware design assurance [as defined in RTCA DO-178() and DO-254(), respectively] commensurate with today's avionics communication system requirements per the applicable RTCA Minimum Operational Performance Standards (MOPS).
  - It is recognized that some future communications applications (e.g., UAS Command Non-Payload Communications) may require the communication functions that have higher design assurance levels. An estimate of the sensitivity of the cost estimates to higher design assurance levels (i.e., Level A and Level B) is provided in Section 23.4.2.
- For the purposes of relative cost comparisons between the candidate technologies (i.e., to develop a "cost score" for each candidate), it has been assumed that all aircraft in the aircraft fleet model (see Section 22.3.4 which describes several aircraft fleet models) are equipped with the particular communications candidate.
  - Note that this assumption was made to enable a better relative comparison of the costs of the various candidates. If this assumption was not made, then those candidates that have the fewest aircraft equipped (e.g., candidates intended for only aircraft that travel in remote/oceanic/polar airspace – like HF) would tend to have the lowest total system cost. This would make the relative cost comparison between technologies very hard to interpret.
  - Less than total aircraft fleet equipage assumptions for each candidate were made when estimating the costs for the integration alternatives as described in Section 6.3.
- For the purposes of relative cost comparisons between the candidate technologies (i.e., to develop a "cost score" for each candidate), the airborne systems have been cost estimated as single (non-redundant) systems. To support many ATM applications, it is

recognized that airborne equipment (e.g., antennas, radios, etc.) may need to have redundant (e.g., typically dual or triple) equipment installations to achieve the performance (e.g., availability) commensurate with the required communications performance (RCP) for the intended operations. However, for the purposes of cost scoring the candidates, single (non-redundant) systems installations was cost estimated.

- It is assumed that the non-recurring costs of system (e.g., design, development, and certification/approval) for equipment are spread across the number of units sold commensurate with a business case. This is one of the reasons that aviation "equipment" costs seem high relative to consumer goods. But when there are low volumes of equipment built, the cost per unit is heavily burdened by the non-recurring costs. While often equipment built for military/government entities sometimes pay the associated NRE and equipment costs separately, it has been modelled as an equivalent cost per unit that has by burdened by NRE costs.
- Costs have been estimated by grouping aircraft into 8 different categories as described in Section 22.3. The airborne equipment, deployment, and operation & maintenance cost estimates are intended to be an average for each group of aircraft, taking into account the cost variation across the aircraft types within a given aircraft category including a mix of new and retrofit aircraft.
- It is assumed that future communication systems will have required performance for A-A and A-G communications equipment in terms of reliability, integrity, continuity, and maintainability that will be similar to today's equipment.
- It is assumed (predicted) that over time, communications equipment manufacturers for airborne, ground, and satellite systems will increase the efficiency of product developments through the use of improved tools (e.g., model based developments) that will reduce the system/hardware/software development, verification, and testing costs.
- It is assumed that future communication system will have additional functional and design requirements (e.g., additional security requirements).
  - It is assumed that the operational and maintenance costs associated with the security aspects of utilizing the A-A and A-G communications candidates in the NAS will be minimal (e.g., not require significant costly operational and maintenance costs associated with the security features for future communications equipment).
- It is assumed that GEO SATCOM antennas will be developed to fit, even on small aircraft with either: a) technology advances that will enable small form factor antennas to both transmit and receive to/from GEO satellites, or b) the small form factor antennas to be capable of receiving GEO satellite transmissions but not transmitting to GEO satellites.
- For the purposes of relative candidate technology cost comparison, it is assumed that re-use of existing infrastructure is rather limited. While there is very high potential re-use of land to site towers/ground facilities, it is assumed and predicted 50 years in the future that there will be very limited to no buildings, towers, satellites, and aircraft equipment that is currently deployed that can be reused and will need to be replaced sometime between now and 50 years in the future. Thus, relative costs between the candidates have been consistently cost scored with the consistent assumption of virtually no reuse.
- Additional assumptions are included in the descriptions of the Airborne, Ground, and Satellite cost models provided in the Sections 22.3, 22.4, and 22.5 (respectively).

22.3 Airborne Cost Models

For the purpose of airborne cost modeling, aircraft were grouped and costs were predicted in eight different aircraft categories including:

1) Air Transport Aircraft (e.g., Boeing 707 to 787 aircraft, A300 to A380 aircraft)
2) Business, Regional, and Other Commercial Aircraft
3) General Aviation
4) UAV Big
5) UAV Small

   Note: The term "UAV Small" in this report refers to UAVs that are between approximately 500 and 15000 pounds, which is different than that for a "small" UAV being defined by the FAA (as of this writing, is notionally less than 55 pounds). Perhaps a better label for the category in this report would be "UAV Medium" to avoid confusion.

6) Military Transport (e.g., C-5, C-17, KC-135, etc.)
7) Military Non-Transport (e.g., fighter, helicopters, trainers, etc.)
8) Space Vehicles

Other aircraft groupings are possible. Even within these groupings, there is a wide variation in the aircraft that fit within the group. The resulting cost estimates for communication equipment, installation, and operation & maintenance are meant to be an average for each group of aircraft, taking into account the cost variation across the aircraft types within a given aircraft category including a mix of new and retrofit aircraft. Individual aircraft types may be significantly higher or lower than the nominal average cost estimated for each category of aircraft.

22.3.1 Airborne Equipment Cost Models

Benchmark airborne equipment costs have been identified in Section 21.3.1 for today's Air Transport and Business and Regional Systems aircraft. Also known, but not included in the text of this report are the approximate equipment costs for today's General Aviation, Military, and UAV aircraft.

It is predicted that over time, avionics manufacturers will increase the efficiency of product developments through the use of improved tools (e.g., model based development) that will reduce the system/hardware/software development, verification, and testing costs. It is also predicted that moving toward more software defined radios will enhance system reuse, and that there will be more aircraft to spread non-recurring costs (e.g., NRE) over. This will over time significantly reduce the relative cost for avionics equipment by a predicted (and assumed) 70% for an equivalent level of functionality as today.

However, many of these systems are expected to become more capable and more complex (utilizing advanced signal, information, and data compression/data acceleration techniques) to improve the operational efficiency of the available communications bandwidth, use directional and/or "smart" antennas technologies that will enable the use of higher order modulations, longer communications ranges, and the ability to form beams to support rejecting interference and improving frequency re-use. To gain further operational efficiencies, customers will likely want more conformal antennas to reduce drag. Future airborne communications equipment is also envisioned to have additional functional requirements (e.g., security requirements, entire band reception requirements). These additional improvements, depending upon the candidate have been estimated (and assumed) to add on the order of 25% to the cost of today's equipment.

For civil aircraft, the Air Transport market today tends to be the most expensive. In the future, the most expensive segment is envisioned to become civil spacecraft (with few aircraft to spread NRE costs over), followed by air transport (which includes extremely large "cargo" UAVs based upon the air transport aircraft), business and regional systems, UAVs in the NAS, and general aviation. Today's airborne equipment sell prices are established by avionics equipment manufacturers developing business cases around the expected markets, and as such the non-recurring costs associated with developing, certifying, and maintaining a product are spread across the avionics equipment costs with assumptions of the number of units that will be sold. In addition, recurring costs for manufacturing and profit are added to the unit price.

The military/government market for airborne equipment has traditionally had a different cost model; whereby, military/government customer have typically paid the non-recurring costs as a cost plus fixed fee, and then there is a specified cost for the production units that is negotiated. The military seems to be moving more toward the civil cost model, to reduce costs. However, the military equipment is typically more expensive than commercial products because of typically higher performance specifications (e.g., temperature, vibration, etc.), often smaller form factors, and additional functional requirements.

The government space vehicle market has traditionally been the most expensive with relatively few aircraft to spread non-recurring costs over and additional functional and performance requirements (e.g., radiation hardening, temperature ranges, antennas that need to be capable of pointing from a variety of aircraft attitudes).

The nominal Air Transport Systems (ATS) airborne system costs have been estimated (single redundancy), based upon benchmarks of today's VHF, HF, and SATCOM systems taking into account expected cost reduction of 70% for equivalent functionality, and a 25% growth in cost resulting from additional requirements/greater capability/greater complexity for an overall cost that is ~55% of today's benchmarks (computed as 55% = 100% - 70% + 25%, or in other words 45% less cost).

Then, based upon the estimated ATS avionics equipment cost, cost factors have been estimated and have been applied to estimate the cost for other aircraft types as follows:

- Business and regional aircraft comm airborne equipment has been estimated to cost 70% of the ATS comm equipment cost (based upon current cost benchmarks), and similarly the cost factors for the remainder of the aircraft categories have been estimate as:
- GA: 10%
- UAV Big: 65%
- UAV Small: 12%

  Note: The term "UAV Small" in this report refers to UAVs that are between approximately 500 and 15000 pounds, which is different than that for a "small" UAV being defined by the FAA (as of this writing, is notionally less than 55 pounds). Perhaps a better label for the category in this report would be "UAV Medium" to avoid confusion.

- Military Transport: 110%
- Military Non-Transport: 150%
- Space Vehicles: 1000%

These costs per airborne system (single redundancy) are then multiplied by the number of aircraft in each aircraft category to develop the total airborne implementation cost score for a given technology candidate.

22.3.2 Airborne Equipment Deployment/Installation Cost Models

The airborne equipment deployment/installation cost model is based upon a model that factors the airborne equipment costs for each of the candidates to obtain an estimate of the installation cost. This factor of 0.25 is used, which is based upon engineering judgment for the approximate nominal cost to install avionics equipment, not including an out-of-service/lost opportunity cost.

22.3.3 Airborne Equipment Operation & Maintenance Cost Models

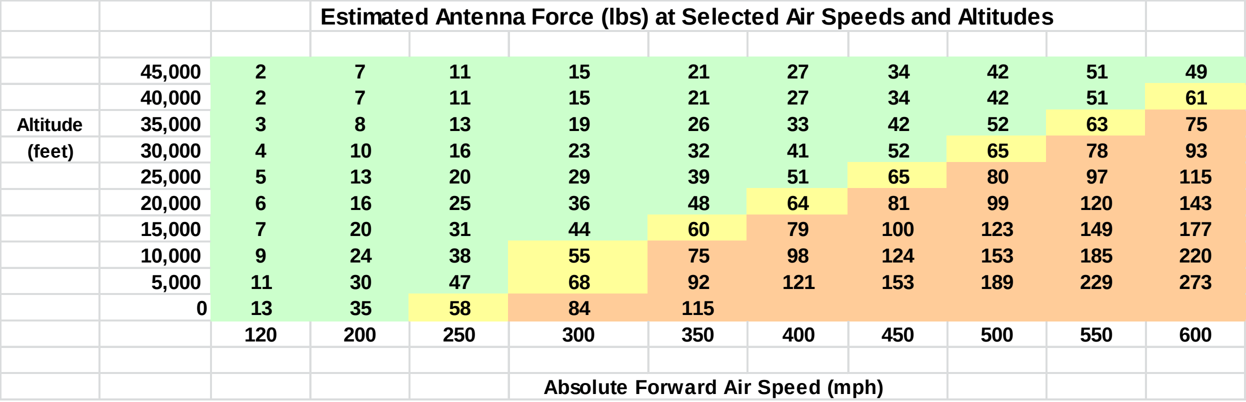
The airborne equipment operation and maintenance cost model is based upon a model that factors the airborne equipment costs for each of the candidates as well as a model for the number of aircraft being operated and maintained during the system life cycle estimate period of 25 years.

The yearly operation and maintenance model for each aircraft has been estimated at 15% of the airborne equipment costs for all aircraft per year in operation. This model has utilized the maintenance benchmark data provided in Section 21.3.4 and engineering judgment for additional costs associated with aircraft maintenance that were not included in the benchmark data and to account for operational costs.

One of the operational costs results from the drag on aircraft antennas, which can be quite significant especially for candidates where their antennas are less conformal to the aircraft. For example, the estimated drag force (in pounds) as a function of aircraft speed and altitude is provided in Figure 223 as representative of today's KU band SATCOM antennas.

Figure 223 depicts the approximate load force of a 0.4167 square foot leading edge Ku band SATCOM antenna (3" high x 20" long) at various cruse altitudes and speeds. This force is significant and impacts the fuel efficiency of an aircraft. For antennas of this size, a cost of $70K or more annually may be the economic fuel penalty when integrating the load over distances and speeds traveled. Generally antennas requiring large aperture areas and low look angles demand radomes that are substantial in height. Antennas such as C, Ku, Ka, L SATCOM, and future optical systems fall into that category. This operational cost must be factored into the decision making when selecting the best communication candidates.

It is predicted that radio equipment reliability will increase over the years. However, antenna reliability may become more prone to needing additional maintenance with the use of advanced antenna technologies (e.g., smart / phased array / conformal antennas).



		Estimated Antenna Force (lbs) at Selected Air Speeds and Altitudes									
	45,000	2	7	11	15	21	27	34	42	51	49
	40,000	2	7	11	15	21	27	34	42	51	61
Altitude	35,000	3	8	13	19	26	33	42	52	63	75
(feet)	30,000	4	10	16	23	32	41	52	65	78	93
	25,000	5	13	20	29	39	51	65	80	97	115
	20,000	6	16	25	36	48	64	81	99	120	143
	15,000	7	20	31	44	60	79	100	123	149	177
	10,000	9	24	38	55	75	98	124	153	185	220
	5,000	11	30	47	68	92	121	153	189	229	273
	0	13	35	58	84	115					
		120	200	250	300	350	400	450	500	550	600
					Absolute Forward Air Speed (mph)						

Figure 223 – Estimated Load Force for 0.42 Square Foot Leading Edge Antenna

22.3.4 Aircraft Fleet Models

When predicting the costs many years in the future, one of the largest unknowns is the aircraft fleet (number and types of aircraft) that need to be equipped with a given communications candidate.

Several aircraft models were considered as indicated in the subsections below. Other aircraft equipage models could be incorporated into the cost model.

22.3.4.1 Aircraft Fleet Model #1 – One Model of US Fleet 2013 to 2038

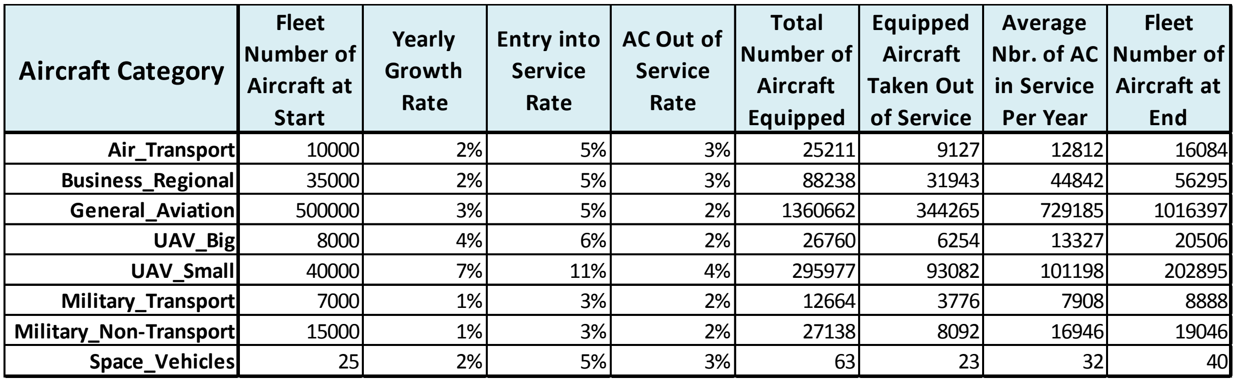
Aircraft fleet model #1 as provided in Figure 224 is intended to be representative of the approximate number and type of the current (2013) active US aircraft fleet with modest incremental growth over the next 25 years, with some liberties taken for the number of UAVs and space vehicles. The model is a 25 year aircraft model with the yearly growth rates for all aircraft types at 2%, formed by an aircraft entry into service rates of 5% and aircraft out of service rates of 3% for each aircraft. For the purposes of this fleet model, the 2013 benchmark data in Section 21.3.5 was utilized to obtain the approximate number of active aircraft in the United States at the start of the 25 year period.

Aircraft Category	Fleet Number of Aircraft at Start	Yearly Growth Rate	Entry into Service Rate	AC Out of Service Rate	Total Number of Aircraft Equipped	Equipped Aircraft Taken Out of Service	Average Nbr. of AC in Service Per Year	Fleet Number of Aircraft at End
Air_Transport	4811	2%	5%	3%	12129	4391	6164	7738
Business_Regional	17112	2%	5%	3%	43141	15617	21924	27524
General_Aviation	223400	2%	5%	3%	563212	203887	286223	359325
UAV_Big	354	2%	5%	3%	892	323	454	569
UAV_Small	2000	2%	5%	3%	5042	1825	2562	3217
Military_Transport	5359	2%	5%	3%	13511	4891	6866	8620
Military_Non-Transport	16599	2%	5%	3%	41848	15150	21267	26698
Space_Vehicles	10	2%	5%	3%	25	9	13	16

Figure 224 – Aircraft Fleet Model #1 (2013 to 2038, 25 Year Duration)

22.3.4.2 Aircraft Fleet Model #2 – One Model of US Fleet 2038 to 2063

Aircraft fleet model #2 as is described in Figure 225 is intended to be representative of one possible model of the United States aircraft fleet starting 25 years in the future and ending 50 years in the future. This model is a 25 year aircraft model with the starting feet of aircraft and rates for yearly growth, entry into service, and out of service for the various aircraft categories as specified in the figure.



Aircraft Category	Fleet Number of Aircraft at Start	Yearly Growth Rate	Entry into Service Rate	AC Out of Service Rate	Total Number of Aircraft Equipped	Equipped Aircraft Taken Out of Service	Average Nbr. of AC in Service Per Year	Fleet Number of Aircraft at End
Air_Transport	10000	2%	5%	3%	25211	9127	12812	16084
Business_Regional	35000	2%	5%	3%	88238	31943	44842	56295
General_Aviation	500000	3%	5%	2%	1360662	344265	729185	1016397
UAV_Big	8000	4%	6%	2%	26760	6254	13327	20506
UAV_Small	40000	7%	11%	4%	295977	93082	101198	202895
Military_Transport	7000	1%	3%	2%	12664	3776	7908	8888
Military_Non-Transport	15000	1%	3%	2%	27138	8092	16946	19046
Space_Vehicles	25	2%	5%	3%	63	23	32	40

Figure 225 – Aircraft Fleet Model #2 (2038 to 2063, 25 Year Duration)

22.3.4.3 Other Aircraft Models

Other aircraft fleet models have been considered for the purposes of A-A and A-G candidate cost estimation. For example, the fleet considered could be the entire world fleet rather than just the US fleet, or one could consider just the fleet of aircraft that fly in the US NAS (e.g., US fleet plus foreign fleet than enters US airspace).

Other aircraft models could be based upon different predictions of the future with significantly more aircraft (e.g., growth from 5X to 1000X within the 50 year study time horizon). Such predictions are aligned with the transformational airspace concepts described in the paper "*Share the Sky: Concepts and Technologies That Will Shape Future Airspace Use*" written by Mark Ballin, Bill Cotton, and Parimal Kopardekar from NASA for the September 2011 AIAA Aviation Technology and Operations Conference.

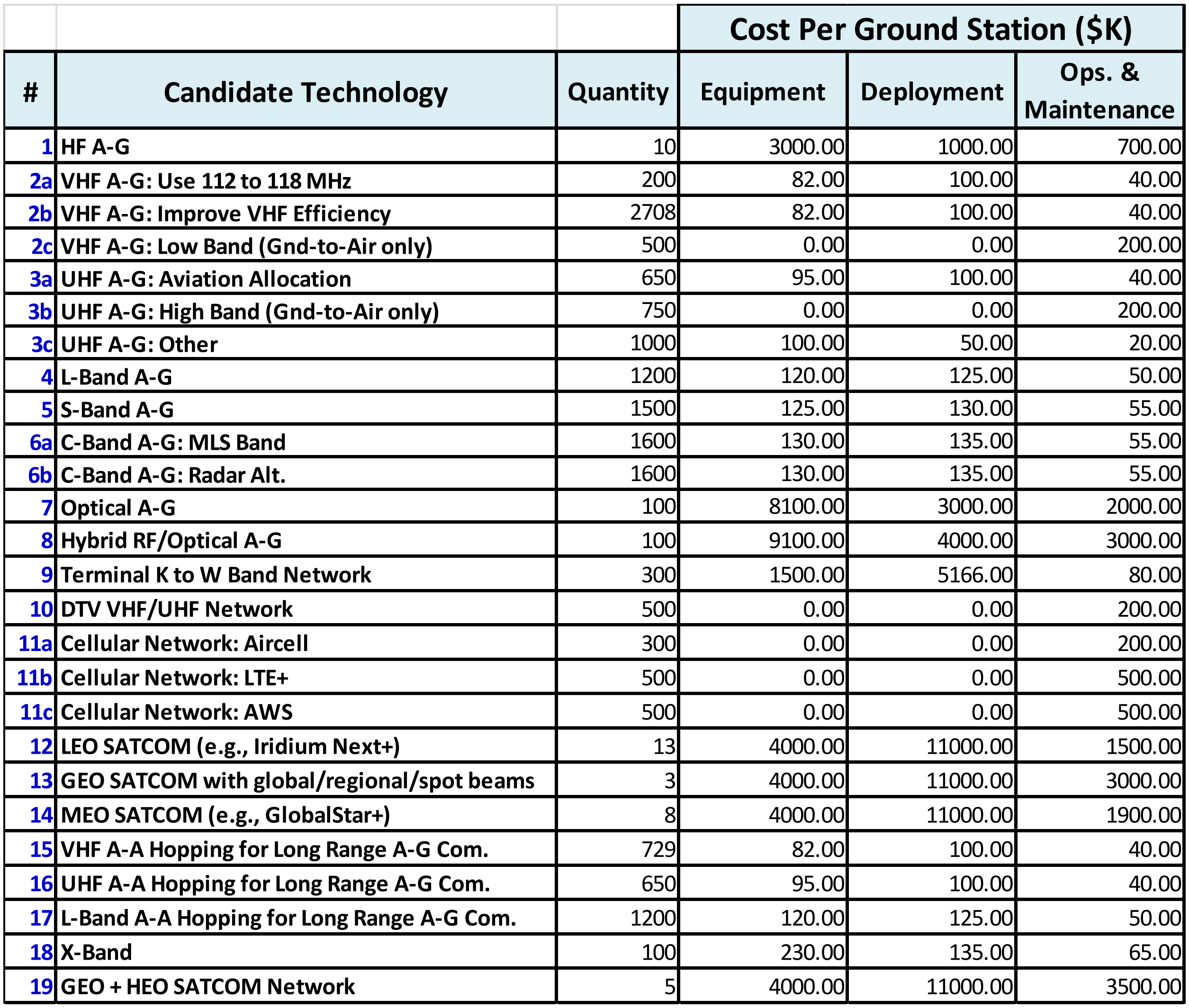
On the contrary, other predictions of the future call for a significant reduction in the aircraft fleet. Such predictions often are based upon projecting the potential impact of a number of changing environmental conditions that could tend to reduce the demand for air travel including, for example, higher fuel costs, technologies that may improve other transportation alternatives (e.g., high-speed trains and ships), virtual meeting technologies that reduce the need for business travel, and immersive virtual reality technologies that allow people to "see" the world without leaving home, etc.

22.4 Ground Cost Models

Ground system cost models have been developed to estimate the costs associated with providing HF, VHF, UHF, L-Band, S-Band, C-Band, Optical, Hybrid RF/Optical, Terminal K to W Band Networks, DTV VHF/UHF Network, and Cellular Networks as described by our A-A and A-G candidates and their infrastructure and architecture needs. All of the cost models have assumed a 25 year lifetime for the ground systems.

The cost models have leveraged the cost benchmark information provided in Section 21.4, with estimated equipment costs, deployment costs, and yearly operations & maintenance costs for all of these configurations as indicated in Figure 226. It is predicted (assumed) that over time, ground system manufacturers will increase the efficiency of their developments through the use of improved tools (e.g., model based development) that reduces the development, verification, and testing costs by 30%. However, it is also predicted that incorporating future communications capabilities that will increase the costs by 30% such that the overall costs (in today's equivalent dollars) will be approximately the same.

Ground cost models for candidates including the DTV VHF/UHF Networks and Cellular Networks (Candidates #2C, #10, #11a, #11b, and #11c) have not attempted to estimate the equipment nor deployment cost of the ground network. Instead, estimates of the operations and maintenance costs estimated to be burdened on the aviation community for use for use of these commercial networks are intended to be representative of the total costs for these candidates.



			Cost Per Ground Station ($K)		
#	**Candidate Technology**	**Quantity**	**Equipment**	**Deployment**	**Ops. & Maintenance**
1	**HF A-G**	10	3000.00	1000.00	700.00
2a	**VHF A-G: Use 112 to 118 MHz**	200	82.00	100.00	40.00
2b	**VHF A-G: Improve VHF Efficiency**	2708	82.00	100.00	40.00
2c	**VHF A-G: Low Band (Gnd-to-Air only)**	500	0.00	0.00	200.00
3a	**UHF A-G: Aviation Allocation**	650	95.00	100.00	40.00
3b	**UHF A-G: High Band (Gnd-to-Air only)**	750	0.00	0.00	200.00
3c	**UHF A-G: Other**	1000	100.00	50.00	20.00
4	**L-Band A-G**	1200	120.00	125.00	50.00
5	**S-Band A-G**	1500	125.00	130.00	55.00
6a	**C-Band A-G: MLS Band**	1600	130.00	135.00	55.00
6b	**C-Band A-G: Radar Alt.**	1600	130.00	135.00	55.00
7	**Optical A-G**	100	8100.00	3000.00	2000.00
8	**Hybrid RF/Optical A-G**	100	9100.00	4000.00	3000.00
9	**Terminal K to W Band Network**	300	1500.00	5166.00	80.00
10	**DTV VHF/UHF Network**	500	0.00	0.00	200.00
11a	**Cellular Network: Aircell**	300	0.00	0.00	200.00
11b	**Cellular Network: LTE+**	500	0.00	0.00	500.00
11c	**Cellular Network: AWS**	500	0.00	0.00	500.00
12	**LEO SATCOM (e.g., Iridium Next+)**	13	4000.00	11000.00	1500.00
13	**GEO SATCOM with global/regional/spot beams**	3	4000.00	11000.00	3000.00
14	**MEO SATCOM (e.g., GlobalStar+)**	8	4000.00	11000.00	1900.00
15	**VHF A-A Hopping for Long Range A-G Com.**	729	82.00	100.00	40.00
16	**UHF A-A Hopping for Long Range A-G Com.**	650	95.00	100.00	40.00
17	**L-Band A-A Hopping for Long Range A-G Com.**	1200	120.00	125.00	50.00
18	**X-Band**	100	230.00	135.00	65.00
19	**GEO + HEO SATCOM Network**	5	4000.00	11000.00	3500.00

Figure 226 – Ground System Cost Models

22.5 SATCOM Cost Models

Models for four SATCOM constellations have been developed based upon benchmark data provided in Section 21.5 and engineering judgment for expected future costs. The four SATCOM constellation models have been developed for LEO, GEO, MEO, and GEO with HEO as documented in Figure 227, Figure 228, Figure 229, and Figure 230, respectively. Note that there are many other possible SATCOM configurations, but these models were used as the basis for the cost estimates provided in Section 23.

System Component	Quantity	Lifetime	Cost Per Unit
Airborne Equipment	Aircraft Model	25	Varies by Aircraft Type: ($150K for ATS)
Ground Stations (GS)	13	25	Equipment: $4M Deployment: $11M Ops. & Maintenance: 1.5M/Year per GS
Satellites	66	6.25	Equipment: $40M per satellite Deployment: $6M per operational satellite Ops. & Maintenance: $4M/year per operational satellite (assumes 15 spares)

Figure 227 – LEO SATCOM Model

System Component	Quantity	Lifetime	Cost Per Unit
Airborne Equipment	Aircraft Model	25	Varies by Aircraft Type: ($225K for ATS)
Ground Stations (GS)	3	25	Equipment: $4M Deployment: $11M Ops. & Maintenance: 3M/Year per GS
Satellites	3	12.5	Equipment: $150M per satellite Deployment: $100M per operational satellite Ops. & Maintenance: $6.67M/year per operational satellite (assumes 1 spare)

Figure 228 – GEO SATCOM Model

System Component	Quantity	Lifetime	Cost Per Unit
Airborne Equipment	Aircraft Model	25	Varies by Aircraft Type: ($160K for ATS)
Ground Stations (GS)	8	25	Equipment: $4M Deployment: $11M Ops. & Maintenance: 1.9M/Year per GS
Satellites	20	8.33	Equipment: $50M per satellite Deployment: $25M per operational satellite Ops. & Maintenance: $1.355M/year per operational satellite (assumes 6 spares)

Figure 229 – MEO SATCOM Model

System Component	Quantity	Lifetime	Cost Per Unit
Airborne Equipment	Aircraft Model	25	Varies by Aircraft Type: ($235K for ATS)
Ground Stations (GS)	5	25	Equipment: $4M Deployment: $11M Ops. & Maintenance: 3.5M/Year per GS
Satellites	6	12.5	Equipment: $170M per satellite Deployment: $85M per operational satellite Ops. & Maintenance: $6.7M/year per operational satellite (assumes 3 spares)

Figure 230 – GEO + HEO SATCOM Model

22.6 Additional Cost Model Factors

Additional cost factors have been added to the cost model to support potential future analyses. For instance, the cost model allows weighting of the costs associated with a given technology by a percentage associated with the particular candidate. This capability may be useful for future evaluations of the candidates, whereby, for example A-A candidate technology number 9 has been envisioned to provide an aircraft-to-aircraft communication link using LEO satellites. However, it is envisioned that the A-A communications would only use ~5% of the total bandwidth associated with the LEO SATCOM network to support the A-A communications. Thus, rather than burdening the entire candidate with the full cost of deploying and implementing the LEO SATCOM network for A-A candidate #9, those costs could be pro-rated on a percentage basis to the percentage of the system costs associated with providing the given candidate. For the cost score results provided in this report, this candidate cost pro-rating was not done.

23 COST ESTIMATES FOR THE A-A AND A-G CANDIDATES AND ALTERNATIVES

It is a challenge to estimate the actual cost of systems that will not be developed and fielded for many years in the future. This is especially true in areas, like wireless communications, where significant technology changes are anticipated to occur over the next several decades.

Nevertheless, this section of the report describes the cost estimates for the purposes of relative comparisons between: a) A-A candidates, b) A-G candidates, c) integration alternatives, and d) cost comparisons across a range of performance characteristics including communications bandwidth, safety, reliability, and security.

The cost estimates in this section were based upon the cost models and assumptions described in Section 22. The total system costs were estimated by adding the costs associated with estimates for the technology maturation and standards, equipment development, deployment, and operation and maintenance, including the costs of airborne, ground, and satellite systems as appropriate for the candidate or integration.

23.1 Cost Scores – Aircraft Fleet Model #1

For the purposes of the cost estimates provided in this section, it was assumed that all the aircraft in the Fleet Model #1 are equipped with each candidate communication technology individually. *Note that Aircraft Fleet Model #1 is described in Section 22.3.4.1 (Figure 224).* It is recognized and understood by the authors that some communication technologies may not be equipped on all aircraft types depending upon the airspace that they cover and the operations that they support. However, for the purposes of the relative cost comparison of the alternative candidates, it was assumed that all aircraft in the fleet were equipped. If this assumption was not made, then candidates that need to be equipped on very few aircraft (e.g., only aircraft that fly in polar regions) will show much smaller total system costs than the candidates that would need to be equipped on virtually all aircraft, making candidate relative cost score comparison more difficult.

These cost estimates should be treated as “cost scores” for relative comparison among the candidates. The cost scores should not be misinterpreted to be the total system costs associated with implementing each candidate, since for relative comparison purposes among the candidates the entire aircraft fleet was assumed to be upgraded with the candidate communication system. The actual costs for implementing a given candidate will vary depending upon many factors, including, for example, the portion of the fleet that equips, the communications quality of service and coverage required to support the intended airspace applications, etc.

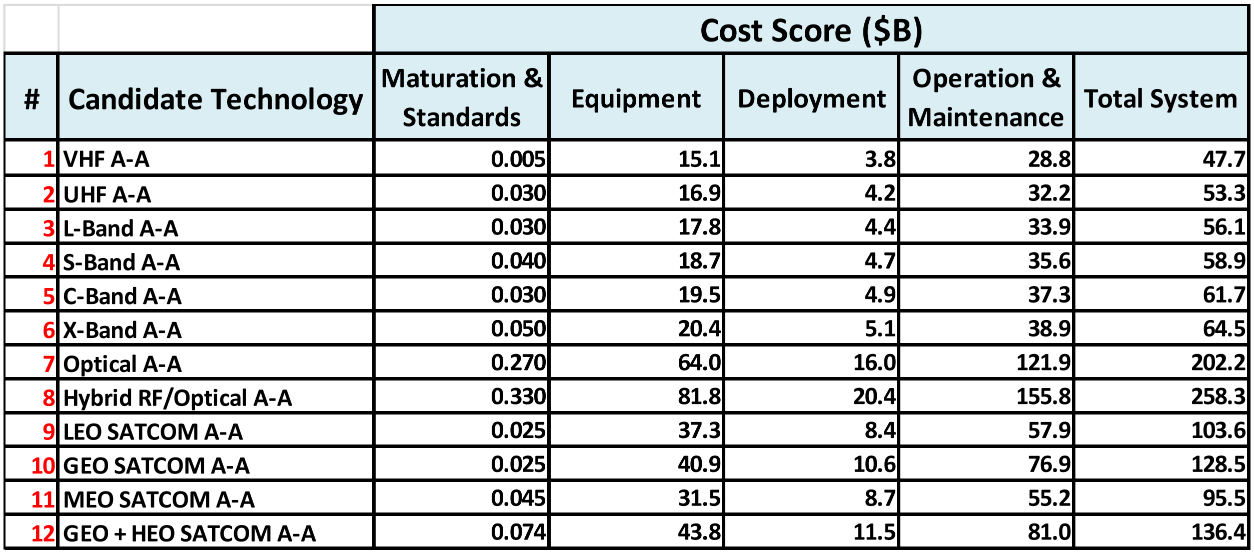
23.1.1 Air-to-Air Candidates Cost Scores – Aircraft Fleet Model #1

Figure 231 and Figure 232 provide a summary table and plot (respectively) for the A-A candidates cost scores broken down into the following cost elements: 1) Maturation & Standards, 2) Equipment, 3) Deployment, 4) Operation & Maintenance, and 5) Total System Costs.

The maturation and standards cost scores are not easily discernable on the total cost score plot provided in Figure 232, since these estimated costs are so low relative to the total costs for building, deploying, operating, and maintaining the communication systems on the fleet of aircraft and ground/satellite systems for 25 years. Thus, Figure 233 provides a plot with just the cost scores for the Maturation and Standards development associated with the A-A candidates. Note that the x-axis for the costs in Figure 233 is in millions of dollars, while the other plots have x-axis costs in billions of dollars.

Figure 234 and Figure 235 provide a summary table and plot (respectively) for the A-A candidate cost scores broken down into the following cost elements: 1) Airborne, 2) Ground, 3) Satellite [A-G-S], and 4) Total System Costs.

Figure 236 to Figure 238 provide the detailed cost score tables for all the A-A candidates.



		Cost Score ($B)				
#	Candidate Technology	Maturation & Standards	Equipment	Deployment	Operation & Maintenance	Total System
1	VHF A-A	0.005	15.1	3.8	28.8	47.7
2	UHF A-A	0.030	16.9	4.2	32.2	53.3
3	L-Band A-A	0.030	17.8	4.4	33.9	56.1
4	S-Band A-A	0.040	18.7	4.7	35.6	58.9
5	C-Band A-A	0.030	19.5	4.9	37.3	61.7
6	X-Band A-A	0.050	20.4	5.1	38.9	64.5
7	Optical A-A	0.270	64.0	16.0	121.9	202.2
8	Hybrid RF/Optical A-A	0.330	81.8	20.4	155.8	258.3
9	LEO SATCOM A-A	0.025	37.3	8.4	57.9	103.6
10	GEO SATCOM A-A	0.025	40.9	10.6	76.9	128.5
11	MEO SATCOM A-A	0.045	31.5	8.7	55.2	95.5
12	GEO + HEO SATCOM A-A	0.074	43.8	11.5	81.0	136.4

Figure 231 – A-A Candidates Cost Score Summary Table – AC Model #1

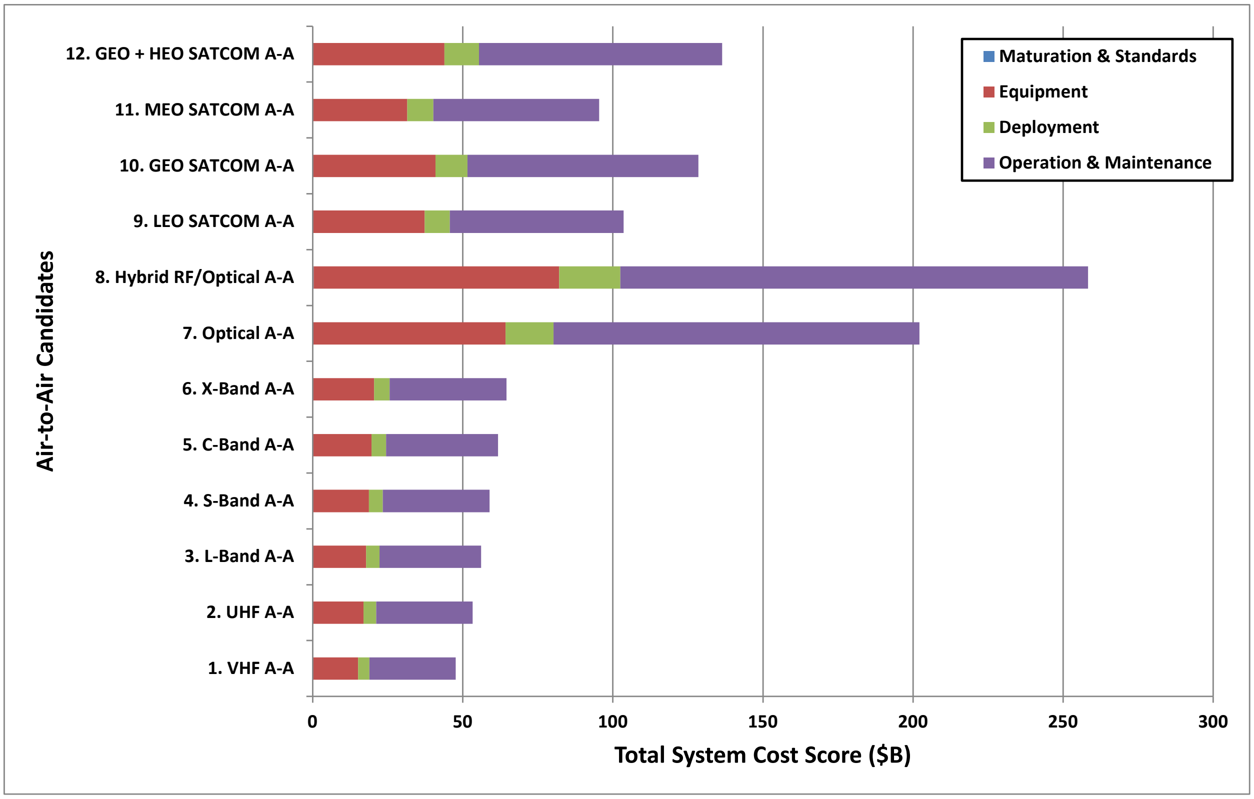


Figure 232 – A-A Candidates Cost Score Summary Plot – AC Model #1

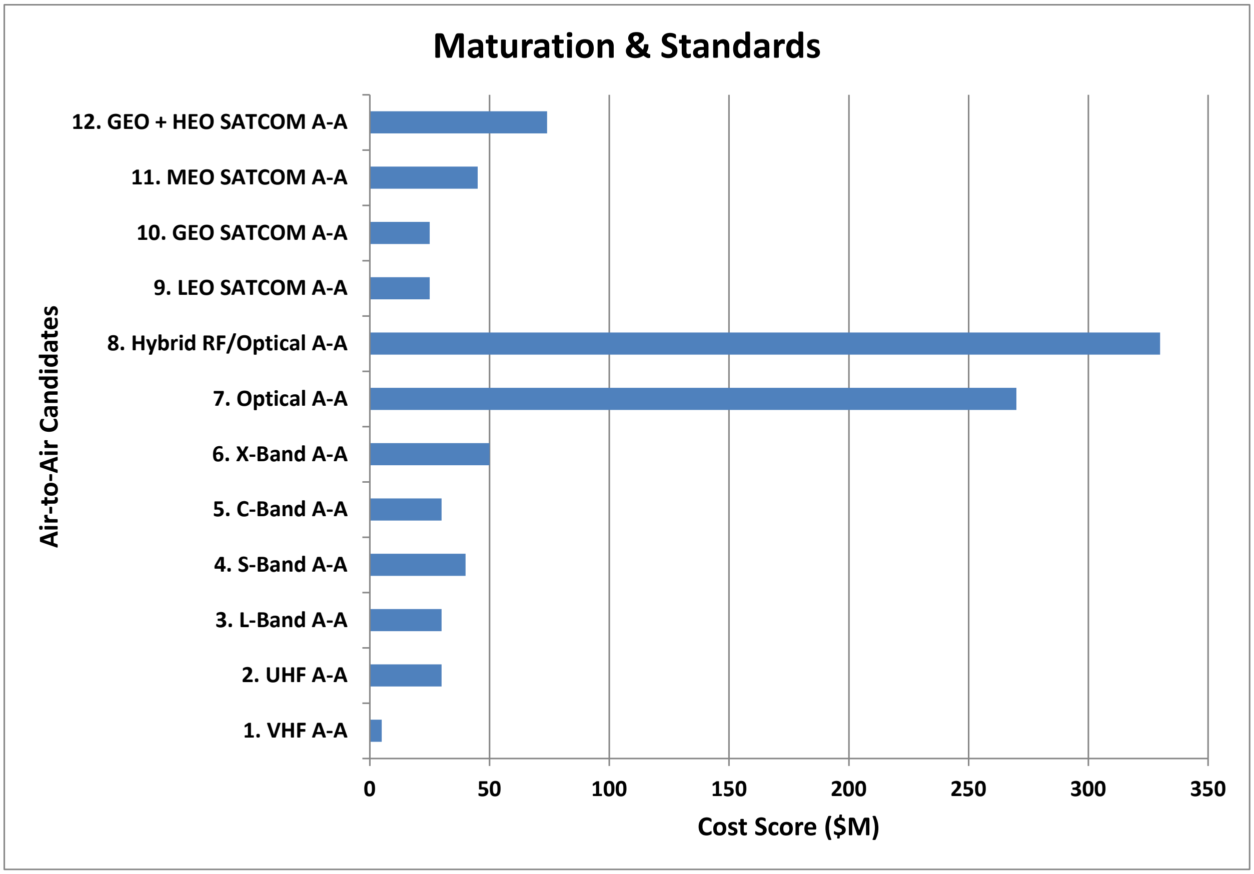


Figure 233 – A-A Candidates Maturation & Standards Plot - AC Model #1 and #2

		Cost Score ($B)			
#	Candidate Technology	Airborne	Ground	Satellite	Total System
1	VHF A-A	47.68	0.00	0.00	47.68
2	UHF A-A	53.31	0.00	0.00	53.31
3	L-Band A-A	56.11	0.00	0.00	56.11
4	S-Band A-A	58.93	0.00	0.00	58.93
5	C-Band A-A	61.72	0.00	0.00	61.72
6	X-Band A-A	64.55	0.00	0.00	64.55
7	Optical A-A	202.17	0.00	0.00	202.17
8	Hybrid RF/Optical A-A	258.31	0.00	0.00	258.31
9	LEO SATCOM A-A	84.14	0.69	18.75	103.58
10	GEO SATCOM A-A	126.20	0.28	2.01	128.48
11	MEO SATCOM A-A	89.75	0.51	5.20	95.46
12	GEO + HEO SATCOM A-A	131.81	0.56	4.07	136.44

Figure 234 – A-A Candidates Cost Score Summary A-G-S Table – AC Model #1

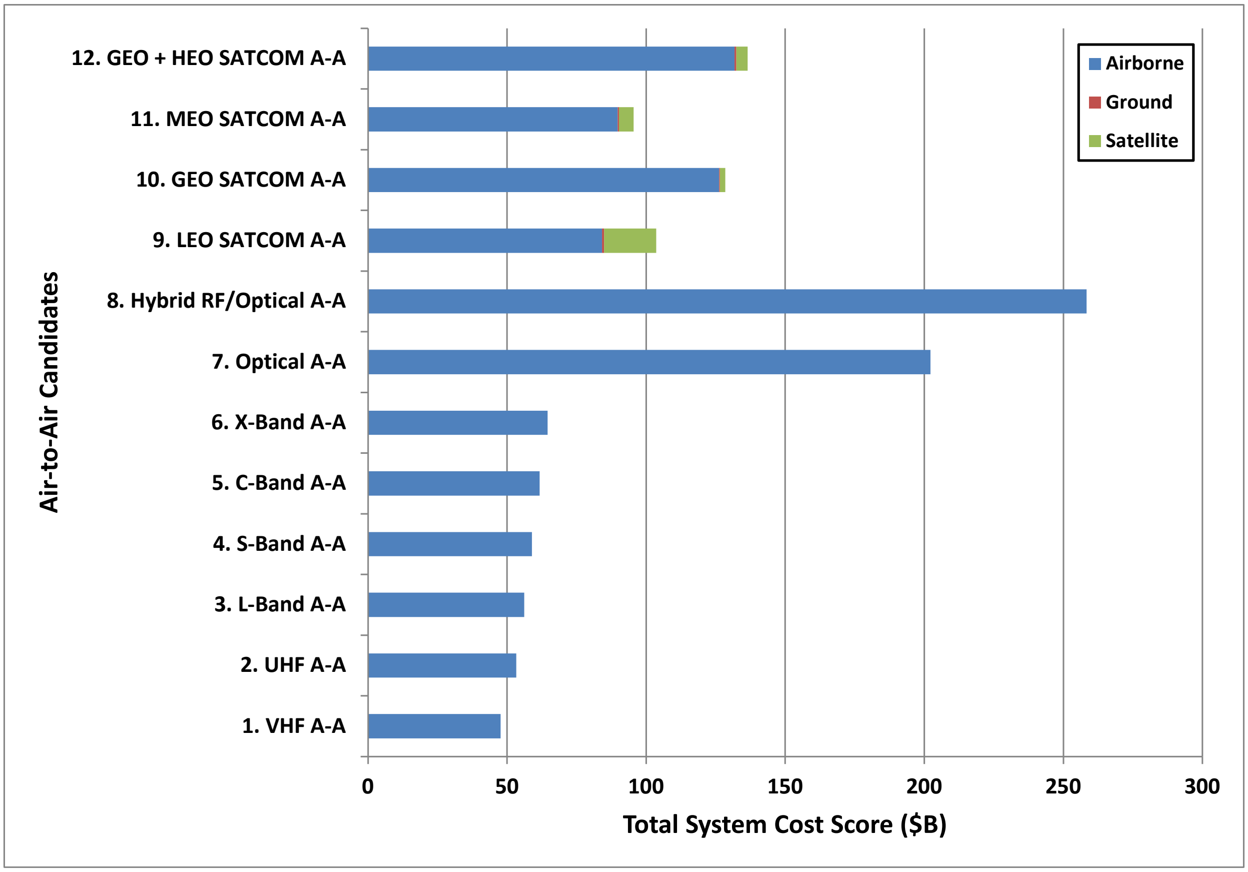


Figure 235 – A-A Candidates Cost Score Summary A-G-S Plot – AC Model #1

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	VHF A-A															**47.68**
	Airborne			0.0	5000.0		**15106016.4**		**3776504.1**		**28788336.1**	**47.68**	100%	**47.68**	**100**	
	Air Transport	12129	25			85.0	1030965.0	21.3	257741.3	12.8	1964746.6					
	Business&Regional	43141	25			59.5	2566889.5	14.9	641722.4	8.9	4891814.7					
	General Aviation	563212	25			8.5	4787302.0	2.1	1196825.5	1.3	9123350.4					
	UAV - Big	892	25			55.3	49283.0	13.8	12320.8	8.3	93969.7					
	UAV - Small	5042	25			10.2	51428.4	2.6	12857.1	1.5	98012.7					
	Military Transport	13511	25			93.5	1263278.5	23.4	315819.6	14.0	2407396.5					
	Military Non-transport	41848	25			127.5	5335620.0	31.9	1333905.0	19.1	10168206.8					
	Space Vehicles	25	25			850.0	21250.0	212.5	5312.5	127.5	40838.6					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
2	UHF A-A															**53.31**
	Airborne			0.0	30000.0		**16883194.8**		**4220798.7**		**32175199.2**	**53.31**	100%	**53.31**	**100**	
	Air Transport	12129	25			95.0	1152255.0	23.8	288063.8	14.3	2195893.3					
	Business&Regional	43141	25			66.5	2868876.5	16.6	717219.1	10.0	5467322.3					
	General Aviation	563212	25			9.5	5350514.0	2.4	1337628.5	1.4	10196685.8					
	UAV - Big	892	25			61.8	55081.0	15.4	13770.3	9.3	105025.0					
	UAV - Small	5042	25			11.4	57478.8	2.9	14369.7	1.7	109543.6					
	Military Transport	13511	25			104.5	1411899.5	26.1	352974.9	15.7	2690619.6					
	Military Non-transport	41848	25			142.5	5963340.0	35.6	1490835.0	21.4	11364466.5					
	Space Vehicles	25	25			950.0	23750.0	237.5	5937.5	142.5	45643.2					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
3	L-Band A-A															**56.11**
	Airborne			0.0	30000.0		**17771784.0**		**4442946.0**		**33868630.7**	**56.11**	100%	**56.11**	**100**	
	Air Transport	12129	25			100.0	1212900.0	25.0	303225.0	15.0	2311466.6					
	Business&Regional	43141	25			70.0	3019870.0	17.5	754967.5	10.5	5755076.1					
	General Aviation	563212	25			10.0	5632120.0	2.5	1408030.0	1.5	10733353.4					
	UAV - Big	892	25			65.0	57980.0	16.3	14495.0	9.8	110552.6					
	UAV - Small	5042	25			12.0	60504.0	3.0	15126.0	1.8	115309.1					
	Military Transport	13511	25			110.0	1486210.0	27.5	371552.5	16.5	2832231.2					
	Military Non-transport	41848	25			150.0	6277200.0	37.5	1569300.0	22.5	11962596.3					
	Space Vehicles	25	25			1000.0	25000.0	250.0	6250.0	150.0	48045.4					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
4	S-Band A-A															**58.93**
	Airborne			0.0	40000.0		**18660373.2**		**4665093.3**		**35562062.3**	**58.93**	100%	**58.93**	**100**	
	Air Transport	12129	25			105.0	1273545.0	26.3	318386.3	15.8	2427039.9					
	Business&Regional	43141	25			73.5	3170863.5	18.4	792715.9	11.0	6042829.9					
	General Aviation	563212	25			10.5	5913726.0	2.6	1478431.5	1.6	11270021.1					
	UAV - Big	892	25			68.3	60879.0	17.1	15219.8	10.2	116080.2					
	UAV - Small	5042	25			12.6	63529.2	3.2	15882.3	1.9	121074.5					
	Military Transport	13511	25			115.5	1560520.5	28.9	390130.1	17.3	2973842.8					
	Military Non-transport	41848	25			157.5	6591060.0	39.4	1647765.0	23.6	12560726.1					
	Space Vehicles	25	25			1050.0	26250.0	262.5	6562.5	157.5	50447.7					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	

Figure 236 – A-A Candidates Detailed Cost Score Table – AC Model #1 [Part 1 of 3]

#	Candidate Technology		Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
					Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5	C-Band A-A																**61.72**
	Airborne				0.0	30000.0		**19548962.4**		**4887240.6**		**37255493.8**	**61.72**	100%	**61.72**	**100**	
		Air Transport	12129	25			110.0	1334190.0	27.5	333547.5	16.5	2542613.2					
		Business&Regional	43141	25			77.0	3321857.0	19.3	830464.3	11.6	6330583.7					
		General Aviation	563212	25			11.0	6195332.0	2.8	1548833.0	1.7	11806688.8					
		UAV - Big	892	25			71.5	63778.0	17.9	15944.5	10.7	121607.8					
		UAV - Small	5042	25			13.2	66554.4	3.3	16638.6	2.0	126840.0					
		Military Transport	13511	25			121.0	1634831.0	30.3	408707.8	18.2	3115454.3					
		Military Non-transport	41848	25			165.0	6904920.0	41.3	1726230.0	24.8	13158855.9					
		Space Vehicles	25	25			1100.0	27500.0	275.0	6875.0	165.0	52850.0					
	Ground		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
6	X-Band A-A																**64.55**
	Airborne				0.0	50000.0		**20437551.6**		**5109387.9**		**38948925.3**	**64.55**	100%	**64.55**	**100**	
		Air Transport	12129	25			115.0	1394835.0	28.8	348708.8	17.3	2658186.6					
		Business&Regional	43141	25			80.5	3472850.5	20.1	868212.6	12.1	6618337.6					
		General Aviation	563212	25			11.5	6476938.0	2.9	1619234.5	1.7	12343356.5					
		UAV - Big	892	25			74.8	66677.0	18.7	16669.3	11.2	127135.5					
		UAV - Small	5042	25			13.8	69579.6	3.5	17394.9	2.1	132605.4					
		Military Transport	13511	25			126.5	1709141.5	31.6	427285.4	19.0	3257065.9					
		Military Non-transport	41848	25			172.5	7218780.0	43.1	1804695.0	25.9	13756985.7					
		Space Vehicles	25	25			1150.0	28750.0	287.5	7187.5	172.5	55252.3					
	Ground		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
7	Optical A-A																**202.17**
	Airborne				200000.0	70000.0		**63978422.4**		**15994605.6**		**121927070.6**	**202.17**	100%	**202.17**	**100**	
		Air Transport	12129	25			360.0	4366440.0	90.0	1091610.0	54.0	8321279.7					
		Business&Regional	43141	25			252.0	10871532.0	63.0	2717883.0	37.8	20718274.1					
		General Aviation	563212	25			36.0	20275632.0	9.0	5068908.0	5.4	38640072.4					
		UAV - Big	892	25			234.0	208728.0	58.5	52182.0	35.1	397989.3					
		UAV - Small	5042	25			43.2	217814.4	10.8	54453.6	6.5	415112.7					
		Military Transport	13511	25			396.0	5350356.0	99.0	1337589.0	59.4	10196032.3					
		Military Non-transport	41848	25			540.0	22597920.0	135.0	5649480.0	81.0	43065346.6					
		Space Vehicles	25	25			3600.0	90000.0	900.0	22500.0	540.0	172963.6					
	Ground		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
8	Hybrid RF/Optical A-A																**258.31**
	Airborne				240000.0	90000.0		**81750206.4**		**20437551.6**		**155795701.4**	**258.31**	100%	**258.31**	**100**	
		Air Transport	12129	25			460.0	5579340.0	115.0	1394835.0	69.0	10632746.3					
		Business&Regional	43141	25			322.0	13891402.0	80.5	3472850.5	48.3	26473350.2					
		General Aviation	563212	25			46.0	25907752.0	11.5	6476938.0	6.9	49373425.8					
		UAV - Big	892	25			299.0	266708.0	74.8	66677.0	44.9	508541.9					
		UAV - Small	5042	25			55.2	278318.4	13.8	69579.6	8.3	530421.8					
		Military Transport	13511	25			506.0	6836566.0	126.5	1709141.5	75.9	13028263.6					
		Military Non-transport	41848	25			690.0	28875120.0	172.5	7218780.0	103.5	55027942.8					
		Space Vehicles	25	25			4600.0	115000.0	1150.0	28750.0	690.0	221009.1					
	Ground		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite		0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	

Figure 237 – A-A Candidates Detailed Cost Score Table – AC Model #1 [Part 2 of 3]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
9 LEO SATCOM A-A															**103.58**
Airborne			0.0	10000.0		**26657676.0**		**6664419.0**		**50802946.1**	**84.14**	100%	**84.14**	**81.23**	
Air Transport	12129	25			150.0	1819350.0	37.5	454837.5	22.5	3467199.9					
Business&Regional	43141	25			105.0	4529805.0	26.3	1132451.3	15.8	8632614.2					
General Aviation	563212	25			15.0	8448180.0	3.8	2112045.0	2.3	16100030.2					
UAV - Big	892	25			97.5	86970.0	24.4	21742.5	14.6	165828.9					
UAV - Small	5042	25			18.0	90756.0	4.5	22689.0	2.7	172963.6					
Military Transport	13511	25			165.0	2229315.0	41.3	557328.8	24.8	4248346.8					
Military Non-transport	41848	25			225.0	9415800.0	56.3	2353950.0	33.8	17943894.4					
Space Vehicles	25	25			1500.0	37500.0	375.0	9375.0	225.0	72068.2					
Ground	13	25	0.0	5000.0	4000.0	**52000.0**	11000.0	**143000.0**	1500.0	**487500.0**	**0.69**	100%	**0.69**	**0.66**	
Satellite	66	6.25	0.0	10000.0	40000.0	**10560000.0**	6000.0	**1584000.0**	4000.0	**6600000.0**	**18.75**	100%	**18.75**	**18.11**	
spares	15														
10 GEO SATCOM A-A															**128.48**
Airborne			0.0	10000.0		**39986514.0**		**9996628.5**		**76204419.1**	**126.20**	100%	**126.20**	**98.22**	
Air Transport	12129	25			225.0	2729025.0	56.3	682256.3	33.8	5200799.8					
Business&Regional	43141	25			157.5	6794707.5	39.4	1698676.9	23.6	12948921.3					
General Aviation	563212	25			22.5	12672270.0	5.6	3168067.5	3.4	24150045.2					
UAV - Big	892	25			146.3	130455.0	36.6	32613.8	21.9	248743.3					
UAV - Small	5042	25			27.0	136134.0	6.8	34033.5	4.1	259445.4					
Military Transport	13511	25			247.5	3343972.5	61.9	835993.1	37.1	6372520.2					
Military Non-transport	41848	25			337.5	14123700.0	84.4	3530925.0	50.6	26915841.6					
Space Vehicles	25	25			2250.0	56250.0	562.5	14062.5	337.5	108102.3					
Ground	3	25	0.0	5000.0	4000.0	**12000.0**	11000.0	**33000.0**	3000.0	**225000.0**	**0.28**	100%	**0.28**	**0.21**	
Satellite	3	12.5	0.0	10000.0	150000.0	**900000.0**	100000.0	**600000.0**	6666.7	**500000.0**	**2.01**	100%	**2.01**	**1.56**	
spare	1														
11 MEO SATCOM A-A															**95.46**
Airborne			0.0	20000.0		**28434854.4**		**7108713.6**		**54189809.2**	**89.75**	100%	**89.75**	**94.03**	
Air Transport	12129	25			160.0	1940640.0	40.0	485160.0	24.0	3698346.5					
Business&Regional	43141	25			112.0	4831792.0	28.0	1207948.0	16.8	9208121.8					
General Aviation	563212	25			16.0	9011392.0	4.0	2252848.0	2.4	17173365.5					
UAV - Big	892	25			104.0	92768.0	26.0	23192.0	15.6	176884.1					
UAV - Small	5042	25			19.2	96806.4	4.8	24201.6	2.9	184494.5					
Military Transport	13511	25			176.0	2377936.0	44.0	594484.0	26.4	4531569.9					
Military Non-transport	41848	25			240.0	10043520.0	60.0	2510880.0	36.0	19140154.0					
Space Vehicles	25	25			1600.0	40000.0	400.0	10000.0	240.0	76872.7					
Ground	8	25	0.0	5000.0	4000.0	**32000.0**	11000.0	**88000.0**	1900.0	**380000.0**	**0.51**	100%	**0.51**	**0.53**	
Satellite	20	8.33	0.0	20000.0	50000.0	**3000000.0**	25000.0	**1500000.0**	1355.0	**677500.0**	**5.20**	100%	**5.20**	**5.44**	
12 GEO + HEO SATCOM A-A															**136.44**
Airborne			0.0	12000.0		**41763692.4**		**10440923.1**		**79591282.2**	**131.81**	100%	**131.81**	**96.60**	
Air Transport	12129	25			235.0	2850315.0	58.8	712578.8	35.3	5431946.5					
Business&Regional	43141	25			164.5	7096694.5	41.1	1774173.6	24.7	13524428.9					
General Aviation	563212	25			23.5	13235482.0	5.9	3308870.5	3.5	25223380.6					
UAV - Big	892	25			152.8	136253.0	38.2	34063.3	22.9	259798.6					
UAV - Small	5042	25			28.2	142184.4	7.1	35546.1	4.2	270976.3					
Military Transport	13511	25			258.5	3492593.5	64.6	873148.4	38.8	6655743.3					
Military Non-transport	41848	25			352.5	14751420.0	88.1	3687855.0	52.9	28112101.2					
Space Vehicles	25	25			2350.0	58750.0	587.5	14687.5	352.5	112906.8					
Ground	5	25	0.0	50000.0	4000.0	**20000.0**	11000.0	**55000.0**	3500.0	**437500.0**	**0.56**	100%	**0.56**	**0.41**	
Satellite	6	12.5	0.0	12000.0	170000.0	**2040000.0**	85000.0	**1020000.0**	6666.7	**1000000.0**	**4.07**	100%	**4.07**	**2.98**	
spare	3														

Figure 238 – A-A Candidates Detailed Cost Score Table – AC Model #1 [Part 3 of 3]

23.1.2 Air-to-Ground Candidates Cost Scores – Aircraft Fleet Model #1

Figure 239 and Figure 240 provide a summary table and plot (respectively) for the A-G candidates cost scores broken down into the following cost elements: 1) Maturation & Standards, 2) Equipment, 3) Deployment, 4) Operation & Maintenance, and 5) Total System Costs. The maturation and standards cost scores are not easily discernable on the total cost score plot provided in Figure 240, since these estimated costs are so low relative to the total costs for building, deploying, operating, and maintaining the communication systems on the fleet of aircraft and ground/satellite systems for 25 years. Thus, Figure 241 provides a plot with just the cost scores for the Maturation and Standards development associated with the A-G candidates. Note that the x-axis for the costs in Figure 241 is in millions of dollars, while the other plots have x-axis costs in billions of dollars.

Figure 242 and Figure 243 provide a summary table and plot (respectively) for the A-G candidate cost scores broken down into the following cost elements: 1) Airborne, 2) Ground, 3) Satellite, and 4) Total System Costs.

Figure 244 to Figure 250 provide the detailed cost score tables for all the A-G candidates.

		Cost Score ($B)				
#	**Candidate Technology**	**Maturation & Standards**	**Equipment**	**Deployment**	**Operation & Maintenance**	**Total System**
1	HF A-G	0.010	17.8	4.5	34.0	56.3
2a	VHF A-G: Use 112 to 118 MHz	0.004	15.1	3.8	29.0	47.9
2b	VHF A-G: Improve VHF Efficiency	0.010	15.9	3.9	32.5	52.3
2c	VHF A-G: Low Band (Gnd-to-Air only)	0.020	16.9	4.2	34.7	55.8
3a	UHF A-G: Aviation Allocation	0.060	16.9	4.3	32.8	54.1
3b	UHF A-G: High Band (Gnd-to-Air only)	0.060	16.9	4.2	35.9	57.1
3c	UHF A-G: Other	0.100	17.0	4.3	32.7	54.0
4	L-Band A-G	0.050	17.9	4.6	35.4	57.9
5	S-Band A-G	0.040	18.0	4.6	35.9	58.6
6a	C-Band A-G: MLS Band	0.070	19.8	5.1	39.5	64.4
6b	C-Band A-G: Radar Alt.	0.080	19.8	5.1	39.5	64.4
7	Optical A-G	0.505	48.8	12.3	96.4	158.0
8	Hybrid RF/Optical A-G	0.495	66.7	16.8	132.8	216.8
9	Terminal K to W Band Network	0.100	5.8	2.9	10.8	19.5
10	DTV VHF/UHF Network	0.020	4.4	1.1	11.0	16.5
11a	Cellular Network: Aircell	0.020	3.6	0.9	8.3	12.7
11b	Cellular Network: LTE+	0.020	3.6	0.9	13.0	17.5
11c	Cellular Network: AWS	0.020	3.6	0.9	13.0	17.5
12	LEO SATCOM (e.g., Iridium Next+)	0.025	37.3	8.4	57.9	103.6
13	GEO SATCOM with global/regional/spot beams	0.025	40.9	10.6	76.9	128.5
14	MEO SATCOM (e.g., GlobalStar+)	0.045	31.5	8.7	55.2	95.5
15	VHF A-A Hopping for Long Range A-G Com.	0.040	17.8	4.4	34.6	56.9
16	UHF A-A Hopping for Long Range A-G Com.	0.050	19.6	5.0	37.9	62.5
17	L-Band A-A Hopping for Long Range A-G Com.	0.050	20.6	5.3	40.4	66.3
18	X-Band	0.030	20.5	5.1	39.1	64.7
19	GEO + HEO SATCOM Network	0.029	43.8	11.5	81.0	136.4

Figure 239 – A-G Candidates Cost Score Summary Table – AC Model #1

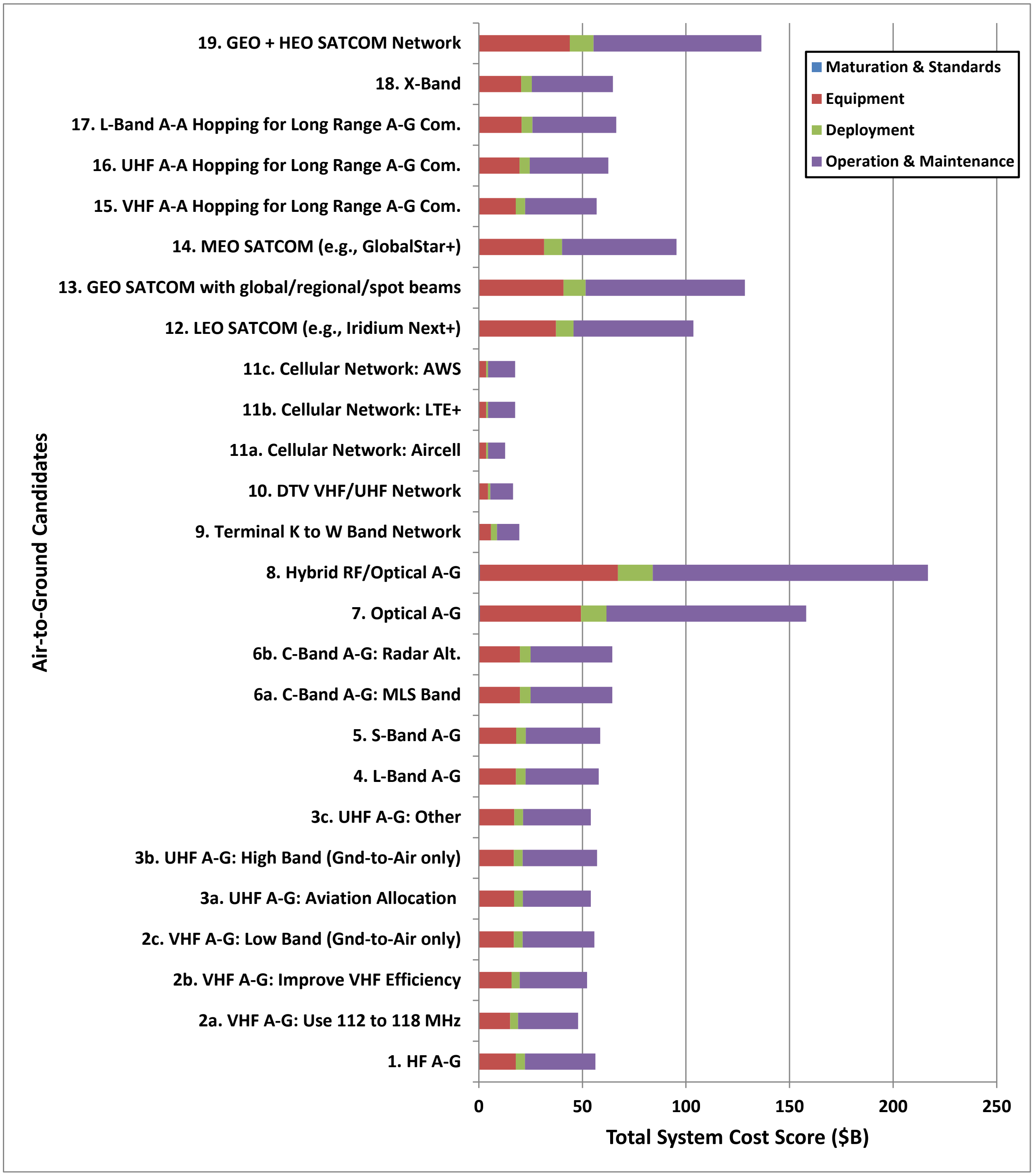


Figure 240 – A-G Candidates Cost Score Summary Plot – AC Model #1

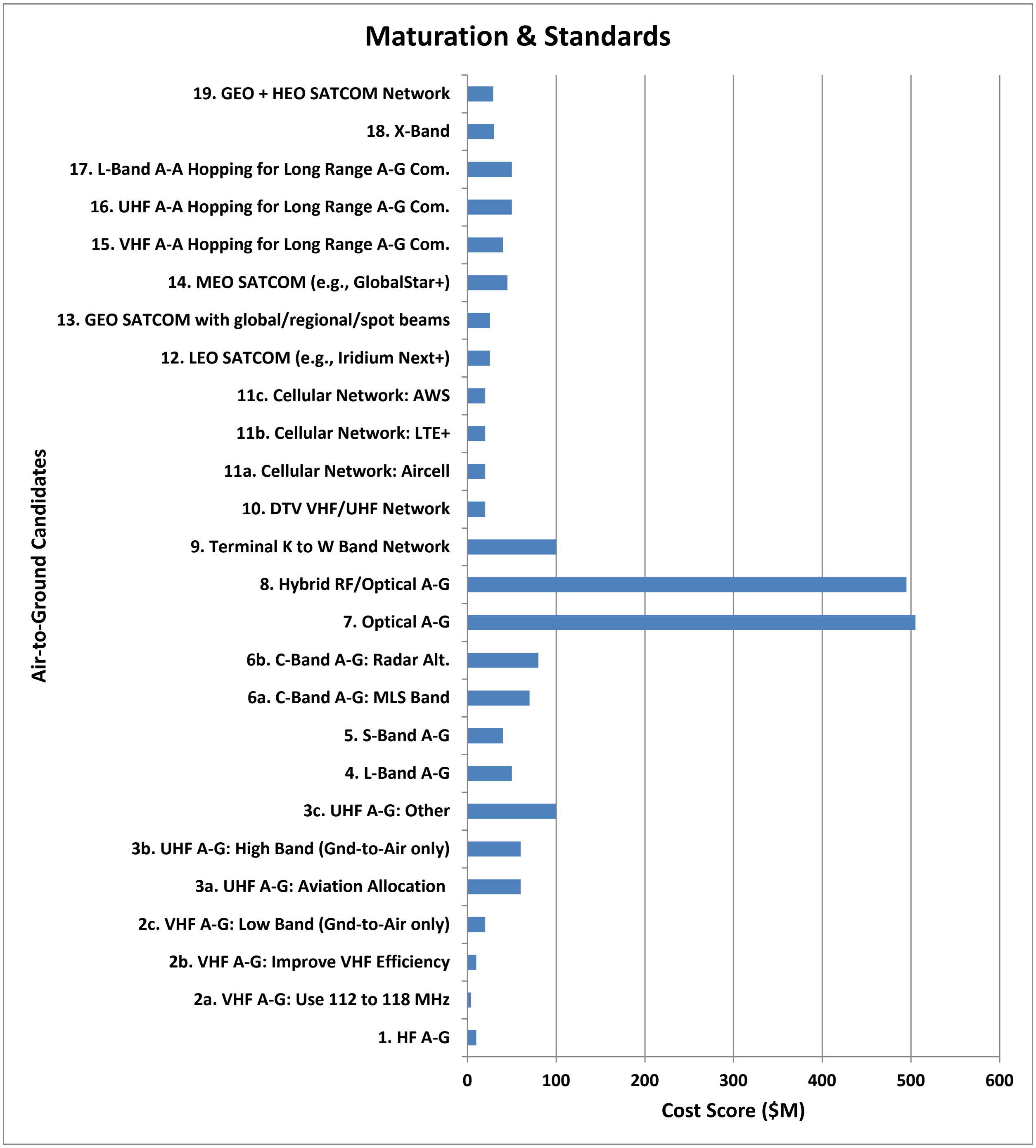


Figure 241 – A-G Candidates Maturation & Standards Plot – AC Model #1 and #2

		Cost Score ($B)			
#	Candidate Technology	Airborne	Ground	Satellite	Total System
1	HF A-G	56.09	0.22	0.00	56.31
2a	VHF A-G: Use 112 to 118 MHz	47.67	0.24	0.00	47.91
2b	VHF A-G: Improve VHF Efficiency	49.36	2.94	0.00	52.29
2c	VHF A-G: Low Band (Gnd-to-Air only)	53.29	2.51	0.00	55.80
3a	UHF A-G: Aviation Allocation	53.31	0.81	0.00	54.12
3b	UHF A-G: High Band (Gnd-to-Air only)	53.31	3.78	0.00	57.09
3c	UHF A-G: Other	53.35	0.68	0.00	54.03
4	L-Band A-G	56.11	1.82	0.00	57.93
5	S-Band A-G	56.10	2.47	0.00	58.57
6a	C-Band A-G: MLS Band	61.73	2.65	0.00	64.39
6b	C-Band A-G: Radar Alt.	61.74	2.65	0.00	64.40
7	Optical A-G	151.70	6.35	0.00	158.04
8	Hybrid RF/Optical A-G	207.84	8.98	0.00	216.81
9	Terminal K to W Band Network	16.88	2.65	0.00	19.52
10	DTV VHF/UHF Network	14.03	2.51	0.00	16.54
11a	Cellular Network: Aircell	11.23	1.51	0.00	12.74
11b	Cellular Network: LTE+	11.23	6.26	0.00	17.49
11c	Cellular Network: AWS	11.23	6.26	0.00	17.49
12	LEO SATCOM (e.g., Iridium Next+)	84.14	0.69	18.75	103.58
13	GEO SATCOM with global/regional/spot beams	126.20	0.28	2.01	128.48
14	MEO SATCOM (e.g., GlobalStar+)	89.75	0.51	5.20	95.46
15	VHF A-A Hopping for Long Range A-G Com.	56.10	0.81	0.00	56.91
16	UHF A-A Hopping for Long Range A-G Com.	61.72	0.80	0.00	62.52
17	L-Band A-A Hopping for Long Range A-G Com.	64.53	1.81	0.00	66.34
18	X-Band	64.53	0.20	0.00	64.72
19	GEO + HEO SATCOM Network	131.81	0.52	4.07	136.40

Figure 242 – A-G Candidates Cost Score Summary A-G-S Table – AC Model #1

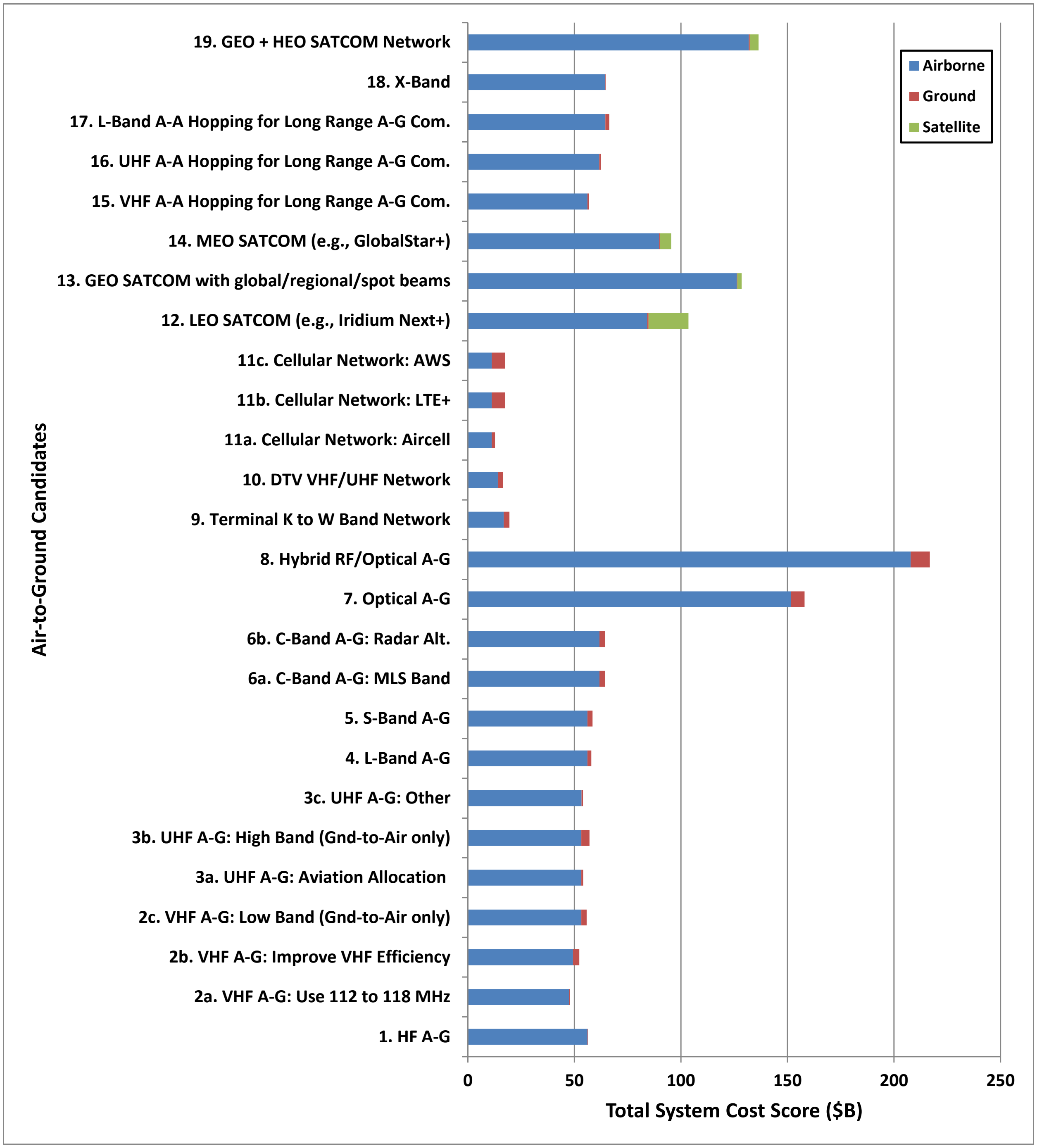


Figure 243 – A-G Candidates Cost Score Summary A-G-S Plot – AC Model #1

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1 HF A-G															56.31
Airborne			0.0	5000.0		**17771784.0**		**4442946.0**		**33868630.7**	**56.09**	100%	**56.09**	**99.61**	
Air Transport	12129	25			100.0	1212900.0	25.0	303225.0	15.0	2311466.6					
Business&Regional	43141	25			70.0	3019870.0	17.5	754967.5	10.5	5755076.1					
General Aviation	563212	25			10.0	5632120.0	2.5	1408030.0	1.5	10733353.4					
UAV - Big	892	25			65.0	57980.0	16.3	14495.0	9.8	110552.6					
UAV - Small	5042	25			12.0	60504.0	3.0	15126.0	1.8	115309.1					
Military Transport	13511	25			110.0	1486210.0	27.5	371552.5	16.5	2832231.2					
Military Non-transport	41848	25			150.0	6277200.0	37.5	1569300.0	22.5	11962596.3					
Space Vehicles	25	25			1000.0	25000.0	250.0	6250.0	150.0	48045.4					
Ground	10	25	0.0	5000.0	3000.0	**30000.0**	1000.0	**10000.0**	700.0	**175000.0**	**0.22**	100%	**0.22**	**0.39**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
2a VHF A-G: Use 112 to 118 MHz															47.91
Airborne			0.0	2000.0		**15106016.4**		**3776504.1**		**28788336.1**	**47.67**	100%	**47.67**	**99.50**	
Air Transport	12129	25			85.0	1030965.0	21.3	257741.3	12.8	1964746.6					
Business&Regional	43141	25			59.5	2566889.5	14.9	641722.4	8.9	4891814.7					
General Aviation	563212	25			8.5	4787302.0	2.1	1196825.5	1.3	9123350.4					
UAV - Big	892	25			55.3	49283.0	13.8	12320.8	8.3	93969.7					
UAV - Small	5042	25			10.2	51428.4	2.6	12857.1	1.5	98012.7					
Military Transport	13511	25			93.5	1263278.5	23.4	315819.6	14.0	2407396.5					
Military Non-transport	41848	25			127.5	5335620.0	31.9	1333905.0	19.1	10168206.8					
Space Vehicles	25	25			850.0	21250.0	212.5	5312.5	127.5	40838.6					
Ground	200	25	0.0	2000.0	82.0	**16400.0**	100.0	**20000.0**	40.0	**200000.0**	**0.24**	100%	**0.24**	**0.50**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
2b VHF A-G: Improve VHF Efficiency															52.29
Airborne			0.0	5000.0		**15639169.9**		**3909792.5**		**29804395.0**	**49.36**	100%	**49.36**	**94.39**	
Air Transport	12129	25			88.0	1067352.0	22.0	266838.0	13.2	2034090.6					
Business&Regional	43141	25			61.6	2657485.6	15.4	664371.4	9.2	5064467.0					
General Aviation	563212	25			8.8	4956265.6	2.2	1239066.4	1.3	9445351.0					
UAV - Big	892	25			57.2	51022.4	14.3	12755.6	8.6	97286.3					
UAV - Small	5042	25			10.6	53243.5	2.6	13310.9	1.6	101472.0					
Military Transport	13511	25			96.8	1307864.8	24.2	326966.2	14.5	2492363.5					
Military Non-transport	41848	25			132.0	5523936.0	33.0	1380984.0	19.8	10527084.7					
Space Vehicles	25	25			880.0	22000.0	220.0	5500.0	132.0	42280.0					
Ground	2708	25	0.0	5000.0	82.0	**222056.0**	100.0	**0.0**	40.0	**2708000.0**	**2.94**	100%	**2.94**	**5.61**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
2c VHF A-G: Low Band (Ground-to-Air only)															55.80
Airborne			0.0	10000.0		**16883194.8**		**4220798.7**		**32175199.2**	**53.29**	100%	**53.29**	**95.50**	
Air Transport	12129	25			95.0	1152255.0	23.8	288063.8	14.3	2195893.3					
Business&Regional	43141	25			66.5	2868876.5	16.6	717219.1	10.0	5467322.3					
General Aviation	563212	25			9.5	5350514.0	2.4	1337628.5	1.4	10196685.8					
UAV - Big	892	25			61.8	55081.0	15.4	13770.3	9.3	105025.0					
UAV - Small	5042	25			11.4	57478.8	2.9	14369.7	1.7	109543.6					
Military Transport	13511	25			104.5	1411899.5	26.1	352974.9	15.7	2690619.6					
Military Non-transport	41848	25			142.5	5963340.0	35.6	1490835.0	21.4	11364466.5					
Space Vehicles	25	25			950.0	23750.0	237.5	5937.5	142.5	45643.2					
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	100%	**2.51**	**4.50**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 244 – A-G Candidates Detailed Cost Score Table – AC Model #1 [Part 1 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
3a UHF A-G: Aviation Allocation															54.12
Airborne			0.0	30000.0		**16883194.8**		**4220798.7**		**32175199.2**	**53.31**	100%	**53.31**	**98.51**	
Air Transport	12129	25			95.0	1152255.0	23.8	288063.8	14.3	2195893.3					
Business&Regional	43141	25			66.5	2868876.5	16.6	717219.1	10.0	5467322.3					
General Aviation	563212	25			9.5	5350514.0	2.4	1337628.5	1.4	10196685.8					
UAV - Big	892	25			61.8	55081.0	15.4	13770.3	9.3	105025.0					
UAV - Small	5042	25			11.4	57478.8	2.9	14369.7	1.7	109543.6					
Military Transport	13511	25			104.5	1411899.5	26.1	352974.9	15.7	2690619.6					
Military Non-transport	41848	25			142.5	5963340.0	35.6	1490835.0	21.4	11364466.5					
Space Vehicles	25	25			950.0	23750.0	237.5	5937.5	142.5	45643.2					
Ground	650	25	0.0	30000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.81**	100%	**0.81**	**1.49**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
3b UHF A-G: High Band (Ground-to-Air only)															57.09
Airborne			0.0	30000.0		**16883194.8**		**4220798.7**		**32175199.2**	**53.31**	100%	**53.31**	**93.38**	
Air Transport	12129	25			95.0	1152255.0	23.8	288063.8	14.3	2195893.3					
Business&Regional	43141	25			66.5	2868876.5	16.6	717219.1	10.0	5467322.3					
General Aviation	563212	25			9.5	5350514.0	2.4	1337628.5	1.4	10196685.8					
UAV - Big	892	25			61.8	55081.0	15.4	13770.3	9.3	105025.0					
UAV - Small	5042	25			11.4	57478.8	2.9	14369.7	1.7	109543.6					
Military Transport	13511	25			104.5	1411899.5	26.1	352974.9	15.7	2690619.6					
Military Non-transport	41848	25			142.5	5963340.0	35.6	1490835.0	21.4	11364466.5					
Space Vehicles	25	25			950.0	23750.0	237.5	5937.5	142.5	45643.2					
Ground	750	25	0.0	30000.0	0.0	**0.0**	0.0	**0.0**	200.0	**3750000.0**	**3.78**	100%	**3.78**	**6.62**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
3c UHF A-G: Other															54.03
Airborne			0.0	70000.0		**16883194.8**		**4220798.7**		**32175199.2**	**53.35**	100%	**53.35**	**98.74**	
Air Transport	12129	25			95.0	1152255.0	23.8	288063.8	14.3	2195893.3					
Business&Regional	43141	25			66.5	2868876.5	16.6	717219.1	10.0	5467322.3					
General Aviation	563212	25			9.5	5350514.0	2.4	1337628.5	1.4	10196685.8					
UAV - Big	892	25			61.8	55081.0	15.4	13770.3	9.3	105025.0					
UAV - Small	5042	25			11.4	57478.8	2.9	14369.7	1.7	109543.6					
Military Transport	13511	25			104.5	1411899.5	26.1	352974.9	15.7	2690619.6					
Military Non-transport	41848	25			142.5	5963340.0	35.6	1490835.0	21.4	11364466.5					
Space Vehicles	25	25			950.0	23750.0	237.5	5937.5	142.5	45643.2					
Ground	1000	25	0.0	30000.0	100.0	**100000.0**	50.0	**50000.0**	20.0	**500000.0**	**0.68**	100%	**0.68**	**1.26**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
4 L-Band A-G															57.93
Airborne			0.0	25000.0		**17771784.0**		**4442946.0**		**33868630.7**	**56.11**	100%	**56.11**	**96.86**	
Air Transport	12129	25			100.0	1212900.0	25.0	303225.0	15.0	2311466.6					
Business&Regional	43141	25			70.0	3019870.0	17.5	754967.5	10.5	5755076.1					
General Aviation	563212	25			10.0	5632120.0	2.5	1408030.0	1.5	10733353.4					
UAV - Big	892	25			65.0	57980.0	16.3	14495.0	9.8	110552.6					
UAV - Small	5042	25			12.0	60504.0	3.0	15126.0	1.8	115309.1					
Military Transport	13511	25			110.0	1486210.0	27.5	371552.5	16.5	2832231.2					
Military Non-transport	41848	25			150.0	6277200.0	37.5	1569300.0	22.5	11962596.3					
Space Vehicles	25	25			1000.0	25000.0	250.0	6250.0	150.0	48045.4					
Ground	1200	25	0.0	25000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.82**	100%	**1.82**	**3.14**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 245 – A-G Candidates Detailed Cost Score Table – AC Model #1 [Part 2 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5 S-Band A-G															58.57
Airborne			0.0	20000.0		**17771784.0**		**4442946.0**		**33868630.7**	**56.10**	100%	**56.10**	**95.79**	
Air Transport	12129	25			100.0	1212900.0	25.0	303225.0	15.0	2311466.6					
Business&Regional	43141	25			70.0	3019870.0	17.5	754967.5	10.5	5755076.1					
General Aviation	563212	25			10.0	5632120.0	2.5	1408030.0	1.5	10733353.4					
UAV - Big	892	25			65.0	57980.0	16.3	14495.0	9.8	110552.6					
UAV - Small	5042	25			12.0	60504.0	3.0	15126.0	1.8	115309.1					
Military Transport	13511	25			110.0	1486210.0	27.5	371552.5	16.5	2832231.2					
Military Non-transport	41848	25			150.0	6277200.0	37.5	1569300.0	22.5	11962596.3					
Space Vehicles	25	25			1000.0	25000.0	250.0	6250.0	150.0	48045.4					
Ground	1500	25	0.0	20000.0	125.0	**187500.0**	130.0	**195000.0**	55.0	**2062500.0**	**2.47**	100%	**2.47**	**4.21**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
6a C-Band A-G: MLS Band															64.39
Airborne			10000.0	30000.0		**19548962.4**		**4887240.6**		**37255493.8**	**61.73**	100%	**61.73**	**95.88**	
Air Transport	12129	25			110.0	1334190.0	27.5	333547.5	16.5	2542613.2					
Business&Regional	43141	25			77.0	3321857.0	19.3	830464.3	11.6	6330583.7					
General Aviation	563212	25			11.0	6195332.0	2.8	1548833.0	1.7	11806688.8					
UAV - Big	892	25			71.5	63778.0	17.9	15944.5	10.7	121607.8					
UAV - Small	5042	25			13.2	66554.4	3.3	16638.6	2.0	126840.0					
Military Transport	13511	25			121.0	1634831.0	30.3	408707.8	18.2	3115454.3					
Military Non-transport	41848	25			165.0	6904920.0	41.3	1726230.0	24.8	13158855.9					
Space Vehicles	25	25			1100.0	27500.0	275.0	6875.0	165.0	52850.0					
Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	100%	**2.65**	**4.12**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
6b C-Band A-G: Radar Alt.															64.40
Airborne			20000.0	30000.0		**19548962.4**		**4887240.6**		**37255493.8**	**61.74**	100%	**61.74**	**95.88**	
Air Transport	12129	25			110.0	1334190.0	27.5	333547.5	16.5	2542613.2					
Business&Regional	43141	25			77.0	3321857.0	19.3	830464.3	11.6	6330583.7					
General Aviation	563212	25			11.0	6195332.0	2.8	1548833.0	1.7	11806688.8					
UAV - Big	892	25			71.5	63778.0	17.9	15944.5	10.7	121607.8					
UAV - Small	5042	25			13.2	66554.4	3.3	16638.6	2.0	126840.0					
Military Transport	13511	25			121.0	1634831.0	30.3	408707.8	18.2	3115454.3					
Military Non-transport	41848	25			165.0	6904920.0	41.3	1726230.0	24.8	13158855.9					
Space Vehicles	25	25			1100.0	27500.0	275.0	6875.0	165.0	52850.0					
Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	100%	**2.65**	**4.12**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
7 Optical A-G															158.04
Airborne			200000.0	70000.0		**47983816.8**		**11995954.2**		**91445303.0**	**151.70**	100%	**151.70**	**95.99**	
Air Transport	12129	25			270.0	3274830.0	67.5	818707.5	40.5	6240959.8					
Business&Regional	43141	25			189.0	8153649.0	47.3	2038412.3	28.4	15538705.6					
General Aviation	563212	25			27.0	15206724.0	6.8	3801681.0	4.1	28980054.3					
UAV - Big	892	25			175.5	156546.0	43.9	39136.5	26.3	298492.0					
UAV - Small	5042	25			32.4	163360.8	8.1	40840.2	4.9	311334.5					
Military Transport	13511	25			297.0	4012767.0	74.3	1003191.8	44.6	7647024.3					
Military Non-transport	41848	25			405.0	16948440.0	101.3	4237110.0	60.8	32299009.9					
Space Vehicles	25	25			2700.0	67500.0	675.0	16875.0	405.0	129722.7					
Ground	100	25	200000.0	35000.0	8100.0	**810000.0**	3000.0	**300000.0**	2000.0	**5000000.0**	**6.35**	100%	**6.35**	**4.01**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 246 – A-G Candidates Detailed Cost Score Table – AC Model #1 [Part 3 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
8 Hybrid RF/Optical A-G															216.81
Airborne			240000.0	90000.0		**65755600.8**		**16438900.2**		**125313933.7**	**207.84**	100%	**207.84**	**95.86**	
Air Transport	12129	25			370.0	4487730.0	92.5	1121932.5	55.5	8552426.3					
Business&Regional	43141	25			259.0	11173519.0	64.8	2793379.8	38.9	21293781.7					
General Aviation	563212	25			37.0	20838844.0	9.3	5209711.0	5.6	39713407.7					
UAV - Big	892	25			240.5	214526.0	60.1	53631.5	36.1	409044.5					
UAV - Small	5042	25			44.4	223864.8	11.1	55966.2	6.7	426643.6					
Military Transport	13511	25			407.0	5498977.0	101.8	1374744.3	61.1	10479255.5					
Military Non-transport	41848	25			555.0	23225640.0	138.8	5806410.0	83.3	44261606.2					
Space Vehicles	25	25			3700.0	92500.0	925.0	23125.0	555.0	177768.2					
Ground	100	25	120000.0	45000.0	9100.0	**910000.0**	4000.0	**400000.0**	3000.0	**7500000.0**	**8.98**	100%	**8.98**	**4.14**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
9 Terminal K to W Band Network (e.g., KU Band QualComm+)															19.52
Airborne			20000.0	30000.0		**5331535.2**		**1332883.8**		**10160589.2**	**16.88**	100%	**16.88**	**86.43**	
Air Transport	12129	25			30.0	363870.0	7.5	90967.5	4.5	693440.0					
Business&Regional	43141	25			21.0	905961.0	5.3	226490.3	3.2	1726522.8					
General Aviation	563212	25			3.0	1689636.0	0.8	422409.0	0.5	3220006.0					
UAV - Big	892	25			19.5	17394.0	4.9	4348.5	2.9	33165.8					
UAV - Small	5042	25			3.6	18151.2	0.9	4537.8	0.5	34592.7					
Military Transport	13511	25			33.0	445863.0	8.3	111465.8	5.0	849669.4					
Military Non-transport	41848	25			45.0	1883160.0	11.3	470790.0	6.8	3588778.9					
Space Vehicles	25	25			300.0	7500.0	75.0	1875.0	45.0	14413.6					
Ground	300	25	20000.0	30000.0	1500.0	**450000.0**	5166.0	**1549800.0**	80.0	**600000.0**	**2.65**	100%	**2.65**	**13.57**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
10 DTV VHF/UHF Network															16.54
Airborne			0.0	10000.0		**4442946.0**		**1110736.5**		**8467157.7**	**14.03**	100%	**14.03**	**84.83**	
Air Transport	12129	25			25.0	303225.0	6.3	75806.3	3.8	577866.6					
Business&Regional	43141	25			17.5	754967.5	4.4	188741.9	2.6	1438769.0					
General Aviation	563212	25			2.5	1408030.0	0.6	352007.5	0.4	2683338.4					
UAV - Big	892	25			16.3	14495.0	4.1	3623.8	2.4	27638.1					
UAV - Small	5042	25			3.0	15126.0	0.8	3781.5	0.5	28827.3					
Military Transport	13511	25			27.5	371552.5	6.9	92888.1	4.1	708057.8					
Military Non-transport	41848	25			37.5	1569300.0	9.4	392325.0	5.6	2990649.1					
Space Vehicles	25	25			250.0	6250.0	62.5	1562.5	37.5	12011.4					
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	100%	**2.51**	**15.17**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
11a Cellular Network: Aircell															12.74
Airborne			0.0	10000.0		**3554356.8**		**888589.2**		**6773726.1**	**11.23**	100%	**11.23**	**88.14**	
Air Transport	12129	25			20.0	242580.0	5.0	60645.0	3.0	462293.3					
Business&Regional	43141	25			14.0	603974.0	3.5	150993.5	2.1	1151015.2					
General Aviation	563212	25			2.0	1126424.0	0.5	281606.0	0.3	2146670.7					
UAV - Big	892	25			13.0	11596.0	3.3	2899.0	2.0	22110.5					
UAV - Small	5042	25			2.4	12100.8	0.6	3025.2	0.4	23061.8					
Military Transport	13511	25			22.0	297242.0	5.5	74310.5	3.3	566446.2					
Military Non-transport	41848	25			30.0	1255440.0	7.5	313860.0	4.5	2392519.3					
Space Vehicles	25	25			200.0	5000.0	50.0	1250.0	30.0	9609.1					
Ground	300	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**1500000.0**	**1.51**	100%	**1.51**	**11.86**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 247 – A-G Candidates Detailed Cost Score Table – AC Model #1 [Part 4 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
11b Cellular Network: LTE+															**17.49**
Airborne			0.0	10000.0		**3554356.8**		**888589.2**		**6773726.1**	**11.23**	100%	**11.23**	**64.20**	
Air Transport	12129	25			20.0	242580.0	5.0	60645.0	3.0	462293.3					
Business&Regional	43141	25			14.0	603974.0	3.5	150993.5	2.1	1151015.2					
General Aviation	563212	25			2.0	1126424.0	0.5	281606.0	0.3	2146670.7					
UAV - Big	892	25			13.0	11596.0	3.3	2899.0	2.0	22110.5					
UAV - Small	5042	25			2.4	12100.8	0.6	3025.2	0.4	23061.8					
Military Transport	13511	25			22.0	297242.0	5.5	74310.5	3.3	566446.2					
Military Non-transport	41848	25			30.0	1255440.0	7.5	313860.0	4.5	2392519.3					
Space Vehicles	25	25			200.0	5000.0	50.0	1250.0	30.0	9609.1					
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	100%	**6.26**	**35.80**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
11c Cellular Network: AWS															**17.49**
Airborne			0.0	10000.0		**3554356.8**		**888589.2**		**6773726.1**	**11.23**	100%	**11.23**	**64.20**	
Air Transport	12129	25			20.0	242580.0	5.0	60645.0	3.0	462293.3					
Business&Regional	43141	25			14.0	603974.0	3.5	150993.5	2.1	1151015.2					
General Aviation	563212	25			2.0	1126424.0	0.5	281606.0	0.3	2146670.7					
UAV - Big	892	25			13.0	11596.0	3.3	2899.0	2.0	22110.5					
UAV - Small	5042	25			2.4	12100.8	0.6	3025.2	0.4	23061.8					
Military Transport	13511	25			22.0	297242.0	5.5	74310.5	3.3	566446.2					
Military Non-transport	41848	25			30.0	1255440.0	7.5	313860.0	4.5	2392519.3					
Space Vehicles	25	25			200.0	5000.0	50.0	1250.0	30.0	9609.1					
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	100%	**6.26**	**35.80**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
12 LEO SATCOM Network (e.g., Iridium Next+)															**103.58**
Airborne			0.0	10000.0		**26657676.0**		**6664419.0**		**50802946.1**	**84.14**	100%	**84.14**	**81.23**	
Air Transport	12129	25			150.0	1819350.0	37.5	454837.5	22.5	3467199.9					
Business&Regional	43141	25			105.0	4529805.0	26.3	1132451.3	15.8	8632614.2					
General Aviation	563212	25			15.0	8448180.0	3.8	2112045.0	2.3	16100030.2					
UAV - Big	892	25			97.5	86970.0	24.4	21742.5	14.6	165828.9					
UAV - Small	5042	25			18.0	90756.0	4.5	22689.0	2.7	172963.6					
Military Transport	13511	25			165.0	2229315.0	41.3	557328.8	24.8	4248346.8					
Military Non-transport	41848	25			225.0	9415800.0	56.3	2353950.0	33.8	17943894.4					
Space Vehicles	25	25			1500.0	37500.0	375.0	9375.0	225.0	72068.2					
Ground	13	25	0.0	5000.0	4000.0	**52000.0**	11000.0	**143000.0**	1500.0	**487500.0**	**0.69**	100%	**0.69**	**0.66**	
Satellite	66	6.25	0.0	10000.0	40000.0	**10560000.0**	6000.0	**1584000.0**	4000.0	**6600000.0**	**18.75**	100%	**18.75**	**18.11**	
spares	15														
13 GEO SATCOM Network with global/regional /spot beams															**128.48**
Airborne			0.0	10000.0		**39986514.0**		**9996628.5**		**76204419.1**	**126.20**	100%	**126.20**	**98.22**	
Air Transport	12129	25			225.0	2729025.0	56.3	682256.3	33.8	5200799.8					
Business&Regional	43141	25			157.5	6794707.5	39.4	1698676.9	23.6	12948921.3					
General Aviation	563212	25			22.5	12672270.0	5.6	3168067.5	3.4	24150045.2					
UAV - Big	892	25			146.3	130455.0	36.6	32613.8	21.9	248743.3					
UAV - Small	5042	25			27.0	136134.0	6.8	34033.5	4.1	259445.4					
Military Transport	13511	25			247.5	3343972.5	61.9	835993.1	37.1	6372520.2					
Military Non-transport	41848	25			337.5	14123700.0	84.4	3530925.0	50.6	26915841.6					
Space Vehicles	25	25			2250.0	56250.0	562.5	14062.5	337.5	108102.3					
Ground	3	25	0.0	5000.0	4000.0	**12000.0**	11000.0	**33000.0**	3000.0	**225000.0**	**0.28**	100%	**0.28**	**0.21**	
Satellite	3	12.5	0.0	10000.0	150000.0	**900000.0**	100000.0	**600000.0**	6666.7	**500000.0**	**2.01**	100%	**2.01**	**1.56**	
spare	1														

Figure 248 – A-G Candidates Detailed Cost Score Table – AC Model #1 [Part 5 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
14 MEO SATCOM Network (e.g., GlobalStar+)															95.46
Airborne			0.0	20000.0		**28434854.4**		**7108713.6**		**54189809.2**	**89.75**	100%	**89.75**	**94.03**	
Air Transport	12129	25			160.0	1940640.0	40.0	485160.0	24.0	3698346.5					
Business&Regional	43141	25			112.0	4831792.0	28.0	1207948.0	16.8	9208121.8					
General Aviation	563212	25			16.0	9011392.0	4.0	2252848.0	2.4	17173365.5					
UAV - Big	892	25			104.0	92768.0	26.0	23192.0	15.6	176884.1					
UAV - Small	5042	25			19.2	96806.4	4.8	24201.6	2.9	184494.5					
Military Transport	13511	25			176.0	2377936.0	44.0	594484.0	26.4	4531569.9					
Military Non-transport	41848	25			240.0	10043520.0	60.0	2510880.0	36.0	19140154.0					
Space Vehicles	25	25			1600.0	40000.0	400.0	10000.0	240.0	76872.7					
Ground	8	25	0.0	5000.0	4000.0	**32000.0**	11000.0	**88000.0**	1900.0	**380000.0**	**0.51**	100%	**0.51**	**0.53**	
Satellite	20	8.33	0.0	20000.0	50000.0	**3000000.0**	25000.0	**1500000.0**	1355.0	**677500.0**	**5.20**	100%	**5.20**	**5.44**	
spares	6														
15 VHF A-A Hopping for Long Range A-G Com.															56.91
Airborne			0.0	20000.0		**17771784.0**		**4442946.0**		**33868630.7**	**56.10**	100%	**56.10**	**98.58**	
Air Transport	12129	25			100.0	1212900.0	25.0	303225.0	15.0	2311466.6					
Business&Regional	43141	25			70.0	3019870.0	17.5	754967.5	10.5	5755076.1					
General Aviation	563212	25			10.0	5632120.0	2.5	1408030.0	1.5	10733353.4					
UAV - Big	892	25			65.0	57980.0	16.3	14495.0	9.8	110552.6					
UAV - Small	5042	25			12.0	60504.0	3.0	15126.0	1.8	115309.1					
Military Transport	13511	25			110.0	1486210.0	27.5	371552.5	16.5	2832231.2					
Military Non-transport	41848	25			150.0	6277200.0	37.5	1569300.0	22.5	11962596.3					
Space Vehicles	25	25			1000.0	25000.0	250.0	6250.0	150.0	48045.4					
Ground **Enroute GS**	729	25	0.0	20000.0	82.0	**59778.0**	100.0	**0.0**	40.0	**729000.0**	**0.81**	100%	**0.81**	**1.42**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
16 UHF A-A Hopping for Long Range A-G Com.															62.52
Airborne			0.0	30000.0		**19548962.4**		**4887240.6**		**37255493.8**	**61.72**	100%	**61.72**	**98.73**	
Air Transport	12129	25			110.0	1334190.0	27.5	333547.5	16.5	2542613.2					
Business&Regional	43141	25			77.0	3321857.0	19.3	830464.3	11.6	6330583.7					
General Aviation	563212	25			11.0	6195332.0	2.8	1548833.0	1.7	11806688.8					
UAV - Big	892	25			71.5	63778.0	17.9	15944.5	10.7	121607.8					
UAV - Small	5042	25			13.2	66554.4	3.3	16638.6	2.0	126840.0					
Military Transport	13511	25			121.0	1634831.0	30.3	408707.8	18.2	3115454.3					
Military Non-transport	41848	25			165.0	6904920.0	41.3	1726230.0	24.8	13158855.9					
Space Vehicles	25	25			1100.0	27500.0	275.0	6875.0	165.0	52850.0					
Ground	650	25	0.0	20000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.80**	100%	**0.80**	**1.27**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
17 L-Band A-A Hopping for Long Range A-G Com.															66.34
Airborne			0.0	30000.0		**20437551.6**		**5109387.9**		**38948925.3**	**64.53**	100%	**64.53**	**97.27**	
Air Transport	12129	25			115.0	1394835.0	28.8	348708.8	17.3	2658186.6					
Business&Regional	43141	25			80.5	3472850.5	20.1	868212.6	12.1	6618337.6					
General Aviation	563212	25			11.5	6476938.0	2.9	1619234.5	1.7	12343356.5					
UAV - Big	892	25			74.8	66677.0	18.7	16669.3	11.2	127135.5					
UAV - Small	5042	25			13.8	69579.6	3.5	17394.9	2.1	132605.4					
Military Transport	13511	25			126.5	1709141.5	31.6	427285.4	19.0	3257065.9					
Military Non-transport	41848	25			172.5	7218780.0	43.1	1804695.0	25.9	13756985.7					
Space Vehicles	25	25			1150.0	28750.0	287.5	7187.5	172.5	55252.3					
Ground	1200	25	0.0	20000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.81**	100%	**1.81**	**2.73**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 249 – A-G Candidates Detailed Cost Score Table – AC Model #1 [Part 6 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
18	X-Band															**64.72**
	Airborne			0.0	30000.0		**20437551.6**		**5109387.9**		**38948925.3**	**64.53**	100%	**64.53**	**99.69**	
	Air Transport	12129	25			115.0	1394835.0	28.8	348708.8	17.3	2658186.6					
	Business&Regional	43141	25			80.5	3472850.5	20.1	868212.6	12.1	6618337.6					
	General Aviation	563212	25			11.5	6476938.0	2.9	1619234.5	1.7	12343356.5					
	UAV - Big	892	25			74.8	66677.0	18.7	16669.3	11.2	127135.5					
	UAV - Small	5042	25			13.8	69579.6	3.5	17394.9	2.1	132605.4					
	Military Transport	13511	25			126.5	1709141.5	31.6	427285.4	19.0	3257065.9					
	Military Non-transport	41848	25			172.5	7218780.0	43.1	1804695.0	25.9	13756985.7					
	Space Vehicles	25	25			1150.0	28750.0	287.5	7187.5	172.5	55252.3					
	Ground	100	25	0.0	0.0	230.0	**23000.0**	135.0	**13500.0**	65.0	**162500.0**	**0.20**	100%	**0.20**	**0.31**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
19	GEO + HEO SATCOM Network															**136.40**
	Airborne			0.0	12000.0		**41763692.4**		**10440923.1**		**79591282.2**	**131.81**	100%	**131.81**	**96.64**	
	Air Transport	12129	25			235.0	2850315.0	58.8	712578.8	35.3	5431946.5					
	Business&Regional	43141	25			164.5	7096694.5	41.1	1774173.6	24.7	13524428.9					
	General Aviation	563212	25			23.5	13235482.0	5.9	3308870.5	3.5	25223380.6					
	UAV - Big	892	25			152.8	136253.0	38.2	34063.3	22.9	259798.6					
	UAV - Small	5042	25			28.2	142184.4	7.1	35546.1	4.2	270976.3					
	Military Transport	13511	25			258.5	3492593.5	64.6	873148.4	38.8	6655743.3					
	Military Non-transport	41848	25			352.5	14751420.0	88.1	3687855.0	52.9	28112101.2					
	Space Vehicles	25	25			2350.0	58750.0	587.5	14687.5	352.5	112906.8					
	Ground	5	25	0.0	5000.0	4000.0	**20000.0**	11000.0	**55000.0**	3500.0	**437500.0**	**0.52**	100%	**0.52**	**0.38**	
	Satellite	6	12.5	0.0	12000.0	170000.0	**2040000.0**	85000.0	**1020000.0**	6666.7	**1000000.0**	**4.07**	100%	**4.07**	**2.99**	
	spare	3														

Figure 250 – A-G Candidates Detailed Cost Score Table – AC Model #1 [Part 7 of 7]

23.2 Cost Scores – Aircraft Fleet Model #2

For the purposes of the cost estimates provided in this section, it was assumed that all the aircraft in the Fleet Model #2 are equipped with each candidate communication technology individually. *Note that Aircraft Fleet Model #2 is described in Section 22.3.4.2 (*Figure 225*).*

These cost estimates should be treated as "cost scores" for relative comparison among the candidates. The cost scores should not be misinterpreted to be the total system costs associated with implementing each candidate, since for relative comparison purposes among the candidates the entire aircraft fleet was assumed to be upgraded with the candidate communication system. The actual costs for implementing a given candidate will vary depending upon many factors, including, for example, the portion of the fleet that equips, the communications quality of service and coverage required to support the intended airspace applications, etc.

23.2.1 Air-to-Air Candidates Cost Scores – Aircraft Fleet Model #2

Figure 251 and Figure 252 provide a summary table and plot (respectively) for the A-A candidates cost scores broken down into the following cost elements: 1) Maturation & Standards, 2) Equipment, 3) Deployment, 4) Operation & Maintenance, and 5) Total System Costs.

The maturation and standards cost scores are not easily discernable on the total cost score plot provided in Figure 252, since these estimated costs are so low relative to the total costs for building, deploying, operating, and maintaining the communication systems on the fleet of aircraft and ground/satellite systems for 25 years. Thus, Figure 233 (on page 349) provides a plot with just the cost scores for the Maturation and Standards development associated with the A-A candidates, which is the same estimated cost regardless of Aircraft Fleet Model #1 or #2. Note that the x-axis for the costs in Figure 233 is in millions of dollars, while the other plots have x-axis costs in billions of dollars.

Figure 253 and Figure 254 provide a summary table and plot (respectively) for the A-A candidate cost scores broken down into the following cost elements: 1) Airborne, 2) Ground, 3) Satellite, and 4) Total System Costs.

Figure 255 to Figure 257 provide the detailed cost score tables for all the A-A candidates.

		Cost Score ($B)				
#	Candidate Technology	Maturation & Standards	Equipment	Deployment	Operation & Maintenance	Total System
1	VHF A-A	0.005	28.2	7.0	54.9	90.1
2	UHF A-A	0.030	31.5	7.9	61.4	100.8
3	L-Band A-A	0.030	33.1	8.3	64.6	106.1
4	S-Band A-A	0.040	34.8	8.7	67.9	111.4
5	C-Band A-A	0.030	36.4	9.1	71.1	116.7
6	X-Band A-A	0.050	38.1	9.5	74.3	122.0
7	Optical A-A	0.270	119.2	29.8	232.7	382.0
8	Hybrid RF/Optical A-A	0.330	152.4	38.1	297.3	488.1
9	LEO SATCOM A-A	0.025	60.3	14.1	104.0	178.5
10	GEO SATCOM A-A	0.025	75.4	19.3	146.2	240.9
11	MEO SATCOM A-A	0.045	56.0	14.8	104.5	175.4
12	GEO + HEO SATCOM A-A	0.074	79.9	20.5	153.3	253.8

Figure 251 – A-A Candidates Cost Score Summary Table – AC Model #2

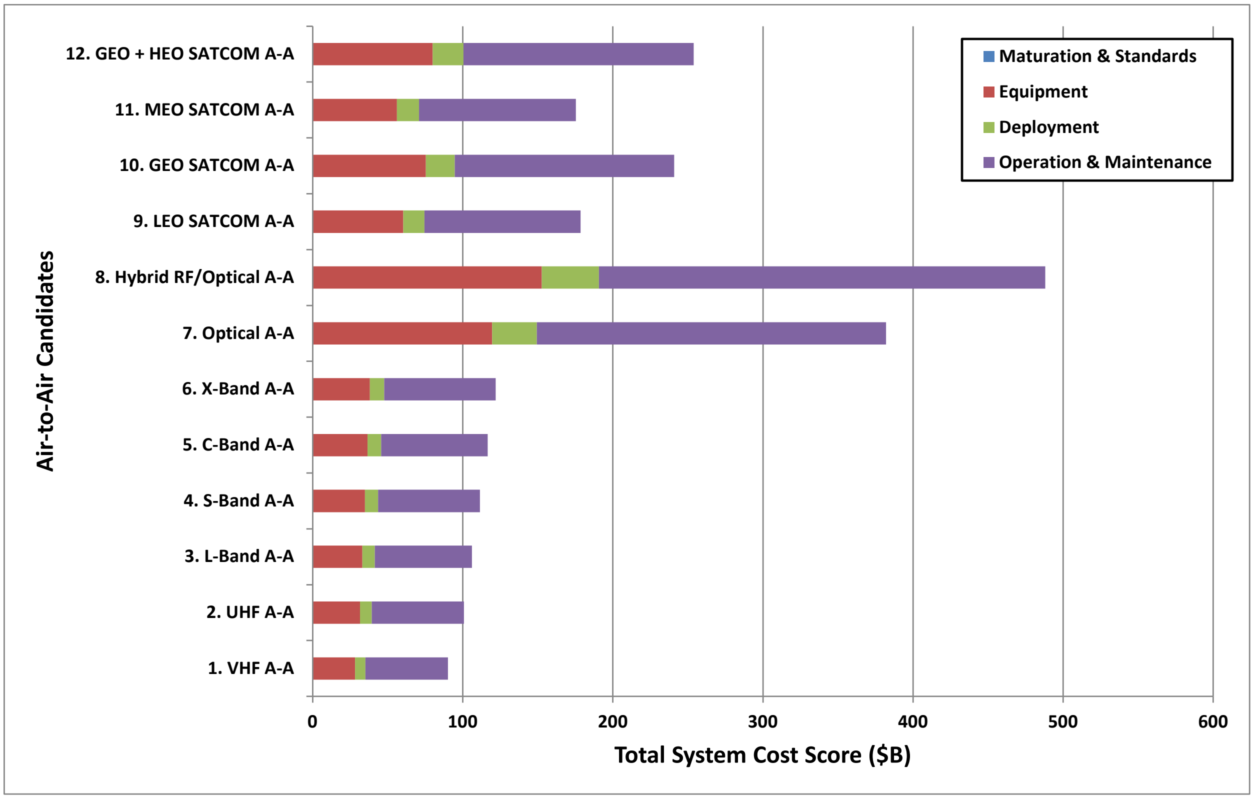


Figure 252 – A-A Candidates Cost Score Summary Plot – AC Model #2

		Cost Score ($B)			
#	Candidate Technology	Airborne	Ground	Satellite	Total System
1	VHF A-A	90.14	0.00	0.00	90.14
2	UHF A-A	100.77	0.00	0.00	100.77
3	L-Band A-A	106.07	0.00	0.00	106.07
4	S-Band A-A	111.38	0.00	0.00	111.38
5	C-Band A-A	116.67	0.00	0.00	116.67
6	X-Band A-A	122.00	0.00	0.00	122.00
7	Optical A-A	382.01	0.00	0.00	382.01
8	Hybrid RF/Optical A-A	488.11	0.00	0.00	488.11
9	LEO SATCOM A-A	159.07	0.69	18.75	178.51
10	GEO SATCOM A-A	238.60	0.28	2.01	240.88
11	MEO SATCOM A-A	169.68	0.51	5.20	175.39
12	GEO + HEO SATCOM A-A	249.20	0.56	4.07	253.84

Figure 253 – A-A Candidates Cost Score Summary A-G-S Table – AC Model #2

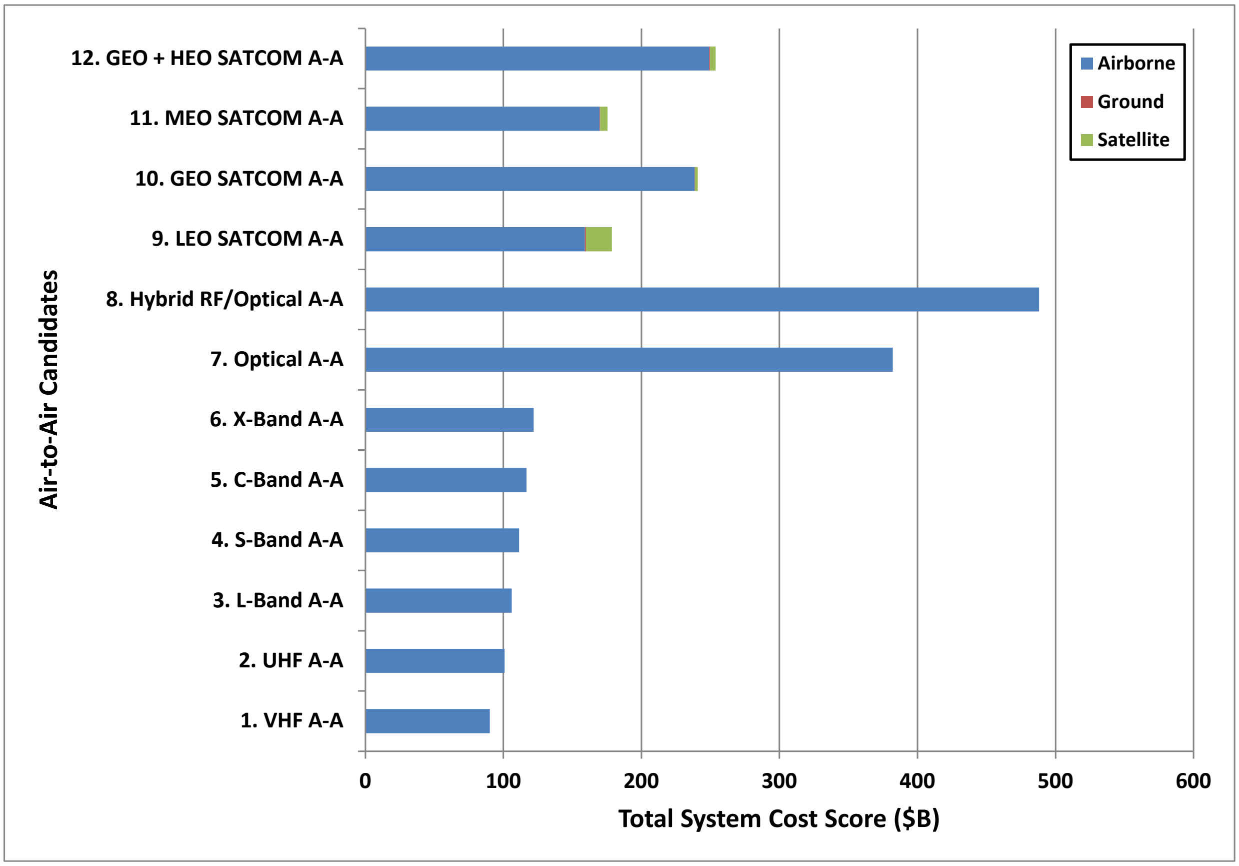


Figure 254 – A-A Candidates Cost Score Summary A-G-S Plot – AC Model #2

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	**VHF A-A**															**90.14**
	Airborne			0.0	5000.0		**28153907.4**		**7038476.9**		**54941214.5**	**90.14**	100%	**90.14**	**100**	
	Air Transport	25211	25			85.0	2142935.0	21.3	535733.8	12.8	4083863.2					
	Business&Regional	88238	25			59.5	5250161.0	14.9	1312540.3	8.9	10005464.9					
	General Aviation	1360662	25			8.5	11565627.0	2.1	2891406.8	1.3	23242781.0					
	UAV - Big	26760	25			55.3	1478490.0	13.8	369622.5	8.3	2761123.7					
	UAV - Small	295977	25			10.2	3018965.4	2.6	754741.4	1.5	3870841.1					
	Military Transport	12664	25			93.5	1184084.0	23.4	296021.0	14.0	2772776.1					
	Military Non-transport	27138	25			127.5	3460095.0	31.9	865023.8	19.1	8102267.9					
	Space Vehicles	63	25			850.0	53550.0	212.5	13387.5	127.5	102096.6					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
2	**UHF A-A**															**100.77**
	Airborne			0.0	30000.0		**31466131.8**		**7866533.0**		**61404886.8**	**100.77**	100%	**100.77**	**100**	
	Air Transport	25211	25			95.0	2395045.0	23.8	598761.3	14.3	4564317.7					
	Business&Regional	88238	25			66.5	5867827.0	16.6	1466956.8	10.0	11182578.4					
	General Aviation	1360662	25			9.5	12926289.0	2.4	3231572.3	1.4	25977225.8					
	UAV - Big	26760	25			61.8	1652430.0	15.4	413107.5	9.3	3085961.8					
	UAV - Small	295977	25			11.4	3374137.8	2.9	843534.5	1.7	4326234.2					
	Military Transport	12664	25			104.5	1323388.0	26.1	330847.0	15.7	3098985.1					
	Military Non-transport	27138	25			142.5	3867165.0	35.6	966791.3	21.4	9055475.8					
	Space Vehicles	63	25			950.0	59850.0	237.5	14962.5	142.5	114107.9					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
3	**L-Band A-A**															**106.07**
	Airborne			0.0	30000.0		**33122244.0**		**8280561.0**		**64636722.9**	**106.07**	100%	**106.07**	**100**	
	Air Transport	25211	25			100.0	2521100.0	25.0	630275.0	15.0	4804545.0					
	Business&Regional	88238	25			70.0	6176660.0	17.5	1544165.0	10.5	11771135.1					
	General Aviation	1360662	25			10.0	13606620.0	2.5	3401655.0	1.5	27344448.2					
	UAV - Big	26760	25			65.0	1739400.0	16.3	434850.0	9.8	3248380.8					
	UAV - Small	295977	25			12.0	3551724.0	3.0	887931.0	1.8	4553930.7					
	Military Transport	12664	25			110.0	1393040.0	27.5	348260.0	16.5	3262089.5					
	Military Non-transport	27138	25			150.0	4070700.0	37.5	1017675.0	22.5	9532079.8					
	Space Vehicles	63	25			1000.0	63000.0	250.0	15750.0	150.0	120113.6					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
4	**S-Band A-A**															**111.38**
	Airborne			0.0	40000.0		**34778356.2**		**8694589.1**		**67868559.1**	**111.38**	100%	**111.38**	**100**	
	Air Transport	25211	25			105.0	2647155.0	26.3	661788.8	15.8	5044772.2					
	Business&Regional	88238	25			73.5	6485493.0	18.4	1621373.3	11.0	12359691.9					
	General Aviation	1360662	25			10.5	14286951.0	2.6	3571737.8	1.6	28711670.7					
	UAV - Big	26760	25			68.3	1826370.0	17.1	456592.5	10.2	3410799.9					
	UAV - Small	295977	25			12.6	3729310.2	3.2	932327.6	1.9	4781627.3					
	Military Transport	12664	25			115.5	1462692.0	28.9	365673.0	17.3	3425194.0					
	Military Non-transport	27138	25			157.5	4274235.0	39.4	1068558.8	23.6	10008683.8					
	Space Vehicles	63	25			1050.0	66150.0	262.5	16537.5	157.5	126119.3					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	

Figure 255 – A-A Candidates Detailed Cost Score Table – AC Model #2 [Part 1 of 3]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5	C-Band A-A															116.67
	Airborne			0.0	30000.0		**36434468.4**		**9108617.1**		**71100395.2**	**116.67**	100%	**116.67**	**100**	
	Air Transport	25211	25			110.0	2773210.0	27.5	693302.5	16.5	5284999.5					
	Business&Regional	88238	25			77.0	6794326.0	19.3	1698581.5	11.6	12948248.7					
	General Aviation	1360662	25			11.0	14967282.0	2.8	3741820.5	1.7	30078893.1					
	UAV - Big	26760	25			71.5	1913340.0	17.9	478335.0	10.7	3573218.9					
	UAV - Small	295977	25			13.2	3906896.4	3.3	976724.1	2.0	5009323.8					
	Military Transport	12664	25			121.0	1532344.0	30.3	383086.0	18.2	3588298.5					
	Military Non-transport	27138	25			165.0	4477770.0	41.3	1119442.5	24.8	10485287.8					
	Space Vehicles	63	25			1100.0	69300.0	275.0	17325.0	165.0	132125.0					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
6	X-Band A-A															122.00
	Airborne			0.0	50000.0		**38090580.6**		**9522645.2**		**74332231.3**	**122.00**	100%	**122.00**	**100**	
	Air Transport	25211	25			115.0	2899265.0	28.8	724816.3	17.3	5525226.7					
	Business&Regional	88238	25			80.5	7103159.0	20.1	1775789.8	12.1	13536805.4					
	General Aviation	1360662	25			11.5	15647613.0	2.9	3911903.3	1.7	31446115.5					
	UAV - Big	26760	25			74.8	2000310.0	18.7	500077.5	11.2	3735638.0					
	UAV - Small	295977	25			13.8	4084482.6	3.5	1021120.7	2.1	5237020.3					
	Military Transport	12664	25			126.5	1601996.0	31.6	400499.0	19.0	3751403.0					
	Military Non-transport	27138	25			172.5	4681305.0	43.1	1170326.3	25.9	10961891.8					
	Space Vehicles	63	25			1150.0	72450.0	287.5	18112.5	172.5	138130.7					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
7	Optical A-A															382.01
	Airborne			200000.0	70000.0		**119240078.4**		**29810019.6**		**232692202.5**	**382.01**	100%	**382.01**	**100**	
	Air Transport	25211	25			360.0	9075960.0	90.0	2268990.0	54.0	17296361.9					
	Business&Regional	88238	25			252.0	22235976.0	63.0	5558994.0	37.8	42376086.5					
	General Aviation	1360662	25			36.0	48983832.0	9.0	12245958.0	5.4	98440013.7					
	UAV - Big	26760	25			234.0	6261840.0	58.5	1565460.0	35.1	11694171.0					
	UAV - Small	295977	25			43.2	12786206.4	10.8	3196551.6	6.5	16394150.6					
	Military Transport	12664	25			396.0	5014944.0	99.0	1253736.0	59.4	11743522.4					
	Military Non-transport	27138	25			540.0	14654520.0	135.0	3663630.0	81.0	34315487.4					
	Space Vehicles	63	25			3600.0	226800.0	900.0	56700.0	540.0	432409.0					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
8	Hybrid RF/Optical A-A															488.11
	Airborne			240000.0	90000.0		**152362322.4**		**38090580.6**		**297328925.4**	**488.11**	100%	**488.11**	**100**	
	Air Transport	25211	25			460.0	11597060.0	115.0	2899265.0	69.0	22100906.8					
	Business&Regional	88238	25			322.0	28412636.0	80.5	7103159.0	48.3	54147221.7					
	General Aviation	1360662	25			46.0	62590452.0	11.5	15647613.0	6.9	125784461.9					
	UAV - Big	26760	25			299.0	8001240.0	74.8	2000310.0	44.9	14942551.9					
	UAV - Small	295977	25			55.2	16337930.4	13.8	4084482.6	8.3	20948081.3					
	Military Transport	12664	25			506.0	6407984.0	126.5	1601996.0	75.9	15005611.9					
	Military Non-transport	27138	25			690.0	18725220.0	172.5	4681305.0	103.5	43847567.2					
	Space Vehicles	63	25			4600.0	289800.0	1150.0	72450.0	690.0	552522.7					
	Ground	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0**	

Figure 256 – A-A Candidates Detailed Cost Score Table – AC Model #2 [Part 2 of 3]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
9	LEO SATCOM A-A															178.51
	Airborne			0.0	10000.0		**49683366.0**		**12420841.5**		**96955084.4**	**159.07**	100%	**159.07**	**89.11**	
	Air Transport	25211	25			150.0	3781650.0	37.5	945412.5	22.5	7206817.4					
	Business&Regional	88238	25			105.0	9264990.0	26.3	2316247.5	15.8	17656702.7					
	General Aviation	1360662	25			15.0	20409930.0	3.8	5102482.5	2.3	41016672.4					
	UAV - Big	26760	25			97.5	2609100.0	24.4	652275.0	14.6	4872571.3					
	UAV - Small	295977	25			18.0	5327586.0	4.5	1331896.5	2.7	6830896.1					
	Military Transport	12664	25			165.0	2089560.0	41.3	522390.0	24.8	4893134.3					
	Military Non-transport	27138	25			225.0	6106050.0	56.3	1526512.5	33.8	14298119.7					
	Space Vehicles	63	25			1500.0	94500.0	375.0	23625.0	225.0	180170.4					
	Ground	13	25	0.0	5000.0	4000.0	**52000.0**	11000.0	**143000.0**	1500.0	**487500.0**	**0.69**	100%	**0.69**	**0.39**	
	Satellite	66	6.25	0.0	10000.0	40000.0	**10560000.0**	6000.0	**1584000.0**	4000.0	**6600000.0**	**18.75**	100%	**18.75**	**10.51**	
	spares	15														
10	GEO SATCOM A-A															240.88
	Airborne			0.0	10000.0		**74525049.0**		**18631262.3**		**145432626.5**	**238.60**	100%	**238.60**	**99.05**	
	Air Transport	25211	25			225.0	5672475.0	56.3	1418118.8	33.8	10810226.2					
	Business&Regional	88238	25			157.5	13897485.0	39.4	3474371.3	23.6	26485054.1					
	General Aviation	1360662	25			22.5	30614895.0	5.6	7653723.8	3.4	61525008.5					
	UAV - Big	26760	25			146.3	3913650.0	36.6	978412.5	21.9	7308856.9					
	UAV - Small	295977	25			27.0	7991379.0	6.8	1997844.8	4.1	10246344.1					
	Military Transport	12664	25			247.5	3134340.0	61.9	783585.0	37.1	7339701.5					
	Military Non-transport	27138	25			337.5	9159075.0	84.4	2289768.8	50.6	21447179.6					
	Space Vehicles	63	25			2250.0	141750.0	562.5	35437.5	337.5	270255.7					
	Ground	3	25	0.0	5000.0	4000.0	**12000.0**	11000.0	**33000.0**	3000.0	**225000.0**	**0.28**	100%	**0.28**	**0.11**	
	Satellite	3	12.5	0.0	10000.0	150000.0	**900000.0**	100000.0	**600000.0**	6666.7	**500000.0**	**2.01**	100%	**2.01**	**0.83**	
	spare	1														
11	MEO SATCOM A-A															175.39
	Airborne			0.0	20000.0		**52995590.4**		**13248897.6**		**103418756.7**	**169.68**	100%	**169.68**	**96.75**	
	Air Transport	25211	25			160.0	4033760.0	40.0	1008440.0	24.0	7687271.9					
	Business&Regional	88238	25			112.0	9882656.0	28.0	2470664.0	16.8	18833816.2					
	General Aviation	1360662	25			16.0	21770592.0	4.0	5442648.0	2.4	43751117.2					
	UAV - Big	26760	25			104.0	2783040.0	26.0	695760.0	15.6	5197409.4					
	UAV - Small	295977	25			19.2	5682758.4	4.8	1420689.6	2.9	7286289.1					
	Military Transport	12664	25			176.0	2228864.0	44.0	557216.0	26.4	5219343.3					
	Military Non-transport	27138	25			240.0	6513120.0	60.0	1628280.0	36.0	15251327.7					
	Space Vehicles	63	25			1600.0	100800.0	400.0	25200.0	240.0	192181.8					
	Ground	8	25	0.0	5000.0	4000.0	**32000.0**	11000.0	**88000.0**	1900.0	**380000.0**	**0.51**	100%	**0.51**	**0.29**	
	Satellite	20	8.33	0.0	20000.0	50000.0	**3000000.0**	25000.0	**1500000.0**	1355.0	**677500.0**	**5.20**	100%	**5.20**	**2.96**	
12	GEO + HEO SATCOM A-A															253.84
	Airborne			0.0	12000.0		**77837273.4**		**19459318.4**		**151896298.8**	**249.20**	100%	**249.20**	**98.17**	
	Air Transport	25211	25			235.0	5924585.0	58.8	1481146.3	35.3	11290680.7					
	Business&Regional	88238	25			164.5	14515151.0	41.1	3628787.8	24.7	27662167.6					
	General Aviation	1360662	25			23.5	31975557.0	5.9	7993889.3	3.5	64259453.4					
	UAV - Big	26760	25			152.8	4087590.0	38.2	1021897.5	22.9	7633695.0					
	UAV - Small	295977	25			28.2	8346551.4	7.1	2086637.9	4.2	10701737.2					
	Military Transport	12664	25			258.5	3273644.0	64.6	818411.0	38.8	7665910.4					
	Military Non-transport	27138	25			352.5	9566145.0	88.1	2391536.3	52.9	22400387.6					
	Space Vehicles	63	25			2350.0	148050.0	587.5	37012.5	352.5	282267.0					
	Ground	5	25	0.0	50000.0	4000.0	**20000.0**	11000.0	**55000.0**	3500.0	**437500.0**	**0.56**	100%	**0.56**	**0.22**	
	Satellite	6	12.5	0.0	12000.0	170000.0	**2040000.0**	85000.0	**1020000.0**	6666.7	**1000000.0**	**4.07**	100%	**4.07**	**1.60**	
	spare	3														

Figure 257 – A-A Candidates Detailed Cost Score Table – AC Model #2 [Part 3 of 3]

23.2.2 Air-to-Ground Candidates Cost Scores – Aircraft Fleet Model #2

Figure 258 and Figure 259 provide a summary table and plot (respectively) for the A-G candidates cost scores broken down into the following cost elements: 1) Maturation & Standards, 2) Equipment, 3) Deployment, 4) Operation & Maintenance, and 5) Total System Costs. The maturation and standards cost scores are not easily discernable on the total cost score plot provided in Figure 259, since these estimated costs are so low relative to the total system costs. Thus, Figure 241 (on page 373) provides a plot with just the cost scores for the Maturation and Standards development associated with the A-G candidates, which is the same estimated cost regardless of Aircraft Fleet Model. Note that the x-axis for the costs in Figure 241 is in millions of dollars, while the other plots have x-axis costs in billions of dollars.

Figure 260 and Figure 261 provide a summary table and plot (respectively) for the A-G candidate cost scores broken down into the following cost elements: 1) Airborne, 2) Ground, 3) Satellite, and 4) Total System Costs.

Figure 262 to Figure 268 provide the detailed cost score tables for all the A-G candidates.

		Cost Score ($B)				
#	**Candidate Technology**	**Maturation & Standards**	**Equipment**	**Deployment**	**Operation & Maintenance**	**Total System**
1	HF A-G	0.010	33.2	8.3	64.8	106.3
2a	VHF A-G: Use 112 to 118 MHz	0.004	28.2	7.1	55.1	90.4
2b	VHF A-G: Improve VHF Efficiency	0.010	29.4	7.3	59.6	96.3
2c	VHF A-G: Low Band (Gnd-to-Air only)	0.020	31.5	7.9	63.9	103.3
3a	UHF A-G: Aviation Allocation	0.060	31.5	7.9	62.1	101.6
3b	UHF A-G: High Band (Gnd-to-Air only)	0.060	31.5	7.9	65.2	104.5
3c	UHF A-G: Other	0.100	31.6	7.9	61.9	101.5
4	L-Band A-G	0.050	33.3	8.4	66.1	107.9
5	S-Band A-G	0.040	33.3	8.5	66.7	108.5
6a	C-Band A-G: MLS Band	0.070	36.6	9.3	73.3	119.3
6b	C-Band A-G: Radar Alt.	0.080	36.6	9.3	73.3	119.3
7	Optical A-G	0.505	90.2	22.7	179.5	292.9
8	Hybrid RF/Optical A-G	0.495	123.5	31.0	246.7	401.7
9	Terminal K to W Band Network	0.100	10.4	4.0	20.0	34.5
10	DTV VHF/UHF Network	0.020	8.3	2.1	18.7	29.0
11a	Cellular Network: Aircell	0.020	6.6	1.7	14.4	22.7
11b	Cellular Network: LTE+	0.020	6.6	1.7	19.2	27.5
11c	Cellular Network: AWS	0.020	6.6	1.7	19.2	27.5
12	LEO SATCOM (e.g., Iridium Next+)	0.025	60.3	14.1	104.0	178.5
13	GEO SATCOM with global/regional/spot beams	0.025	75.4	19.3	146.2	240.9
14	MEO SATCOM (e.g., GlobalStar+)	0.045	56.0	14.8	104.5	175.4
15	VHF A-A Hopping for Long Range A-G Com.	0.040	33.2	8.3	65.4	106.9
16	UHF A-A Hopping for Long Range A-G Com.	0.050	36.5	9.2	71.8	117.5
17	L-Band A-A Hopping for Long Range A-G Com.	0.050	38.2	9.7	75.8	123.8
18	X-Band	0.030	38.1	9.5	74.5	122.2
19	GEO + HEO SATCOM Network	0.029	79.9	20.5	153.3	253.8

Figure 258 – A-G Candidates Cost Score Summary Table – AC Model #2

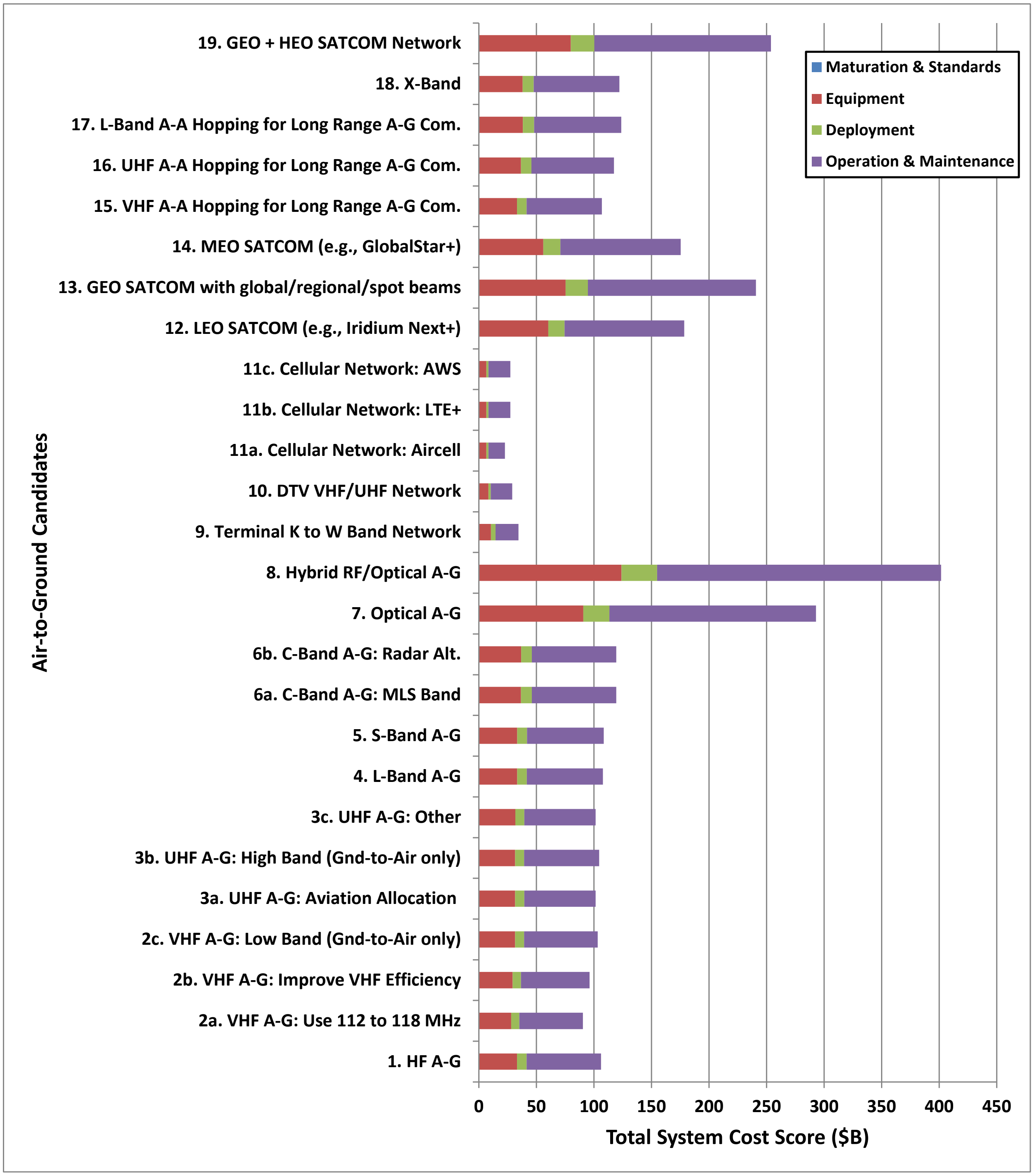


Figure 259 – A-G Candidates Cost Score Summary Plot – AC Model #2

		Cost Score ($B)			
#	Candidate Technology	Airborne	Ground	Satellite	Total System
1	HF A-G	106.04	0.22	0.00	106.26
2a	VHF A-G: Use 112 to 118 MHz	90.14	0.24	0.00	90.37
2b	VHF A-G: Improve VHF Efficiency	93.32	2.94	0.00	96.25
2c	VHF A-G: Low Band (Gnd-to-Air only)	100.75	2.51	0.00	103.26
3a	UHF A-G: Aviation Allocation	100.77	0.81	0.00	101.57
3b	UHF A-G: High Band (Gnd-to-Air only)	100.77	3.78	0.00	104.55
3c	UHF A-G: Other	100.81	0.68	0.00	101.49
4	L-Band A-G	106.06	1.82	0.00	107.88
5	S-Band A-G	106.06	2.47	0.00	108.52
6a	C-Band A-G: MLS Band	116.68	2.65	0.00	119.34
6b	C-Band A-G: Radar Alt.	116.69	2.65	0.00	119.35
7	Optical A-G	286.58	6.35	0.00	292.92
8	Hybrid RF/Optical A-G	392.68	8.98	0.00	401.65
9	Terminal K to W Band Network	31.86	2.65	0.00	34.51
10	DTV VHF/UHF Network	26.52	2.51	0.00	29.03
11a	Cellular Network: Aircell	21.22	1.51	0.00	22.73
11b	Cellular Network: LTE+	21.22	6.26	0.00	27.48
11c	Cellular Network: AWS	21.22	6.26	0.00	27.48
12	LEO SATCOM (e.g., Iridium Next+)	159.07	0.69	18.75	178.51
13	GEO SATCOM with global/regional/spot beams	238.60	0.28	2.01	240.88
14	MEO SATCOM (e.g., GlobalStar+)	169.68	0.51	5.20	175.39
15	VHF A-A Hopping for Long Range A-G Com.	106.06	0.81	0.00	106.87
16	UHF A-A Hopping for Long Range A-G Com.	116.67	0.80	0.00	117.47
17	L-Band A-A Hopping for Long Range A-G Com.	121.98	1.81	0.00	123.79
18	X-Band	121.98	0.20	0.00	122.17
19	GEO + HEO SATCOM Network	249.20	0.52	4.07	253.79

Figure 260 – A-G Candidates Cost Score Summary A-G-S Table – AC Model #2

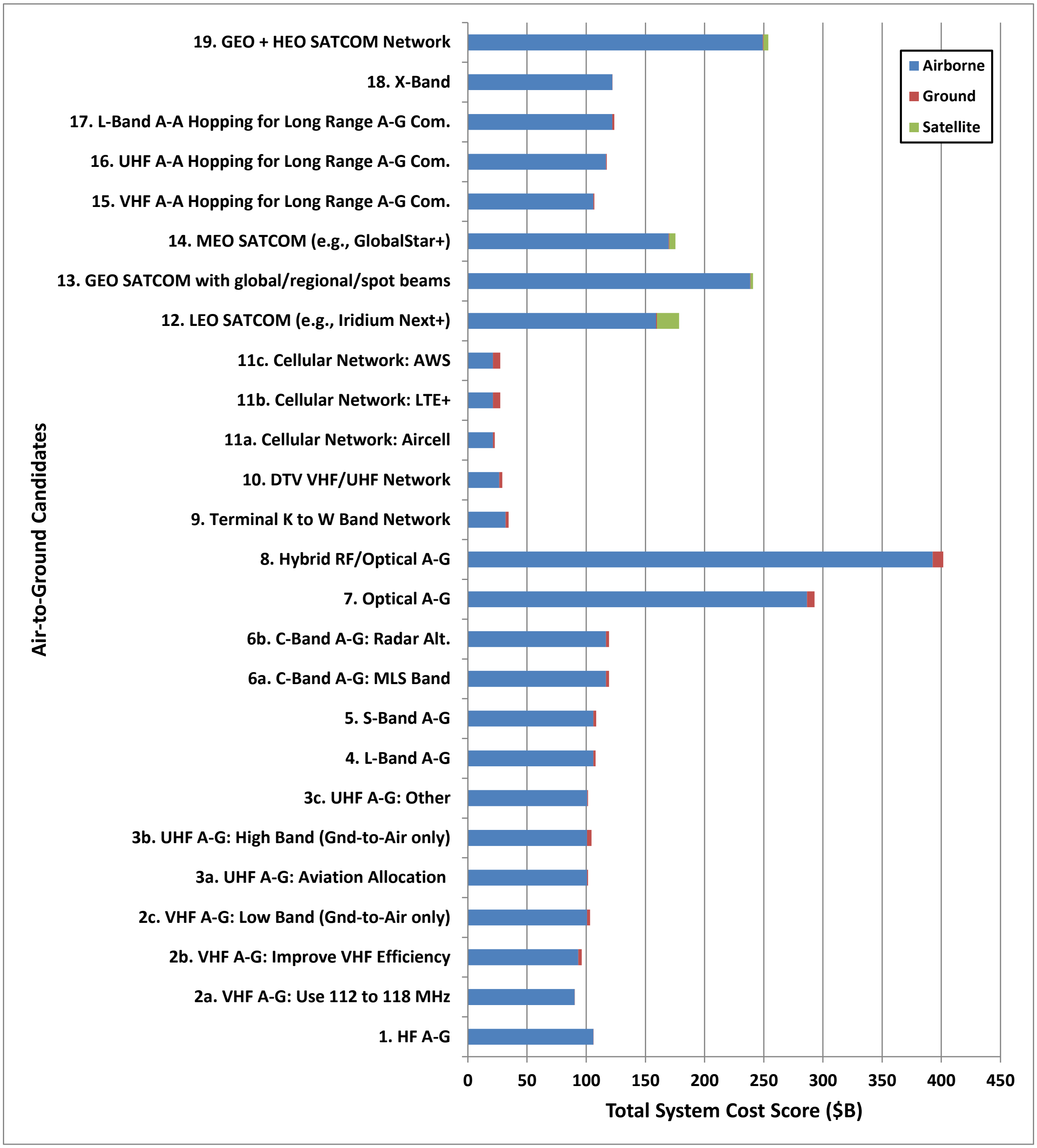


Figure 261 – A-G Candidates Cost Score Summary A-G-S Plot – AC Model #2

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	HF A-G															**106.26**
	Airborne			0.0	5000.0		**33122244.0**		**8280561.0**		**64636722.9**	**106.04**	100%	**106.04**	**99.79**	
	Air Transport	25211	25			100.0	2521100.0	25.0	630275.0	15.0	4804545.0					
	Business&Regional	88238	25			70.0	6176660.0	17.5	1544165.0	10.5	11771135.1					
	General Aviation	1360662	25			10.0	13606620.0	2.5	3401655.0	1.5	27344448.2					
	UAV - Big	26760	25			65.0	1739400.0	16.3	434850.0	9.8	3248380.8					
	UAV - Small	295977	25			12.0	3551724.0	3.0	887931.0	1.8	4553930.7					
	Military Transport	12664	25			110.0	1393040.0	27.5	348260.0	16.5	3262089.5					
	Military Non-transport	27138	25			150.0	4070700.0	37.5	1017675.0	22.5	9532079.8					
	Space Vehicles	63	25			1000.0	63000.0	250.0	15750.0	150.0	120113.6					
	Ground	10	25	0.0	5000.0	3000.0	**30000.0**	1000.0	**10000.0**	700.0	**175000.0**	**0.22**	100%	**0.22**	**0.21**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
2a	VHF A-G: Use 112 to 118 MHz															**90.37**
	Airborne			0.0	2000.0		**28153907.4**		**7038476.9**		**54941214.5**	**90.14**	100%	**90.14**	**99.74**	
	Air Transport	25211	25			85.0	2142935.0	21.3	535733.8	12.8	4083863.2					
	Business&Regional	88238	25			59.5	5250161.0	14.9	1312540.3	8.9	10005464.9					
	General Aviation	1360662	25			8.5	11565627.0	2.1	2891406.8	1.3	23242781.0					
	UAV - Big	26760	25			55.3	1478490.0	13.8	369622.5	8.3	2761123.7					
	UAV - Small	295977	25			10.2	3018965.4	2.6	754741.4	1.5	3870841.1					
	Military Transport	12664	25			93.5	1184084.0	23.4	296021.0	14.0	2772776.1					
	Military Non-transport	27138	25			127.5	3460095.0	31.9	865023.8	19.1	8102267.9					
	Space Vehicles	63	25			850.0	53550.0	212.5	13387.5	127.5	102096.6					
	Ground	200	25	0.0	2000.0	82.0	**16400.0**	100.0	**20000.0**	40.0	**200000.0**	**0.24**	100%	**0.24**	**0.26**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
2b	VHF A-G: Improve VHF Efficiency															**96.25**
	Airborne			0.0	5000.0		**29147574.7**		**7286893.7**		**56880316.2**	**93.32**	100%	**93.32**	**96.95**	
	Air Transport	25211	25			88.0	2218568.0	22.0	554642.0	13.2	4227999.6					
	Business&Regional	88238	25			61.6	5435460.8	15.4	1358865.2	9.2	10358598.9					
	General Aviation	1360662	25			8.8	11973825.6	2.2	2993456.4	1.3	24063114.5					
	UAV - Big	26760	25			57.2	1530672.0	14.3	382668.0	8.6	2858575.1					
	UAV - Small	295977	25			10.6	3125517.1	2.6	781379.3	1.6	4007459.0					
	Military Transport	12664	25			96.8	1225875.2	24.2	306468.8	14.5	2870638.8					
	Military Non-transport	27138	25			132.0	3582216.0	33.0	895554.0	19.8	8388230.3					
	Space Vehicles	63	25			880.0	55440.0	220.0	13860.0	132.0	105700.0					
	Ground	2708	25	0.0	5000.0	82.0	**222056.0**	100.0	**0.0**	40.0	**2708000.0**	**2.94**	100%	**2.94**	**3.05**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
2c	VHF A-G: Low Band (Ground-to-Air only)															**103.26**
	Airborne			0.0	10000.0		**31466131.8**		**7866533.0**		**61404886.8**	**100.75**	100%	**100.75**	**97.57**	
	Air Transport	25211	25			95.0	2395045.0	23.8	598761.3	14.3	4564317.7					
	Business&Regional	88238	25			66.5	5867827.0	16.6	1466956.8	10.0	11182578.4					
	General Aviation	1360662	25			9.5	12926289.0	2.4	3231572.3	1.4	25977225.8					
	UAV - Big	26760	25			61.8	1652430.0	15.4	413107.5	9.3	3085961.8					
	UAV - Small	295977	25			11.4	3374137.8	2.9	843534.5	1.7	4326234.2					
	Military Transport	12664	25			104.5	1323388.0	26.1	330847.0	15.7	3098985.1					
	Military Non-transport	27138	25			142.5	3867165.0	35.6	966791.3	21.4	9055475.8					
	Space Vehicles	63	25			950.0	59850.0	237.5	14962.5	142.5	114107.9					
	Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	100%	**2.51**	**2.43**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 262 – A-G Candidates Detailed Cost Score Table – AC Model #2 [Part 1 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
3a UHF A-G: Aviation Allocation															**101.57**
Airborne			0.0	30000.0		**31466131.8**		**7866533.0**		**61404886.8**	**100.77**	100%	**100.77**	**99.21**	
Air Transport	25211	25			95.0	2395045.0	23.8	598761.3	14.3	4564317.7					
Business&Regional	88238	25			66.5	5867827.0	16.6	1466956.8	10.0	11182578.4					
General Aviation	1360662	25			9.5	12926289.0	2.4	3231572.3	1.4	25977225.8					
UAV - Big	26760	25			61.8	1652430.0	15.4	413107.5	9.3	3085961.8					
UAV - Small	295977	25			11.4	3374137.8	2.9	843534.5	1.7	4326234.2					
Military Transport	12664	25			104.5	1323388.0	26.1	330847.0	15.7	3098985.1					
Military Non-transport	27138	25			142.5	3867165.0	35.6	966791.3	21.4	9055475.8					
Space Vehicles	63	25			950.0	59850.0	237.5	14962.5	142.5	114107.9					
Ground	650	25	0.0	30000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.81**	100%	**0.81**	**0.79**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
3b UHF A-G: High Band (Ground-to-Air only)															**104.55**
Airborne			0.0	30000.0		**31466131.8**		**7866533.0**		**61404886.8**	**100.77**	100%	**100.77**	**96.38**	
Air Transport	25211	25			95.0	2395045.0	23.8	598761.3	14.3	4564317.7					
Business&Regional	88238	25			66.5	5867827.0	16.6	1466956.8	10.0	11182578.4					
General Aviation	1360662	25			9.5	12926289.0	2.4	3231572.3	1.4	25977225.8					
UAV - Big	26760	25			61.8	1652430.0	15.4	413107.5	9.3	3085961.8					
UAV - Small	295977	25			11.4	3374137.8	2.9	843534.5	1.7	4326234.2					
Military Transport	12664	25			104.5	1323388.0	26.1	330847.0	15.7	3098985.1					
Military Non-transport	27138	25			142.5	3867165.0	35.6	966791.3	21.4	9055475.8					
Space Vehicles	63	25			950.0	59850.0	237.5	14962.5	142.5	114107.9					
Ground	750	25	0.0	30000.0	0.0	**0.0**	0.0	**0.0**	200.0	**3750000.0**	**3.78**	100%	**3.78**	**3.62**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
3c UHF A-G: Other															**101.49**
Airborne			0.0	70000.0		**31466131.8**		**7866533.0**		**61404886.8**	**100.81**	100%	**100.81**	**99.33**	
Air Transport	25211	25			95.0	2395045.0	23.8	598761.3	14.3	4564317.7					
Business&Regional	88238	25			66.5	5867827.0	16.6	1466956.8	10.0	11182578.4					
General Aviation	1360662	25			9.5	12926289.0	2.4	3231572.3	1.4	25977225.8					
UAV - Big	26760	25			61.8	1652430.0	15.4	413107.5	9.3	3085961.8					
UAV - Small	295977	25			11.4	3374137.8	2.9	843534.5	1.7	4326234.2					
Military Transport	12664	25			104.5	1323388.0	26.1	330847.0	15.7	3098985.1					
Military Non-transport	27138	25			142.5	3867165.0	35.6	966791.3	21.4	9055475.8					
Space Vehicles	63	25			950.0	59850.0	237.5	14962.5	142.5	114107.9					
Ground	1000	25	0.0	30000.0	100.0	**100000.0**	50.0	**50000.0**	20.0	**500000.0**	**0.68**	100%	**0.68**	**0.67**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
4 L-Band A-G															**107.88**
Airborne			0.0	25000.0		**33122244.0**		**8280561.0**		**64636722.9**	**106.06**	100%	**106.06**	**98.31**	
Air Transport	25211	25			100.0	2521100.0	25.0	630275.0	15.0	4804545.0					
Business&Regional	88238	25			70.0	6176660.0	17.5	1544165.0	10.5	11771135.1					
General Aviation	1360662	25			10.0	13606620.0	2.5	3401655.0	1.5	27344448.2					
UAV - Big	26760	25			65.0	1739400.0	16.3	434850.0	9.8	3248380.8					
UAV - Small	295977	25			12.0	3551724.0	3.0	887931.0	1.8	4553930.7					
Military Transport	12664	25			110.0	1393040.0	27.5	348260.0	16.5	3262089.5					
Military Non-transport	27138	25			150.0	4070700.0	37.5	1017675.0	22.5	9532079.8					
Space Vehicles	63	25			1000.0	63000.0	250.0	15750.0	150.0	120113.6					
Ground	1200	25	0.0	25000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.82**	100%	**1.82**	**1.69**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 263 – A-G Candidates Detailed Cost Score Table – AC Model #2 [Part 2 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5 S-Band A-G															**108.52**
Airborne			0.0	20000.0		**33122244.0**		**8280561.0**		**64636722.9**	**106.06**	100%	**106.06**	**97.73**	
Air Transport	25211	25			100.0	2521100.0	25.0	630275.0	15.0	4804545.0					
Business&Regional	88238	25			70.0	6176660.0	17.5	1544165.0	10.5	11771135.1					
General Aviation	1360662	25			10.0	13606620.0	2.5	3401655.0	1.5	27344448.2					
UAV - Big	26760	25			65.0	1739400.0	16.3	434850.0	9.8	3248380.8					
UAV - Small	295977	25			12.0	3551724.0	3.0	887931.0	1.8	4553930.7					
Military Transport	12664	25			110.0	1393040.0	27.5	348260.0	16.5	3262089.5					
Military Non-transport	27138	25			150.0	4070700.0	37.5	1017675.0	22.5	9532079.8					
Space Vehicles	63	25			1000.0	63000.0	250.0	15750.0	150.0	120113.6					
Ground	1500	25	0.0	20000.0	125.0	**187500.0**	130.0	**195000.0**	55.0	**2062500.0**	**2.47**	100%	**2.47**	**2.27**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
6a C-Band A-G: MLS Band															**119.34**
Airborne			10000.0	30000.0		**36434468.4**		**9108617.1**		**71100395.2**	**116.68**	100%	**116.68**	**97.78**	
Air Transport	25211	25			110.0	2773210.0	27.5	693302.5	16.5	5284999.5					
Business&Regional	88238	25			77.0	6794326.0	19.3	1698581.5	11.6	12948248.7					
General Aviation	1360662	25			11.0	14967282.0	2.8	3741820.5	1.7	30078893.1					
UAV - Big	26760	25			71.5	1913340.0	17.9	478335.0	10.7	3573218.9					
UAV - Small	295977	25			13.2	3906896.4	3.3	976724.1	2.0	5009323.8					
Military Transport	12664	25			121.0	1532344.0	30.3	383086.0	18.2	3588298.5					
Military Non-transport	27138	25			165.0	4477770.0	41.3	1119442.5	24.8	10485287.8					
Space Vehicles	63	25			1100.0	69300.0	275.0	17325.0	165.0	132125.0					
Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	100%	**2.65**	**2.22**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
6b C-Band A-G: Radar Alt.															**119.35**
Airborne			20000.0	30000.0		**36434468.4**		**9108617.1**		**71100395.2**	**116.69**	100%	**116.69**	**97.78**	
Air Transport	25211	25			110.0	2773210.0	27.5	693302.5	16.5	5284999.5					
Business&Regional	88238	25			77.0	6794326.0	19.3	1698581.5	11.6	12948248.7					
General Aviation	1360662	25			11.0	14967282.0	2.8	3741820.5	1.7	30078893.1					
UAV - Big	26760	25			71.5	1913340.0	17.9	478335.0	10.7	3573218.9					
UAV - Small	295977	25			13.2	3906896.4	3.3	976724.1	2.0	5009323.8					
Military Transport	12664	25			121.0	1532344.0	30.3	383086.0	18.2	3588298.5					
Military Non-transport	27138	25			165.0	4477770.0	41.3	1119442.5	24.8	10485287.8					
Space Vehicles	63	25			1100.0	69300.0	275.0	17325.0	165.0	132125.0					
Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	100%	**2.65**	**2.22**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
7 Optical A-G															**292.92**
Airborne			200000.0	70000.0		**89430058.8**		**22357514.7**		**174519151.9**	**286.58**	100%	**286.58**	**97.83**	
Air Transport	25211	25			270.0	6806970.0	67.5	1701742.5	40.5	12972271.4					
Business&Regional	88238	25			189.0	16676982.0	47.3	4169245.5	28.4	31782064.9					
General Aviation	1360662	25			27.0	36737874.0	6.8	9184468.5	4.1	73830010.3					
UAV - Big	26760	25			175.5	4696380.0	43.9	1174095.0	26.3	8770628.3					
UAV - Small	295977	25			32.4	9589654.8	8.1	2397413.7	4.9	12295612.9					
Military Transport	12664	25			297.0	3761208.0	74.3	940302.0	44.6	8807641.8					
Military Non-transport	27138	25			405.0	10990890.0	101.3	2747722.5	60.8	25736615.5					
Space Vehicles	63	25			2700.0	170100.0	675.0	42525.0	405.0	324306.8					
Ground	100	25	200000.0	35000.0	8100.0	**810000.0**	3000.0	**300000.0**	2000.0	**5000000.0**	**6.35**	100%	**6.35**	**2.17**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 264 – A-G Candidates Detailed Cost Score Table – AC Model #2 [Part 3 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
8 Hybrid RF/Optical A-G															**401.65**
Airborne			240000.0	90000.0		**122552302.8**		**30638075.7**		**239155874.8**	**392.68**	100%	**392.68**	**97.77**	
Air Transport	25211	25			370.0	9328070.0	92.5	2332017.5	55.5	17776816.3					
Business&Regional	88238	25			259.0	22853642.0	64.8	5713410.5	38.9	43553200.0					
General Aviation	1360662	25			37.0	50344494.0	9.3	12586123.5	5.6	101174458.5					
UAV - Big	26760	25			240.5	6435780.0	60.1	1608945.0	36.1	12019009.1					
UAV - Small	295977	25			44.4	13141378.8	11.1	3285344.7	6.7	16849543.6					
Military Transport	12664	25			407.0	5154248.0	101.8	1288562.0	61.1	12069731.3					
Military Non-transport	27138	25			555.0	15061590.0	138.8	3765397.5	83.3	35268695.4					
Space Vehicles	63	25			3700.0	233100.0	925.0	58275.0	555.0	444420.4					
Ground	100	25	120000.0	45000.0	9100.0	**910000.0**	4000.0	**400000.0**	3000.0	**7500000.0**	**8.98**	100%	**8.98**	**2.23**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
9 Terminal K to W Band Network (e.g., KU Band QualComm+)															**34.51**
Airborne			20000.0	30000.0		**9936673.2**		**2484168.3**		**19391016.9**	**31.86**	100%	**31.86**	**92.32**	
Air Transport	25211	25			30.0	756330.0	7.5	189082.5	4.5	1441363.5					
Business&Regional	88238	25			21.0	1852998.0	5.3	463249.5	3.2	3531340.5					
General Aviation	1360662	25			3.0	4081986.0	0.8	1020496.5	0.5	8203334.5					
UAV - Big	26760	25			19.5	521820.0	4.9	130455.0	2.9	974514.3					
UAV - Small	295977	25			3.6	1065517.2	0.9	266379.3	0.5	1366179.2					
Military Transport	12664	25			33.0	417912.0	8.3	104478.0	5.0	978626.9					
Military Non-transport	27138	25			45.0	1221210.0	11.3	305302.5	6.8	2859623.9					
Space Vehicles	63	25			300.0	18900.0	75.0	4725.0	45.0	36034.1					
Ground	300	25	20000.0	30000.0	1500.0	**450000.0**	5166.0	**1549800.0**	80.0	**600000.0**	**2.65**	100%	**2.65**	**7.68**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
10 DTV VHF/UHF Network															**29.03**
Airborne			0.0	10000.0		**8280561.0**		**2070140.3**		**16159180.7**	**26.52**	100%	**26.52**	**91.35**	
Air Transport	25211	25			25.0	630275.0	6.3	157568.8	3.8	1201136.2					
Business&Regional	88238	25			17.5	1544165.0	4.4	386041.3	2.6	2942783.8					
General Aviation	1360662	25			2.5	3401655.0	0.6	850413.8	0.4	6836112.1					
UAV - Big	26760	25			16.3	434850.0	4.1	108712.5	2.4	812095.2					
UAV - Small	295977	25			3.0	887931.0	0.8	221982.8	0.5	1138482.7					
Military Transport	12664	25			27.5	348260.0	6.9	87065.0	4.1	815522.4					
Military Non-transport	27138	25			37.5	1017675.0	9.4	254418.8	5.6	2383020.0					
Space Vehicles	63	25			250.0	15750.0	62.5	3937.5	37.5	30028.4					
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	100%	**2.51**	**8.65**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
11a Cellular Network: Aircell															**22.73**
Airborne			0.0	10000.0		**6624448.8**		**1656112.2**		**12927344.6**	**21.22**	100%	**21.22**	**93.36**	
Air Transport	25211	25			20.0	504220.0	5.0	126055.0	3.0	960909.0					
Business&Regional	88238	25			14.0	1235332.0	3.5	308833.0	2.1	2354227.0					
General Aviation	1360662	25			2.0	2721324.0	0.5	680331.0	0.3	5468889.6					
UAV - Big	26760	25			13.0	347880.0	3.3	86970.0	2.0	649676.2					
UAV - Small	295977	25			2.4	710344.8	0.6	177586.2	0.4	910786.1					
Military Transport	12664	25			22.0	278608.0	5.5	69652.0	3.3	652417.9					
Military Non-transport	27138	25			30.0	814140.0	7.5	203535.0	4.5	1906416.0					
Space Vehicles	63	25			200.0	12600.0	50.0	3150.0	30.0	24022.7					
Ground	300	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**1500000.0**	**1.51**	100%	**1.51**	**6.64**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 265 – A-G Candidates Detailed Cost Score Table – AC Model #2 [Part 4 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
11b Cellular Network: LTE+															27.48
Airborne			0.0	10000.0		**6624448.8**		**1656112.2**		**12927344.6**	**21.22**	100%	**21.22**	**77.22**	
Air Transport	25211	25			20.0	504220.0	5.0	126055.0	3.0	960909.0					
Business&Regional	88238	25			14.0	1235332.0	3.5	308833.0	2.1	2354227.0					
General Aviation	1360662	25			2.0	2721324.0	0.5	680331.0	0.3	5468889.6					
UAV - Big	26760	25			13.0	347880.0	3.3	86970.0	2.0	649676.2					
UAV - Small	295977	25			2.4	710344.8	0.6	177586.2	0.4	910786.1					
Military Transport	12664	25			22.0	278608.0	5.5	69652.0	3.3	652417.9					
Military Non-transport	27138	25			30.0	814140.0	7.5	203535.0	4.5	1906416.0					
Space Vehicles	63	25			200.0	12600.0	50.0	3150.0	30.0	24022.7					
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	100%	**6.26**	**22.78**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
11c Cellular Network: AWS															27.48
Airborne			0.0	10000.0		**6624448.8**		**1656112.2**		**12927344.6**	**21.22**	100%	**21.22**	**77.22**	
Air Transport	25211	25			20.0	504220.0	5.0	126055.0	3.0	960909.0					
Business&Regional	88238	25			14.0	1235332.0	3.5	308833.0	2.1	2354227.0					
General Aviation	1360662	25			2.0	2721324.0	0.5	680331.0	0.3	5468889.6					
UAV - Big	26760	25			13.0	347880.0	3.3	86970.0	2.0	649676.2					
UAV - Small	295977	25			2.4	710344.8	0.6	177586.2	0.4	910786.1					
Military Transport	12664	25			22.0	278608.0	5.5	69652.0	3.3	652417.9					
Military Non-transport	27138	25			30.0	814140.0	7.5	203535.0	4.5	1906416.0					
Space Vehicles	63	25			200.0	12600.0	50.0	3150.0	30.0	24022.7					
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	100%	**6.26**	**22.78**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
12 LEO SATCOM Network (e.g., Iridium Next+)															178.51
Airborne			0.0	10000.0		**49683366.0**		**12420841.5**		**96955084.4**	**159.07**	100%	**159.07**	**89.11**	
Air Transport	25211	25			150.0	3781650.0	37.5	945412.5	22.5	7206817.4					
Business&Regional	88238	25			105.0	9264990.0	26.3	2316247.5	15.8	17656702.7					
General Aviation	1360662	25			15.0	20409930.0	3.8	5102482.5	2.3	41016672.4					
UAV - Big	26760	25			97.5	2609100.0	24.4	652275.0	14.6	4872571.3					
UAV - Small	295977	25			18.0	5327586.0	4.5	1331896.5	2.7	6830896.1					
Military Transport	12664	25			165.0	2089560.0	41.3	522390.0	24.8	4893134.3					
Military Non-transport	27138	25			225.0	6106050.0	56.3	1526512.5	33.8	14298119.7					
Space Vehicles	63	25			1500.0	94500.0	375.0	23625.0	225.0	180170.4					
Ground	13	25	0.0	5000.0	4000.0	**52000.0**	11000.0	**143000.0**	1500.0	**487500.0**	**0.69**	100%	**0.69**	**0.39**	
Satellite	66	6.25	0.0	10000.0	40000.0	**10560000.0**	6000.0	**1584000.0**	4000.0	**6600000.0**	**18.75**	100%	**18.75**	**10.51**	
spares	15														
13 GEO SATCOM Network with global/regional /spot beams															240.88
Airborne			0.0	10000.0		**74525049.0**		**18631262.3**		**145432626.5**	**238.60**	100%	**238.60**	**99.05**	
Air Transport	25211	25			225.0	5672475.0	56.3	1418118.8	33.8	10810226.2					
Business&Regional	88238	25			157.5	13897485.0	39.4	3474371.3	23.6	26485054.1					
General Aviation	1360662	25			22.5	30614895.0	5.6	7653723.8	3.4	61525008.5					
UAV - Big	26760	25			146.3	3913650.0	36.6	978412.5	21.9	7308856.9					
UAV - Small	295977	25			27.0	7991379.0	6.8	1997844.8	4.1	10246344.1					
Military Transport	12664	25			247.5	3134340.0	61.9	783585.0	37.1	7339701.5					
Military Non-transport	27138	25			337.5	9159075.0	84.4	2289768.8	50.6	21447179.6					
Space Vehicles	63	25			2250.0	141750.0	562.5	35437.5	337.5	270255.7					
Ground	3	25	0.0	5000.0	4000.0	**12000.0**	11000.0	**33000.0**	3000.0	**225000.0**	**0.28**	100%	**0.28**	**0.11**	
Satellite	3	12.5	0.0	10000.0	150000.0	**900000.0**	100000.0	**600000.0**	6666.7	**500000.0**	**2.01**	100%	**2.01**	**0.83**	
spare	1														

Figure 266 – A-G Candidates Detailed Cost Score Table – AC Model #2 [Part 5 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
14 MEO SATCOM Network (e.g., GlobalStar+)															175.39
Airborne			0.0	20000.0		**52995590.4**		**13248897.6**		**103418756.7**	**169.68**	100%	**169.68**	**96.75**	
Air Transport	25211	25			160.0	4033760.0	40.0	1008440.0	24.0	7687271.9					
Business&Regional	88238	25			112.0	9882656.0	28.0	2470664.0	16.8	18833816.2					
General Aviation	1360662	25			16.0	21770592.0	4.0	5442648.0	2.4	43751117.2					
UAV - Big	26760	25			104.0	2783040.0	26.0	695760.0	15.6	5197409.4					
UAV - Small	295977	25			19.2	5682758.4	4.8	1420689.6	2.9	7286289.1					
Military Transport	12664	25			176.0	2228864.0	44.0	557216.0	26.4	5219343.3					
Military Non-transport	27138	25			240.0	6513120.0	60.0	1628280.0	36.0	15251327.7					
Space Vehicles	63	25			1600.0	100800.0	400.0	25200.0	240.0	192181.8					
Ground	8	25	0.0	5000.0	4000.0	**32000.0**	11000.0	**88000.0**	1900.0	**380000.0**	**0.51**	100%	**0.51**	**0.29**	
Satellite	20	8.33	0.0	20000.0	50000.0	**3000000.0**	25000.0	**1500000.0**	1355.0	**677500.0**	**5.20**	100%	**5.20**	**2.96**	
spares	6														
15 VHF A-A Hopping for Long Range A-G Com.															106.87
Airborne			0.0	20000.0		**33122244.0**		**8280561.0**		**64636722.9**	**106.06**	100%	**106.06**	**99.24**	
Air Transport	25211	25			100.0	2521100.0	25.0	630275.0	15.0	4804545.0					
Business&Regional	88238	25			70.0	6176660.0	17.5	1544165.0	10.5	11771135.1					
General Aviation	1360662	25			10.0	13606620.0	2.5	3401655.0	1.5	27344448.2					
UAV - Big	26760	25			65.0	1739400.0	16.3	434850.0	9.8	3248380.8					
UAV - Small	295977	25			12.0	3551724.0	3.0	887931.0	1.8	4553930.7					
Military Transport	12664	25			110.0	1393040.0	27.5	348260.0	16.5	3262089.5					
Military Non-transport	27138	25			150.0	4070700.0	37.5	1017675.0	22.5	9532079.8					
Space Vehicles	63	25			1000.0	63000.0	250.0	15750.0	150.0	120113.6					
Ground **Enroute GS**	729	25	0.0	20000.0	82.0	**59778.0**	100.0	**0.0**	40.0	**729000.0**	**0.81**	100%	**0.81**	**0.76**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
16 UHF A-A Hopping for Long Range A-G Com.															117.47
Airborne			0.0	30000.0		**36434468.4**		**9108617.1**		**71100395.2**	**116.67**	100%	**116.67**	**99.32**	
Air Transport	25211	25			110.0	2773210.0	27.5	693302.5	16.5	5284999.5					
Business&Regional	88238	25			77.0	6794326.0	19.3	1698581.5	11.6	12948248.7					
General Aviation	1360662	25			11.0	14967282.0	2.8	3741820.5	1.7	30078893.1					
UAV - Big	26760	25			71.5	1913340.0	17.9	478335.0	10.7	3573218.9					
UAV - Small	295977	25			13.2	3906896.4	3.3	976724.1	2.0	5009323.8					
Military Transport	12664	25			121.0	1532344.0	30.3	383086.0	18.2	3588298.5					
Military Non-transport	27138	25			165.0	4477770.0	41.3	1119442.5	24.8	10485287.8					
Space Vehicles	63	25			1100.0	69300.0	275.0	17325.0	165.0	132125.0					
Ground	650	25	0.0	20000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.80**	100%	**0.80**	**0.68**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
17 L-Band A-A Hopping for Long Range A-G Com.															123.79
Airborne			0.0	30000.0		**38090580.6**		**9522645.2**		**74332231.3**	**121.98**	100%	**121.98**	**98.53**	
Air Transport	25211	25			115.0	2899265.0	28.8	724816.3	17.3	5525226.7					
Business&Regional	88238	25			80.5	7103159.0	20.1	1775789.8	12.1	13536805.4					
General Aviation	1360662	25			11.5	15647613.0	2.9	3911903.3	1.7	31446115.5					
UAV - Big	26760	25			74.8	2000310.0	18.7	500077.5	11.2	3735638.0					
UAV - Small	295977	25			13.8	4084482.6	3.5	1021120.7	2.1	5237020.3					
Military Transport	12664	25			126.5	1601996.0	31.6	400499.0	19.0	3751403.0					
Military Non-transport	27138	25			172.5	4681305.0	43.1	1170326.3	25.9	10961891.8					
Space Vehicles	63	25			1150.0	72450.0	287.5	18112.5	172.5	138130.7					
Ground	1200	25	0.0	20000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.81**	100%	**1.81**	**1.47**	
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	

Figure 267 – A-G Candidates Detailed Cost Score Table – AC Model #2 [Part 6 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	% Associated with Candidate	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
18	X-Band															**122.17**
	Airborne			0.0	30000.0		**38090580.6**		**9522645.2**		**74332231.3**	**121.98**	100%	**121.98**	**99.84**	
	Air Transport	25211	25			115.0	2899265.0	28.8	724816.3	17.3	5525226.7					
	Business&Regional	88238	25			80.5	7103159.0	20.1	1775789.8	12.1	13536805.4					
	General Aviation	1360662	25			11.5	15647613.0	2.9	3911903.3	1.7	31446115.5					
	UAV - Big	26760	25			74.8	2000310.0	18.7	500077.5	11.2	3735638.0					
	UAV - Small	295977	25			13.8	4084482.6	3.5	1021120.7	2.1	5237020.3					
	Military Transport	12664	25			126.5	1601996.0	31.6	400499.0	19.0	3751403.0					
	Military Non-transport	27138	25			172.5	4681305.0	43.1	1170326.3	25.9	10961891.8					
	Space Vehicles	63	25			1150.0	72450.0	287.5	18112.5	172.5	138130.7					
	Ground	100	25	0.0	0.0	230.0	**23000.0**	135.0	**13500.0**	65.0	**162500.0**	**0.20**	100%	**0.20**	**0.16**	
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	100%	**0.00**	**0.00**	
19	GEO + HEO SATCOM Network															**253.79**
	Airborne			0.0	12000.0		**77837273.4**		**19459318.4**		**151896298.8**	**249.20**	100%	**249.20**	**98.19**	
	Air Transport	25211	25			235.0	5924585.0	58.8	1481146.3	35.3	11290680.7					
	Business&Regional	88238	25			164.5	14515151.0	41.1	3628787.8	24.7	27662167.6					
	General Aviation	1360662	25			23.5	31975557.0	5.9	7993889.3	3.5	64259453.4					
	UAV - Big	26760	25			152.8	4087590.0	38.2	1021897.5	22.9	7633695.0					
	UAV - Small	295977	25			28.2	8346551.4	7.1	2086637.9	4.2	10701737.2					
	Military Transport	12664	25			258.5	3273644.0	64.6	818411.0	38.8	7665910.4					
	Military Non-transport	27138	25			352.5	9566145.0	88.1	2391536.3	52.9	22400387.6					
	Space Vehicles	63	25			2350.0	148050.0	587.5	37012.5	352.5	282267.0					
	Ground	5	25	0.0	5000.0	4000.0	**20000.0**	11000.0	**55000.0**	3500.0	**437500.0**	**0.52**	100%	**0.52**	**0.20**	
	Satellite	6	12.5	0.0	12000.0	170000.0	**2040000.0**	85000.0	**1020000.0**	6666.7	**1000000.0**	**4.07**	100%	**4.07**	**1.60**	
	spare	3														

Figure 268 – A-G Candidates Detailed Cost Score Table – AC Model #2 [Part 7 of 7]

23.3 Cost Comparisons for Example Integration Alternatives

The costs for eight example A-G integration alternatives have been estimated. The eight integration alternatives are based upon incorporating multiple A-G communication technologies to collectively meet the NAS communication needs for all airspaces, including surface, terminal area, enroute, oceanic/remote, and polar. The set of eight integration alternatives include a number of the candidates as identified below:

1) HF + VHF + L-Band + C-Band (MLS) + GEO SATCOM + LEO SATCOM
2) VHF + L-Band + C-Band (MLS) + GEO SATCOM + LEO SATCOM + VHF A-A Hopping
3) VHF + Cellular + Terminal Network + GEO&HEO SATCOM + VHF A-A Hopping
4) HF + VHF + L-Band + Hybrid RF/Optical + LEO SATCOM + MEO SATCOM + GEO&HEO SATCOM
5) VHF + Cellular + DTV VHF/UHF Network + GEO SATCOM + MEO SATCOM
6) UHF + L-Band + S-Band + C-Band + Optical + Cellular + GEO&HEO SATCOM + UHF A-A Hopping
7) UHF + C-Band + Hybrid RF/Optical + Cellular + GEO SATCOM + LEO SATCOM + UHF A-A Hopping
8) HF + VHF + C-Band (MLS) + C-Band(RA) + X-Band + Cellular + Terminal Network + GEO&HEO + MEO SATCOM

The subsections below provide summary tables and plots for the costs associated with the eight integration alternatives for which costs have been computed. The total cost is broken down by communications system element, where by element “A” corresponds to the first system element included in the integration alternative, “B” corresponds with the second system element, etc. Thus, for integration alternative #1, element “A” refers to the cost of the HF system, element “B” refers to the cost of the VHF system, element “C” refers to the L-Band system, etc.

These estimates were based upon using the aircraft fleet models previously described in Section 22.3.4. However, rather than assuming 100% equipage for all aircraft categories for each of the A-G candidates as was done in the relative candidate scoring comparisons provided in Sections 23.1 and 23.2, less than 100% fleet equipage was assumed commensurate with predictions of the percentages of the aircraft equipped in each category with the communications technologies as indicated in column 17 of the detailed cost tables provided in Figure 271 to Figure 277 (pages 385 to 391, respectively) for Aircraft Fleet Model #1 and Figure 280 to Figure 286 (pages 394 to 400, respectively) for Aircraft Fleet Model #2. This is referred to in this report as a “factored” aircraft fleet model.

23.3.1 Cost Comparisons of Integration Alternatives – Factored Aircraft Fleet Model #1

Figure 269 and Figure 270 provide a summary table and plot (respectively) for the eight integration alternatives for which costs have been computed based upon factored Aircraft Fleet Model #1 (for description of “factored” aircraft fleet model, see Section 23.3). Figure 271 to Figure 277 (pages 385 to 391, respectively) provide the detailed cost tables used to generate the total cost of the integration alternatives based upon factored Aircraft Fleet Model #1.

	Integrated System Cost Elements ($B)									
Integration Alternatives	A	B	C	D	E	F	G	H	I	Total
1) HF + VHF + L-Band + C-Band (MLS) + GEO SATCOM + LEO SATCOM	15.93	52.29	52.32	22.04	43.58	52.13	---	---	---	238.30
2) VHF + L-Band + C-Band (MLS) + GEO SATCOM + LEO SATCOM + VHF A-A Hopping	52.29	52.32	22.04	43.58	52.13	0.00	---	---	---	222.37
3) VHF + Cellular + Terminal Network + GEO&HEO SATCOM + VHF A-A Hopping	52.29	14.41	8.04	47.72	0.00	---	---	---	---	122.47
4) HF + VHF + L-Band + Hybrid RF/Optical + LEO SATCOM + MEO SATCOM + GEO&HEO SATCOM	15.93	52.29	52.32	81.27	52.13	40.72	47.72	---	---	342.40
5) VHF + Cellular + DTV VHF/UHF Network + GEO SATCOM + MEO SATCOM	52.29	14.41	8.13	43.58	40.72	---	---	---	---	159.13
6) UHF + L-Band + S-Band + C-Band + Optical + Cellular + GEO&HEO SATCOM + UHF A-A Hopping	48.79	52.32	41.74	22.04	59.13	14.41	47.72	0.00	---	286.16
7) UHF + C-Band + Hybrid RF/Optical + Cellular + GEO SATCOM + LEO SATCOM + UHF A-A Hopping	48.79	22.04	81.27	14.41	43.58	0.00	---	---	---	210.09
8) HF + VHF + C-Band (MLS) + C-Band(RA) + X-Band + Cellular + Terminal Network + GEO&HEO + MEO SATCOM	15.93	52.29	22.04	10.67	45.38	14.41	8.04	47.72	40.72	257.22

Figure 269 – Cost Comparison Table of A-G Integration Alternatives (Factored AC Fleet Model #1)

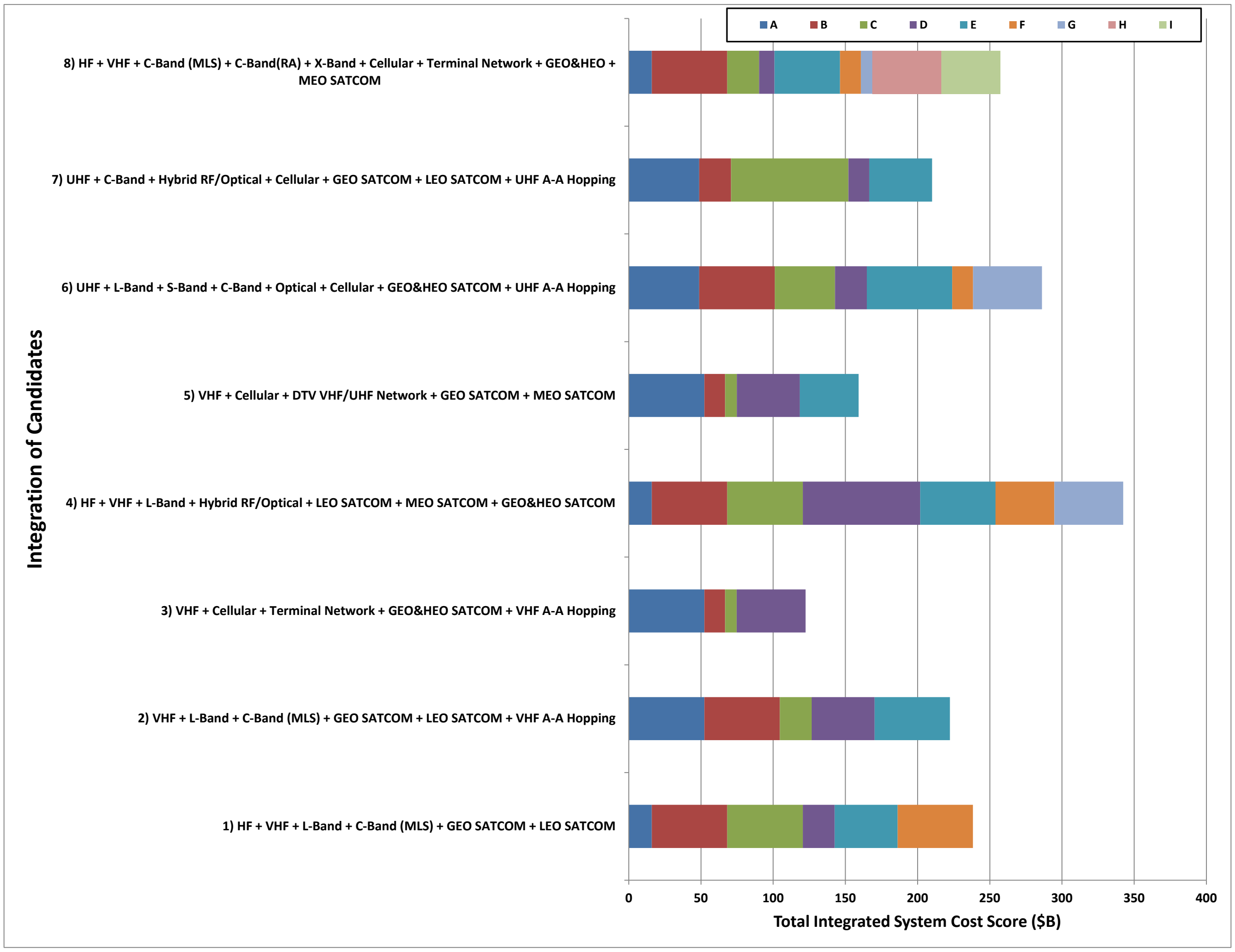


Figure 270 – Cost Comparison Plot of A-G Integration Alternatives (Factored AC Fleet Model #1)

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
1	HF A-G														**15.93**	
	Airborne			0.0	5000.0		**4978485.0**		**1244621.3**		**9486674.9**	**15.71**	**15.71**	**98.62**		
	Air Transport	10310	25			100.0	1031000.0	25.0	257750.0	15.0	1964746.6					85%
	Business&Regional	8628	25			70.0	603960.0	17.5	150990.0	10.5	1151015.2					20%
	General Aviation	0	25			10.0	0.0	2.5	0.0	1.5	0.0					0%
	UAV - Big	89	25			65.0	5785.0	16.3	1446.3	9.8	11055.3					10%
	UAV - Small	0	25			12.0	0.0	3.0	0.0	1.8	0.0					0%
	Military Transport	11484	25			110.0	1263240.0	27.5	315810.0	16.5	2407396.5					85%
	Military Non-transport	13810	25			150.0	2071500.0	37.5	517875.0	22.5	3947656.8					33%
	Space Vehicles	3	25			1000.0	3000.0	250.0	750.0	150.0	4804.5					10%
	Ground	10	25	0.0	5000.0	3000.0	**30000.0**	1000.0	**10000.0**	700.0	**175000.0**	**0.22**	**0.22**	**1.38**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
2a	VHF A-G: Use 112 to 118 MHz														**47.91**	
	Airborne			0.0	2000.0		**15106016.4**		**3776504.1**		**28788336.1**	**47.67**	**47.67**	**99.50**		
	Air Transport	12129	25			85.0	1030965.0	21.3	257741.3	12.8	1964746.6					100%
	Business&Regional	43141	25			59.5	2566889.5	14.9	641722.4	8.9	4891814.7					100%
	General Aviation	563212	25			8.5	4787302.0	2.1	1196825.5	1.3	9123350.4					100%
	UAV - Big	892	25			55.3	49283.0	13.8	12320.8	8.3	93969.7					100%
	UAV - Small	5042	25			10.2	51428.4	2.6	12857.1	1.5	98012.7					100%
	Military Transport	13511	25			93.5	1263278.5	23.4	315819.6	14.0	2407396.5					100%
	Military Non-transport	41848	25			127.5	5335620.0	31.9	1333905.0	19.1	10168206.8					100%
	Space Vehicles	25	25			850.0	21250.0	212.5	5312.5	127.5	40838.6					100%
	Ground	200	25	0.0	2000.0	82.0	**16400.0**	100.0	**20000.0**	40.0	**200000.0**	**0.24**	**0.24**	**0.50**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
2b	VHF A-G: Improve VHF Efficiency														**52.29**	
	Airborne			0.0	5000.0		**15639169.9**		**3909792.5**		**29804395.0**	**49.36**	**49.36**	**94.39**		
	Air Transport	12129	25			88.0	1067352.0	22.0	266838.0	13.2	2034090.6					100%
	Business&Regional	43141	25			61.6	2657485.6	15.4	664371.4	9.2	5064467.0					100%
	General Aviation	563212	25			8.8	4956265.6	2.2	1239066.4	1.3	9445351.0					100%
	UAV - Big	892	25			57.2	51022.4	14.3	12755.6	8.6	97286.3					100%
	UAV - Small	5042	25			10.6	53243.5	2.6	13310.9	1.6	101472.0					100%
	Military Transport	13511	25			96.8	1307864.8	24.2	326966.2	14.5	2492363.5					100%
	Military Non-transport	41848	25			132.0	5523936.0	33.0	1380984.0	19.8	10527084.7					100%
	Space Vehicles	25	25			880.0	22000.0	220.0	5500.0	132.0	42280.0					100%
	Ground	2708	25	0.0	5000.0	82.0	**222056.0**	100.0	**0.0**	40.0	**2708000.0**	**2.94**	**2.94**	**5.61**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
2c	VHF A-G: Low Band (Ground-to-Air only)														**16.67**	
	Airborne			0.0	10000.0		**4484437.0**		**1121109.3**		**8546150.9**	**14.16**	**14.16**	**84.94**		
	Air Transport	3639	25			95.0	345705.0	23.8	86426.3	14.3	658768.0					30%
	Business&Regional	8628	25			66.5	573762.0	16.6	143440.5	10.0	1093464.5					20%
	General Aviation	281606	25			9.5	2675257.0	2.4	668814.3	1.4	5098342.9					50%
	UAV - Big	178	25			61.8	10991.5	15.4	2747.9	9.3	21005.0					20%
	UAV - Small	0	25			11.4	0.0	2.9	0.0	1.7	0.0					0%
	Military Transport	2702	25			104.5	282359.0	26.1	70589.8	15.7	538123.9					20%
	Military Non-transport	4185	25			142.5	596362.5	35.6	149090.6	21.4	1136446.6					10%
	Space Vehicles	0	25			950.0	0.0	237.5	0.0	142.5	0.0					0%
	Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	**2.51**	**15.06**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 271 – Int. Alternatives Subsystem Costs–Factored AC Model#1 [Part 1 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
3a	UHF A-G: Aviation Allocation														48.79	
	Airborne			0.0	30000.0		**15195346.0**		**3798836.5**		**28957679.3**	**47.98**	**47.98**	**98.35**		
	Air Transport	10916	25			95.0	1037020.0	23.8	259255.0	14.3	1976303.9					90%
	Business&Regional	38827	25			66.5	2581995.5	16.6	645498.9	10.0	4920590.1					90%
	General Aviation	506891	25			9.5	4815464.5	2.4	1203866.1	1.4	9177017.2					90%
	UAV - Big	803	25			61.8	49585.3	15.4	12396.3	9.3	94522.5					90%
	UAV - Small	4538	25			11.4	51733.2	2.9	12933.3	1.7	98589.3					90%
	Military Transport	12160	25			104.5	1270720.0	26.1	317680.0	15.7	2421557.7					90%
	Military Non-transport	37663	25			142.5	5366977.5	35.6	1341744.4	21.4	10228019.8					90%
	Space Vehicles	23	25			950.0	21850.0	237.5	5462.5	142.5	41078.9					90%
	Ground	650	25	0.0	30000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.81**	**0.81**	**1.65**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
3b	UHF A-G: High Band (Ground-to-Air only)														28.48	
	Airborne			0.0	30000.0		**7818178.0**		**1954544.5**		**14899402.7**	**24.70**	**24.70**	**86.73**		
	Air Transport	9703	25			95.0	921785.0	23.8	230446.3	14.3	1756714.6					80%
	Business&Regional	25885	25			66.5	1721352.5	16.6	430338.1	10.0	3280393.4					60%
	General Aviation	168964	25			9.5	1605158.0	2.4	401289.5	1.4	3059005.7					30%
	UAV - Big	535	25			61.8	33036.3	15.4	8259.1	9.3	63015.0					60%
	UAV - Small	1513	25			11.4	17248.2	2.9	4312.1	1.7	32863.1					30%
	Military Transport	10809	25			104.5	1129540.5	26.1	282385.1	15.7	2152495.7					80%
	Military Non-transport	16739	25			142.5	2385307.5	35.6	596326.9	21.4	4545786.6					40%
	Space Vehicles	5	25			950.0	4750.0	237.5	1187.5	142.5	9128.6					20%
	Ground	750	25	0.0	30000.0	0.0	**0.0**	0.0	**0.0**	200.0	**3750000.0**	**3.78**	**3.78**	**13.27**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
3c	UHF A-G: Other														48.70	
	Airborne			0.0	70000.0		**15195346.0**		**3798836.5**		**28957679.3**	**48.02**	**48.02**	**98.60**		
	Air Transport	10916	25			95.0	1037020.0	23.8	259255.0	14.3	1976303.9					90%
	Business&Regional	38827	25			66.5	2581995.5	16.6	645498.9	10.0	4920590.1					90%
	General Aviation	506891	25			9.5	4815464.5	2.4	1203866.1	1.4	9177017.2					90%
	UAV - Big	803	25			61.8	49585.3	15.4	12396.3	9.3	94522.5					90%
	UAV - Small	4538	25			11.4	51733.2	2.9	12933.3	1.7	98589.3					90%
	Military Transport	12160	25			104.5	1270720.0	26.1	317680.0	15.7	2421557.7					90%
	Military Non-transport	37663	25			142.5	5366977.5	35.6	1341744.4	21.4	10228019.8					90%
	Space Vehicles	23	25			950.0	21850.0	237.5	5462.5	142.5	41078.9					90%
	Ground	1000	25	0.0	30000.0	100.0	**100000.0**	50.0	**50000.0**	20.0	**500000.0**	**0.68**	**0.68**	**1.40**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
4	L-Band A-G														52.32	
	Airborne			0.0	25000.0		**15995101.0**		**3998775.3**		**30481767.7**	**50.50**	**50.50**	**96.52**		
	Air Transport	10916	25			100.0	1091600.0	25.0	272900.0	15.0	2080319.9					90%
	Business&Regional	38827	25			70.0	2717890.0	17.5	679472.5	10.5	5179568.5					90%
	General Aviation	506891	25			10.0	5068910.0	2.5	1267227.5	1.5	9660018.1					90%
	UAV - Big	803	25			65.0	52195.0	16.3	13048.8	9.8	99497.3					90%
	UAV - Small	4538	25			12.0	54456.0	3.0	13614.0	1.8	103778.2					90%
	Military Transport	12160	25			110.0	1337600.0	27.5	334400.0	16.5	2549008.1					90%
	Military Non-transport	37663	25			150.0	5649450.0	37.5	1412362.5	22.5	10766336.6					90%
	Space Vehicles	23	25			1000.0	23000.0	250.0	5750.0	150.0	43240.9					90%
	Ground	1200	25	0.0	25000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.82**	**1.82**	**3.48**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 272 – Int. Alternatives Subsystem Costs–Factored AC Model#1 [Part 2 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
5	S-Band A-G														41.74	
	Airborne			0.0	20000.0		**12440798.0**		**3110199.5**		**23708041.5**	**39.28**	**39.28**	**94.09**		
	Air Transport	8490	25			100.0	849000.0	25.0	212250.0	15.0	1618026.6					70%
	Business&Regional	30199	25			70.0	2113930.0	17.5	528482.5	10.5	4028553.3					70%
	General Aviation	394248	25			10.0	3942480.0	2.5	985620.0	1.5	7513347.4					70%
	UAV - Big	624	25			65.0	40560.0	16.3	10140.0	9.8	77386.8					70%
	UAV - Small	3529	25			12.0	42348.0	3.0	10587.0	1.8	80716.4					70%
	Military Transport	9458	25			110.0	1040380.0	27.5	260095.0	16.5	1982561.8					70%
	Military Non-transport	29294	25			150.0	4394100.0	37.5	1098525.0	22.5	8373817.4					70%
	Space Vehicles	18	25			1000.0	18000.0	250.0	4500.0	150.0	33631.8					70%
	Ground	1500	25	0.0	20000.0	125.0	**187500.0**	130.0	**195000.0**	55.0	**2062500.0**	**2.47**	**2.47**	**5.91**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
6a	C-Band A-G: MLS Band														22.04	
	Airborne			10000.0	30000.0		**6130839.0**		**1532709.8**		**11682742.3**	**19.39**	**19.39**	**87.96**		
	Air Transport	9703	25			110.0	1067330.0	27.5	266832.5	16.5	2034090.6					80%
	Business&Regional	25885	25			77.0	1993145.0	19.3	498286.3	11.6	3798350.2					60%
	General Aviation	28161	25			11.0	309771.0	2.8	77442.8	1.7	590334.4					5%
	UAV - Big	624	25			71.5	44616.0	17.9	11154.0	10.7	85125.5					70%
	UAV - Small	0	25			13.2	0.0	3.3	0.0	2.0	0.0					0%
	Military Transport	8107	25			121.0	980947.0	30.3	245236.8	18.2	1869272.6					60%
	Military Non-transport	10462	25			165.0	1726230.0	41.3	431557.5	24.8	3289714.0					25%
	Space Vehicles	8	25			1100.0	8800.0	275.0	2200.0	165.0	15855.0					30%
	Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	**2.65**	**12.04**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
6b	C-Band A-G: Radar Alt.														10.67	
	Airborne			20000.0	30000.0		**2525171.0**		**631292.8**		**4812266.8**	**8.02**	**8.02**	**75.13**		
	Air Transport	6065	25			110.0	667150.0	27.5	166787.5	16.5	1271306.6					50%
	Business&Regional	8628	25			77.0	664356.0	19.3	166089.0	11.6	1266116.7					20%
	General Aviation	0	25			11.0	0.0	2.8	0.0	1.7	0.0					0%
	UAV - Big	178	25			71.5	12727.0	17.9	3181.8	10.7	24321.6					20%
	UAV - Small	0	25			13.2	0.0	3.3	0.0	2.0	0.0					0%
	Military Transport	4053	25			121.0	490413.0	30.3	122603.3	18.2	934636.3					30%
	Military Non-transport	4185	25			165.0	690525.0	41.3	172631.3	24.8	1315885.6					10%
	Space Vehicles	0	25			1100.0	0.0	275.0	0.0	165.0	0.0					0%
	Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	**2.65**	**24.87**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
7	Optical A-G														59.13	
	Airborne			200000.0	70000.0		**16642311.3**		**4160577.8**		**31715536.6**	**52.79**	**52.79**	**89.27**		
	Air Transport	9703	25			270.0	2619810.0	67.5	654952.5	40.5	4992767.8					80%
	Business&Regional	34513	25			189.0	6522957.0	47.3	1630739.3	28.4	12430964.4					80%
	General Aviation	28161	25			27.0	760347.0	6.8	190086.8	4.1	1449002.7					5%
	UAV - Big	669	25			175.5	117409.5	43.9	29352.4	26.3	223869.0					75%
	UAV - Small	252	25			32.4	8164.8	8.1	2041.2	4.9	15566.7					5%
	Military Transport	10809	25			297.0	3210273.0	74.3	802568.3	44.6	6117619.4					80%
	Military Non-transport	8370	25			405.0	3389850.0	101.3	847462.5	60.8	6459802.0					20%
	Space Vehicles	5	25			2700.0	13500.0	675.0	3375.0	405.0	25944.5					20%
	Ground	100	25	200000.0	35000.0	8100.0	**810000.0**	3000.0	**300000.0**	2000.0	**5000000.0**	**6.35**	**6.35**	**10.73**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 273 – Int. Alternatives Subsystem Costs–Factored AC Model#1 [Part 3 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column 1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
8 Hybrid RF/Optical A-G														81.27	
Airborne			240000.0	90000.0		**22806130.3**		**5701532.6**		**43462031.6**	**72.30**	**72.30**	**88.96**		
Air Transport	9703	25			370.0	3590110.0	92.5	897527.5	55.5	6841941.1					80%
Business&Regional	34513	25			259.0	8938867.0	64.8	2234716.8	38.9	17035025.4					80%
General Aviation	28161	25			37.0	1041957.0	9.3	260489.3	5.6	1985670.4					5%
UAV - Big	669	25			240.5	160894.5	60.1	40223.6	36.1	306783.4					75%
UAV - Small	252	25			44.4	11188.8	11.1	2797.2	6.7	21332.2					5%
Military Transport	10809	25			407.0	4399263.0	101.8	1099815.8	61.1	8383404.4					80%
Military Non-transport	8370	25			555.0	4645350.0	138.8	1161337.5	83.3	8852321.2					20%
Space Vehicles	5	25			3700.0	18500.0	925.0	4625.0	555.0	35553.6					20%
Ground	100	25	120000.0	45000.0	9100.0	**910000.0**	4000.0	**400000.0**	3000.0	**7500000.0**	**8.98**	**8.98**	**11.04**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
9 Terminal K to W Band Network (e.g., KU Band QualComm+)														8.04	
Airborne			20000.0	30000.0		**1693567.5**		**423391.9**		**3227227.3**	**5.39**	**5.39**	**67.06**		
Air Transport	10310	25			30.0	309300.0	7.5	77325.0	4.5	589424.0					85%
Business&Regional	21571	25			21.0	452991.0	5.3	113247.8	3.2	863261.4					50%
General Aviation	28161	25			3.0	84483.0	0.8	21120.8	0.5	161000.3					5%
UAV - Big	535	25			19.5	10432.5	4.9	2608.1	2.9	19899.5					60%
UAV - Small	0	25			3.6	0.0	0.9	0.0	0.5	0.0					0%
Military Transport	8107	25			33.0	267531.0	8.3	66882.8	5.0	509801.6					60%
Military Non-transport	12554	25			45.0	564930.0	11.3	141232.5	6.8	1076633.7					30%
Space Vehicles	13	25			300.0	3900.0	75.0	975.0	45.0	7206.8					50%
Ground	300	25	20000.0	30000.0	1500.0	**450000.0**	5166.0	**1549800.0**	80.0	**600000.0**	**2.65**	**2.65**	**32.94**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
10 DTV VHF/UHF Network														8.13	
Airborne			0.0	10000.0		**1776178.0**		**444044.5**		**3384902.8**	**5.62**	**5.62**	**69.11**		
Air Transport	7277	25			25.0	181925.0	6.3	45481.3	3.8	346720.0					60%
Business&Regional	25885	25			17.5	452987.5	4.4	113246.9	2.6	863261.4					60%
General Aviation	281606	25			2.5	704015.0	0.6	176003.8	0.4	1341669.2					50%
UAV - Big	268	25			16.3	4355.0	4.1	1088.8	2.4	8291.4					30%
UAV - Small	2521	25			3.0	7563.0	0.8	1890.8	0.5	14413.6					50%
Military Transport	4053	25			27.5	111457.5	6.9	27864.4	4.1	212417.3					30%
Military Non-transport	8370	25			37.5	313875.0	9.4	78468.8	5.6	598129.8					20%
Space Vehicles	0	25			250.0	0.0	62.5	0.0	37.5	0.0					0%
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	**2.51**	**30.89**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
11a Cellular Network: Aircell														9.66	
Airborne			0.0	10000.0		**2578148.4**		**644537.1**		**4913078.7**	**8.15**	**8.15**	**84.36**		
Air Transport	10310	25			20.0	206200.0	5.0	51550.0	3.0	392949.3					85%
Business&Regional	36670	25			14.0	513380.0	3.5	128345.0	2.1	978362.9					85%
General Aviation	478730	25			2.0	957460.0	0.5	239365.0	0.3	1824670.1					85%
UAV - Big	758	25			13.0	9854.0	3.3	2463.5	2.0	18793.9					85%
UAV - Small	4286	25			2.4	10286.4	0.6	2571.6	0.4	19602.5					85%
Military Transport	11484	25			22.0	252648.0	5.5	63162.0	3.3	481479.3					85%
Military Non-transport	20924	25			30.0	627720.0	7.5	156930.0	4.5	1196259.6					50%
Space Vehicles	3	25			200.0	600.0	50.0	150.0	30.0	960.9					10%
Ground	300	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**1500000.0**	**1.51**	**1.51**	**15.64**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 274 – Int. Alternatives Subsystem Costs–Factored AC Model#1 [Part 4 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column 1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
11b Cellular Network: LTE+														**14.41**	
Airborne			0.0	10000.0		**2578148.4**		**644537.1**		**4913078.7**	**8.15**	**8.15**	**56.55**		
Air Transport	10310	25			20.0	206200.0	5.0	51550.0	3.0	392949.3					85%
Business&Regional	36670	25			14.0	513380.0	3.5	128345.0	2.1	978362.9					85%
General Aviation	478730	25			2.0	957460.0	0.5	239365.0	0.3	1824670.1					85%
UAV - Big	758	25			13.0	9854.0	3.3	2463.5	2.0	18793.9					85%
UAV - Small	4286	25			2.4	10286.4	0.6	2571.6	0.4	19602.5					85%
Military Transport	11484	25			22.0	252648.0	5.5	63162.0	3.3	481479.3					85%
Military Non-transport	20924	25			30.0	627720.0	7.5	156930.0	4.5	1196259.6					50%
Space Vehicles	3	25			200.0	600.0	50.0	150.0	30.0	960.9					10%
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	**6.26**	**43.45**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
11c Cellular Network: AWS														**14.41**	
Airborne			0.0	10000.0		**2578148.4**		**644537.1**		**4913078.7**	**8.15**	**8.15**	**56.55**		
Air Transport	10310	25			20.0	206200.0	5.0	51550.0	3.0	392949.3					85%
Business&Regional	36670	25			14.0	513380.0	3.5	128345.0	2.1	978362.9					85%
General Aviation	478730	25			2.0	957460.0	0.5	239365.0	0.3	1824670.1					85%
UAV - Big	758	25			13.0	9854.0	3.3	2463.5	2.0	18793.9					85%
UAV - Small	4286	25			2.4	10286.4	0.6	2571.6	0.4	19602.5					85%
Military Transport	11484	25			22.0	252648.0	5.5	63162.0	3.3	481479.3					85%
Military Non-transport	20924	25			30.0	627720.0	7.5	156930.0	4.5	1196259.6					50%
Space Vehicles	3	25			200.0	600.0	50.0	150.0	30.0	960.9					10%
Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	**6.26**	**43.45**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
12 LEO SATCOM Network (e.g., Iridium Next+)														**52.13**	
Airborne			0.0	10000.0		**10356265.5**		**2589066.4**		**19735044.4**	**32.69**	**32.69**	**62.71**		
Air Transport	10310	25			150.0	1546500.0	37.5	386625.0	22.5	2947119.9					85%
Business&Regional	21571	25			105.0	2264955.0	26.3	566238.8	15.8	4316307.1					50%
General Aviation	112642	25			15.0	1689630.0	3.8	422407.5	2.3	3220006.0					20%
UAV - Big	803	25			97.5	78292.5	24.4	19573.1	14.6	149246.0					90%
UAV - Small	2521	25			18.0	45378.0	4.5	11344.5	2.7	86481.8					50%
Military Transport	11484	25			165.0	1894860.0	41.3	473715.0	24.8	3611094.8					85%
Military Non-transport	12554	25			225.0	2824650.0	56.3	706162.5	33.8	5383168.3					30%
Space Vehicles	8	25			1500.0	12000.0	375.0	3000.0	225.0	21620.5					30%
Ground	13	25	0.0	5000.0	4000.0	**52000.0**	11000.0	**143000.0**	1500.0	**487500.0**	**0.69**	**0.69**	**1.32**		
Satellite	66	6.25	0.0	10000.0	40000.0	**10560000.0**	6000.0	**1584000.0**	4000.0	**6600000.0**	**18.75**	**18.75**	**35.97**		
spares	15														
13 GEO SATCOM Network with global/regional /spot beams														**43.58**	
Airborne			0.0	10000.0		**13083738.8**		**3270934.7**		**24932975.9**	**41.30**	**41.30**	**94.76**		
Air Transport	10916	25			225.0	2456100.0	56.3	614025.0	33.8	4680719.8					90%
Business&Regional	17256	25			157.5	2717820.0	39.4	679455.0	23.6	5179568.5					40%
General Aviation	56321	25			22.5	1267222.5	5.6	316805.6	3.4	2415004.5					10%
UAV - Big	89	25			146.3	13016.3	36.6	3254.1	21.9	24874.3					10%
UAV - Small	0	25			27.0	0.0	6.8	0.0	4.1	0.0					0%
Military Transport	9458	25			247.5	2340855.0	61.9	585213.8	37.1	4460764.2					70%
Military Non-transport	12554	25			337.5	4236975.0	84.4	1059243.8	50.6	8074752.5					30%
Space Vehicles	23	25			2250.0	51750.0	562.5	12937.5	337.5	97292.0					90%
Ground	3	25	0.0	5000.0	4000.0	**12000.0**	11000.0	**33000.0**	3000.0	**225000.0**	**0.28**	**0.28**	**0.63**		
Satellite	3	12.5	0.0	10000.0	150000.0	**900000.0**	100000.0	**600000.0**	6666.7	**500000.0**	**2.01**	**2.01**	**4.61**		
spare	1														

Figure 275 – Int. Alternatives Subsystem Costs–Factored AC Model#1 [Part 5 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
14	MEO SATCOM Network (e.g., GlobalStar+)														40.72	
	Airborne			0.0	20000.0		**11091324.8**		**2772831.2**		**21137307.3**	**35.02**	**35.02**	**86.00**		
	Air Transport	10916	25			160.0	1746560.0	40.0	436640.0	24.0	3328511.9					90%
	Business&Regional	21571	25			112.0	2415952.0	28.0	603988.0	16.8	4604060.9					50%
	General Aviation	56321	25			16.0	901136.0	4.0	225284.0	2.4	1717336.5					10%
	UAV - Big	714	25			104.0	74256.0	26.0	18564.0	15.6	141507.3					80%
	UAV - Small	504	25			19.2	9676.8	4.8	2419.2	2.9	18449.5					10%
	Military Transport	10809	25			176.0	1902384.0	44.0	475596.0	26.4	3625255.9					80%
	Military Non-transport	16739	25			240.0	4017360.0	60.0	1004340.0	36.0	7656061.6					40%
	Space Vehicles	15	25			1600.0	24000.0	400.0	6000.0	240.0	46123.6					60%
	Ground	8	25	0.0	5000.0	4000.0	**32000.0**	11000.0	**88000.0**	1900.0	**380000.0**	**0.51**	**0.51**	**1.24**		
	Satellite	20	8.33	0.0	20000.0	50000.0	**3000000.0**	25000.0	**1500000.0**	1355.0	**677500.0**	**5.20**	**5.20**	**12.76**		
	spares	6														
15	VHF A-A Hopping for Long Range A-G Com.														17.09	
	Airborne			0.0	20000.0		**5153260.0**		**1288315.0**		**9821518.1**	**16.28**	**16.28**	**95.27**		
	Air Transport	10310	25			100.0	1031000.0	25.0	257750.0	15.0	1964746.6					85%
	Business&Regional	10785	25			70.0	754950.0	17.5	188737.5	10.5	1438769.0					25%
	General Aviation	0	25			10.0	0.0	2.5	0.0	1.5	0.0					0%
	UAV - Big	178	25			65.0	11570.0	16.3	2892.5	9.8	22110.5					20%
	UAV - Small	0	25			12.0	0.0	3.0	0.0	1.8	0.0					0%
	Military Transport	11484	25			110.0	1263240.0	27.5	315810.0	16.5	2407396.5					85%
	Military Non-transport	13810	25			150.0	2071500.0	37.5	517875.0	22.5	3947656.8					33%
	Space Vehicles	21	25			1000.0	21000.0	250.0	5250.0	150.0	40838.6					85%
	Ground **Enroute GS**	729	25	0.0	20000.0	82.0	**59778.0**	100.0	**0.0**	40.0	**729000.0**	**0.81**	**0.81**	**4.73**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
16	UHF A-A Hopping for Long Range A-G Com.														18.72	
	Airborne			0.0	30000.0		**5668586.0**		**1417146.5**		**10803669.9**	**17.92**	**17.92**	**95.74**		
	Air Transport	10310	25			110.0	1134100.0	27.5	283525.0	16.5	2161221.3					85%
	Business&Regional	10785	25			77.0	830445.0	19.3	207611.3	11.6	1582645.9					25%
	General Aviation	0	25			11.0	0.0	2.8	0.0	1.7	0.0					0%
	UAV - Big	178	25			71.5	12727.0	17.9	3181.8	10.7	24321.6					20%
	UAV - Small	0	25			13.2	0.0	3.3	0.0	2.0	0.0					0%
	Military Transport	11484	25			121.0	1389564.0	30.3	347391.0	18.2	2648136.2					85%
	Military Non-transport	13810	25			165.0	2278650.0	41.3	569662.5	24.8	4342422.4					33%
	Space Vehicles	21	25			1100.0	23100.0	275.0	5775.0	165.0	44922.5					85%
	Ground	650	25	0.0	20000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.80**	**0.80**	**4.26**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
17	L-Band A-A Hopping for Long Range A-G Com.														20.55	
	Airborne			0.0	30000.0		**5926249.0**		**1481562.3**		**11294745.8**	**18.73**	**18.73**	**91.17**		
	Air Transport	10310	25			115.0	1185650.0	28.8	296412.5	17.3	2259458.6					85%
	Business&Regional	10785	25			80.5	868192.5	20.1	217048.1	12.1	1654584.4					25%
	General Aviation	0	25			11.5	0.0	2.9	0.0	1.7	0.0					0%
	UAV - Big	178	25			74.8	13305.5	18.7	3326.4	11.2	25427.1					20%
	UAV - Small	0	25			13.8	0.0	3.5	0.0	2.1	0.0					0%
	Military Transport	11484	25			126.5	1452726.0	31.6	363181.5	19.0	2768506.0					85%
	Military Non-transport	13810	25			172.5	2382225.0	43.1	595556.3	25.9	4539805.3					33%
	Space Vehicles	21	25			1150.0	24150.0	287.5	6037.5	172.5	46964.4					85%
	Ground	1200	25	0.0	20000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.81**	**1.81**	**8.83**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

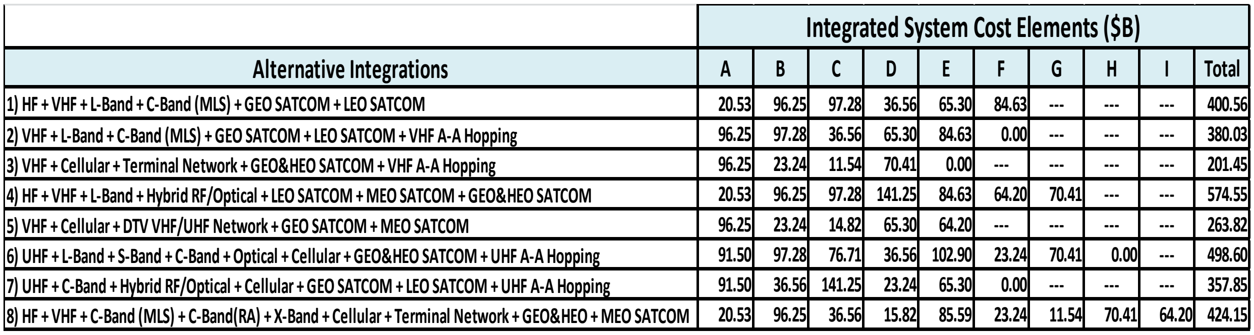
Figure 276 – Int. Alternatives Subsystem Costs–Factored AC Model#1 [Part 6 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
18	X-Band														45.38	
	Airborne			0.0	30000.0		**14306917.7**		**3576729.4**		**27264247.7**	**45.18**	**45.18**	**99.56**		
	Air Transport	8490	25			115.0	976350.0	28.8	244087.5	17.3	1860730.6					70%
	Business&Regional	30199	25			80.5	2431019.5	20.1	607754.9	12.1	4632836.3					70%
	General Aviation	394248	25			11.5	4533852.0	2.9	1133463.0	1.7	8640349.5					70%
	UAV - Big	624	25			74.8	46644.0	18.7	11661.0	11.2	88994.8					70%
	UAV - Small	3529	25			13.8	48700.2	3.5	12175.1	2.1	92823.8					70%
	Military Transport	9458	25			126.5	1196437.0	31.6	299109.3	19.0	2279946.1					70%
	Military Non-transport	29294	25			172.5	5053215.0	43.1	1263303.8	25.9	9629890.0					70%
	Space Vehicles	18	25			1150.0	20700.0	287.5	5175.0	172.5	38676.6					70%
	Ground	100	25	0.0	0.0	230.0	**23000.0**	135.0	**13500.0**	65.0	**162500.0**	**0.20**	**0.20**	**0.44**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
19	GEO + HEO SATCOM Network														47.72	
	Airborne			0.0	12000.0		**13665238.3**		**3416309.6**		**26041108.1**	**43.13**	**43.13**	**90.38**		
	Air Transport	10916	25			235.0	2565260.0	58.8	641315.0	35.3	4888751.8					90%
	Business&Regional	17256	25			164.5	2838612.0	41.1	709653.0	24.7	5409771.6					40%
	General Aviation	56321	25			23.5	1323543.5	5.9	330885.9	3.5	2522338.1					10%
	UAV - Big	89	25			152.8	13594.8	38.2	3398.7	22.9	25979.9					10%
	UAV - Small	0	25			28.2	0.0	7.1	0.0	4.2	0.0					0%
	Military Transport	9458	25			258.5	2444893.0	64.6	611223.3	38.8	4659020.3					70%
	Military Non-transport	12554	25			352.5	4425285.0	88.1	1106321.3	52.9	8433630.4					30%
	Space Vehicles	23	25			2350.0	54050.0	587.5	13512.5	352.5	101616.1					90%
	Ground	5	25	0.0	5000.0	4000.0	**20000.0**	11000.0	**55000.0**	3500.0	**437500.0**	**0.52**	**0.52**	**1.08**		
	Satellite	6	12.5	0.0	12000.0	170000.0	**2040000.0**	85000.0	**1020000.0**	6666.7	**1000000.0**	**4.07**	**4.07**	**8.53**		
	spare	3														

Figure 277 – Int. Alternatives Subsystem Costs–Factored AC Model#1 [Part 7 of 7]

23.3.2 Cost Comparisons of Integration Alternatives – Factored Aircraft Fleet Model #2

Figure 278 and Figure 279 provide a summary table and plot (respectively) for the eight integration alternatives for which costs have been computed based upon factored Aircraft Fleet Model #2 (for description of “factored” aircraft fleet model, see Section 23.3). Figure 280 to Figure 286 (pages 394 to 400, respectively) provide the detailed cost tables used to generate the total cost of the integration alternatives based upon factored Aircraft Fleet Model #2.



	Integrated System Cost Elements ($B)									
Alternative Integrations	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**Total**
1) HF + VHF + L-Band + C-Band (MLS) + GEO SATCOM + LEO SATCOM	20.53	96.25	97.28	36.56	65.30	84.63	---	---	---	400.56
2) VHF + L-Band + C-Band (MLS) + GEO SATCOM + LEO SATCOM + VHF A-A Hopping	96.25	97.28	36.56	65.30	84.63	0.00	---	---	---	380.03
3) VHF + Cellular + Terminal Network + GEO&HEO SATCOM + VHF A-A Hopping	96.25	23.24	11.54	70.41	0.00	---	---	---	---	201.45
4) HF + VHF + L-Band + Hybrid RF/Optical + LEO SATCOM + MEO SATCOM + GEO&HEO SATCOM	20.53	96.25	97.28	141.25	84.63	64.20	70.41	---	---	574.55
5) VHF + Cellular + DTV VHF/UHF Network + GEO SATCOM + MEO SATCOM	96.25	23.24	14.82	65.30	64.20	---	---	---	---	263.82
6) UHF + L-Band + S-Band + C-Band + Optical + Cellular + GEO&HEO SATCOM + UHF A-A Hopping	91.50	97.28	76.71	36.56	102.90	23.24	70.41	0.00	---	498.60
7) UHF + C-Band + Hybrid RF/Optical + Cellular + GEO SATCOM + LEO SATCOM + UHF A-A Hopping	91.50	36.56	141.25	23.24	65.30	0.00	---	---	---	357.85
8) HF + VHF + C-Band (MLS) + C-Band(RA) + X-Band + Cellular + Terminal Network + GEO&HEO + MEO SATCOM	20.53	96.25	36.56	15.82	85.59	23.24	11.54	70.41	64.20	424.15

Figure 278 – Cost Comparison Table of A-G Integration Alternatives (Factored AC Fleet Model #2)

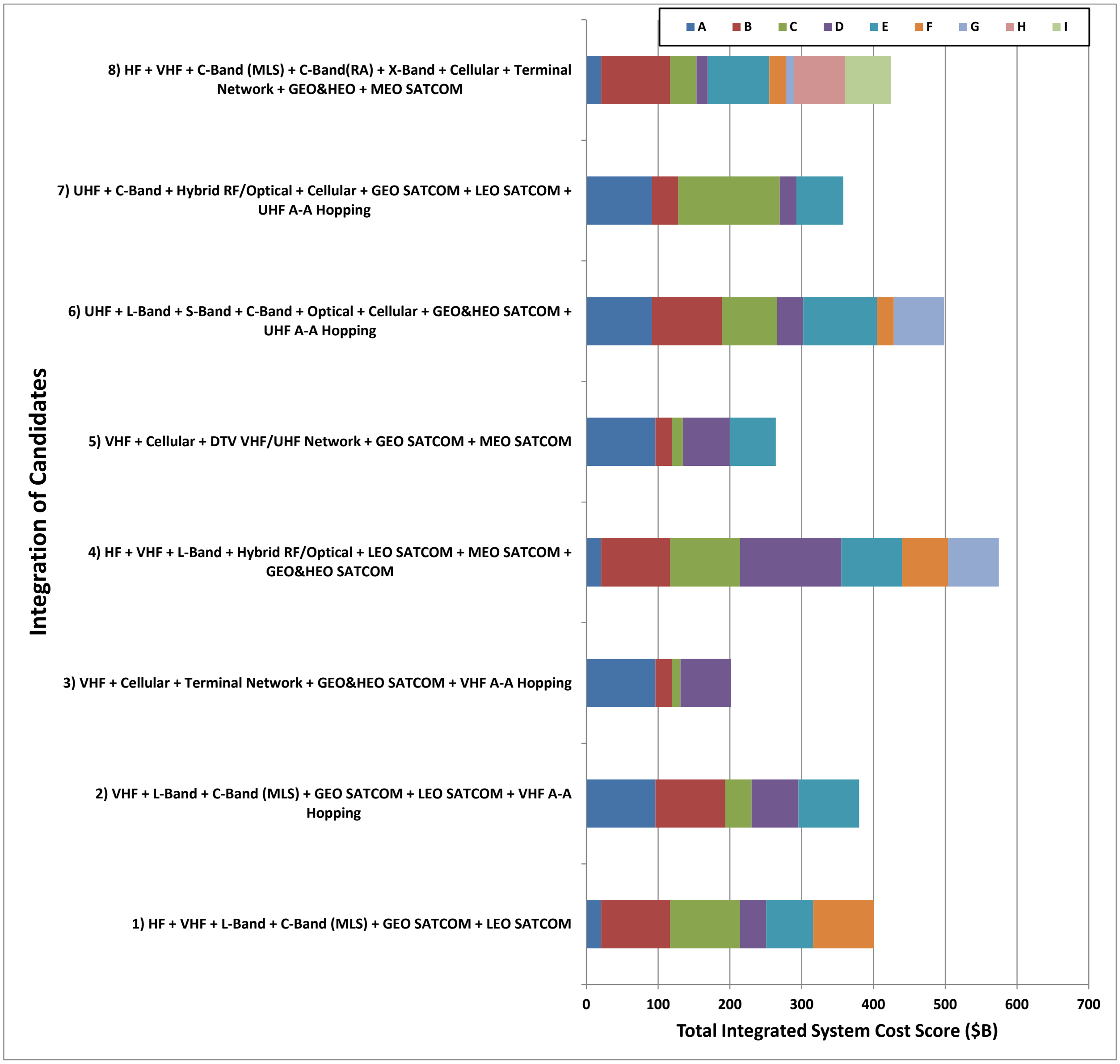


Figure 279 – Cost Comparison Plot of A-G Integration Alternatives (Factored AC Fleet Model #2)

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
1	HF A-G														20.53	
	Airborne			0.0	5000.0		**6085640.0**		**1521410.0**		**12693302.1**	**20.31**	**20.31**	**98.93**		
	Air Transport	21429	25			100.0	2142900.0	25.0	535725.0	15.0	4083863.2					85%
	Business&Regional	17648	25			70.0	1235360.0	17.5	308840.0	10.5	2354227.0					20%
	General Aviation	0	25			10.0	0.0	2.5	0.0	1.5	0.0					0%
	UAV - Big	2676	25			65.0	173940.0	16.3	43485.0	9.8	324838.1					10%
	UAV - Small	0	25			12.0	0.0	3.0	0.0	1.8	0.0					0%
	Military Transport	10764	25			110.0	1184040.0	27.5	296010.0	16.5	2772776.1					85%
	Military Non-transport	8956	25			150.0	1343400.0	37.5	335850.0	22.5	3145586.3					33%
	Space Vehicles	6	25			1000.0	6000.0	250.0	1500.0	150.0	12011.4					10%
	Ground	10	25	0.0	5000.0	3000.0	**30000.0**	1000.0	**10000.0**	700.0	**175000.0**	**0.22**	**0.22**	**1.07**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
2a	VHF A-G: Use 112 to 118 MHz														90.37	
	Airborne			0.0	2000.0		**28153907.4**		**7038476.9**		**54941214.5**	**90.14**	**90.14**	**99.74**		
	Air Transport	25211	25			85.0	2142935.0	21.3	535733.8	12.8	4083863.2					100%
	Business&Regional	88238	25			59.5	5250161.0	14.9	1312540.3	8.9	10005464.9					100%
	General Aviation	1360662	25			8.5	11565627.0	2.1	2891406.8	1.3	23242781.0					100%
	UAV - Big	26760	25			55.3	1478490.0	13.8	369622.5	8.3	2761123.7					100%
	UAV - Small	295977	25			10.2	3018965.4	2.6	754741.4	1.5	3870841.1					100%
	Military Transport	12664	25			93.5	1184084.0	23.4	296021.0	14.0	2772776.1					100%
	Military Non-transport	27138	25			127.5	3460095.0	31.9	865023.8	19.1	8102267.9					100%
	Space Vehicles	63	25			850.0	53550.0	212.5	13387.5	127.5	102096.6					100%
	Ground	200	25	0.0	2000.0	82.0	**16400.0**	100.0	**20000.0**	40.0	**200000.0**	**0.24**	**0.24**	**0.26**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
2b	VHF A-G: Improve VHF Efficiency														96.25	
	Airborne			0.0	5000.0		**29147574.7**		**7286893.7**		**56880316.2**	**93.32**	**93.32**	**96.95**		
	Air Transport	25211	25			88.0	2218568.0	22.0	554642.0	13.2	4227999.6					100%
	Business&Regional	88238	25			61.6	5435460.8	15.4	1358865.2	9.2	10358598.9					100%
	General Aviation	1360662	25			8.8	11973825.6	2.2	2993456.4	1.3	24063114.5					100%
	UAV - Big	26760	25			57.2	1530672.0	14.3	382668.0	8.6	2858575.1					100%
	UAV - Small	295977	25			10.6	3125517.1	2.6	781379.3	1.6	4007459.0					100%
	Military Transport	12664	25			96.8	1225875.2	24.2	306468.8	14.5	2870638.8					100%
	Military Non-transport	27138	25			132.0	3582216.0	33.0	895554.0	19.8	8388230.3					100%
	Space Vehicles	63	25			880.0	55440.0	220.0	13860.0	132.0	105700.0					100%
	Ground	2708	25	0.0	5000.0	82.0	**222056.0**	100.0	**0.0**	40.0	**2708000.0**	**2.94**	**2.94**	**3.05**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
2c	VHF A-G: Low Band (Ground-to-Air only)														32.93	
	Airborne			0.0	10000.0		**9337151.0**		**2334287.8**		**18736960.9**	**30.42**	**30.42**	**92.38**		
	Air Transport	7563	25			95.0	718485.0	23.8	179621.3	14.3	1369295.3					30%
	Business&Regional	17648	25			66.5	1173592.0	16.6	293398.0	10.0	2236515.7					20%
	General Aviation	680331	25			9.5	6463144.5	2.4	1615786.1	1.4	12988612.9					50%
	UAV - Big	5352	25			61.8	330486.0	15.4	82621.5	9.3	617192.4					20%
	UAV - Small	0	25			11.4	0.0	2.9	0.0	1.7	0.0					0%
	Military Transport	2533	25			104.5	264698.5	26.1	66174.6	15.7	619797.0					20%
	Military Non-transport	2714	25			142.5	386745.0	35.6	96686.3	21.4	905547.6					10%
	Space Vehicles	0	25			950.0	0.0	237.5	0.0	142.5	0.0					0%
	Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	**2.51**	**7.62**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 280 – Int. Alternatives Subsystem Costs–Factored AC Model#2 [Part 1 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score: Maturation Cost ($K)	Technology Maturation & Standards Cost Score: Standards Cost ($K)	Equipment Cost Score: Average Per Unit ($K)	Equipment Cost Score: Total ($K)	Deployment Cost Score: Average Per Unit ($K)	Deployment Cost Score: Total ($K)	Ops. & Maintenance Cost Score: Per Unit Per Year ($K)	Ops. & Maintenance Cost Score: Total ($K)	Total System Cost Score: Non-Factored ($B)	Total System Cost Score: Total Cost of Candidate ($B)	Total System Cost Score: Percentage of Total Cost	Total System Cost Score: Total Cost for Candidate ($B)	Percentage of AC in Fleet Model Being Run in Sheet
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
3a	UHF A-G: Aviation Allocation														91.50	
	Airborne			0.0	30000.0		**28319811.6**		**7079952.9**		**55264398.1**	**90.69**	**90.69**	**99.12**		
	Air Transport	22690	25			95.0	2155550.0	23.8	538887.5	14.3	4107885.9					90%
	Business&Regional	79414	25			66.5	5281031.0	16.6	1320257.8	10.0	10064320.6					90%
	General Aviation	1224596	25			9.5	11633662.0	2.4	2908415.5	1.4	23379503.2					90%
	UAV - Big	24084	25			61.8	1487187.0	15.4	371796.8	9.3	2777365.6					90%
	UAV - Small	266379	25			11.4	3036720.6	2.9	759180.2	1.7	3893610.8					90%
	Military Transport	11398	25			104.5	1191091.0	26.1	297772.8	15.7	2789086.6					90%
	Military Non-transport	24424	25			142.5	3480420.0	35.6	870105.0	21.4	8149928.3					90%
	Space Vehicles	57	25			950.0	54150.0	237.5	13537.5	142.5	102697.1					90%
	Ground	650	25	0.0	30000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.81**	**0.81**	**0.88**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
3b	UHF A-G: High Band (Ground-to-Air only)														48.66	
	Airborne			0.0	30000.0		**13936230.2**		**3484057.6**		**27427816.3**	**44.88**	**44.88**	**92.23**		
	Air Transport	20169	25			95.0	1916055.0	23.8	479013.8	14.3	3651454.2					80%
	Business&Regional	52943	25			66.5	3520709.5	16.6	880177.4	10.0	6709547.0					60%
	General Aviation	408199	25			9.5	3877890.5	2.4	969472.6	1.4	7793167.7					30%
	UAV - Big	16056	25			61.8	991458.0	15.4	247864.5	9.3	1851577.1					60%
	UAV - Small	88793	25			11.4	1012240.2	2.9	253060.1	1.7	1297870.3					30%
	Military Transport	10131	25			104.5	1058689.5	26.1	264672.4	15.7	2479188.1					80%
	Military Non-transport	10855	25			142.5	1546837.5	35.6	386709.4	21.4	3622190.3					40%
	Space Vehicles	13	25			950.0	12350.0	237.5	3087.5	142.5	22821.6					20%
	Ground	750	25	0.0	30000.0	0.0	**0.0**	0.0	**0.0**	200.0	**3750000.0**	**3.78**	**3.78**	**7.77**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
3c	UHF A-G: Other														91.41	
	Airborne			0.0	70000.0		**28319811.6**		**7079952.9**		**55264398.1**	**90.73**	**90.73**	**99.26**		
	Air Transport	22690	25			95.0	2155550.0	23.8	538887.5	14.3	4107885.9					90%
	Business&Regional	79414	25			66.5	5281031.0	16.6	1320257.8	10.0	10064320.6					90%
	General Aviation	1224596	25			9.5	11633662.0	2.4	2908415.5	1.4	23379503.2					90%
	UAV - Big	24084	25			61.8	1487187.0	15.4	371796.8	9.3	2777365.6					90%
	UAV - Small	266379	25			11.4	3036720.6	2.9	759180.2	1.7	3893610.8					90%
	Military Transport	11398	25			104.5	1191091.0	26.1	297772.8	15.7	2789086.6					90%
	Military Non-transport	24424	25			142.5	3480420.0	35.6	870105.0	21.4	8149928.3					90%
	Space Vehicles	57	25			950.0	54150.0	237.5	13537.5	142.5	102697.1					90%
	Ground	1000	25	0.0	30000.0	100.0	**100000.0**	50.0	**50000.0**	20.0	**500000.0**	**0.68**	**0.68**	**0.74**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
4	L-Band A-G														97.28	
	Airborne			0.0	25000.0		**29810328.0**		**7452582.0**		**58173050.6**	**95.46**	**95.46**	**98.13**		
	Air Transport	22690	25			100.0	2269000.0	25.0	567250.0	15.0	4324090.5					90%
	Business&Regional	79414	25			70.0	5558980.0	17.5	1389745.0	10.5	10594021.6					90%
	General Aviation	1224596	25			10.0	12245960.0	2.5	3061490.0	1.5	24610003.4					90%
	UAV - Big	24084	25			65.0	1565460.0	16.3	391365.0	9.8	2923542.8					90%
	UAV - Small	266379	25			12.0	3196548.0	3.0	799137.0	1.8	4098537.6					90%
	Military Transport	11398	25			110.0	1253780.0	27.5	313445.0	16.5	2935880.6					90%
	Military Non-transport	24424	25			150.0	3663600.0	37.5	915900.0	22.5	8578871.8					90%
	Space Vehicles	57	25			1000.0	57000.0	250.0	14250.0	150.0	108102.3					90%
	Ground	1200	25	0.0	25000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.82**	**1.82**	**1.87**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 281 – Int. Alternatives Subsystem Costs–Factored AC Model#2 [Part 2 of 7]

# Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
			Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column 1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
5 S-Band A-G														76.71	
Airborne			0.0	20000.0		**23185608.0**		**5796402.0**		**45245706.0**	**74.25**	**74.25**	**96.79**		
Air Transport	17648	25			100.0	1764800.0	25.0	441200.0	15.0	3363181.5					70%
Business&Regional	61767	25			70.0	4323690.0	17.5	1080922.5	10.5	8239794.6					70%
General Aviation	952463	25			10.0	9524630.0	2.5	2381157.5	1.5	19141113.8					70%
UAV - Big	18732	25			65.0	1217580.0	16.3	304395.0	9.8	2273866.6					70%
UAV - Small	207184	25			12.0	2486208.0	3.0	621552.0	1.8	3187751.5					70%
Military Transport	8865	25			110.0	975150.0	27.5	243787.5	16.5	2283462.7					70%
Military Non-transport	18997	25			150.0	2849550.0	37.5	712387.5	22.5	6672455.9					70%
Space Vehicles	44	25			1000.0	44000.0	250.0	11000.0	150.0	84079.5					70%
Ground	1500	25	0.0	20000.0	125.0	**187500.0**	130.0	**195000.0**	55.0	**2062500.0**	**2.47**	**2.47**	**3.21**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
6a C-Band A-G: MLS Band														36.56	
Airborne			10000.0	30000.0		**10442685.0**		**2610671.3**		**20816085.2**	**33.91**	**33.91**	**92.74**		
Air Transport	20169	25			110.0	2218590.0	27.5	554647.5	16.5	4227999.6					80%
Business&Regional	52943	25			77.0	4076611.0	19.3	1019152.8	11.6	7768949.2					60%
General Aviation	68033	25			11.0	748363.0	2.8	187090.8	1.7	1503944.7					5%
UAV - Big	18732	25			71.5	1339338.0	17.9	334834.5	10.7	2501253.3					70%
UAV - Small	0	25			13.2	0.0	3.3	0.0	2.0	0.0					0%
Military Transport	7598	25			121.0	919358.0	30.3	229839.5	18.2	2152979.1					60%
Military Non-transport	6785	25			165.0	1119525.0	41.3	279881.3	24.8	2621322.0					25%
Space Vehicles	19	25			1100.0	20900.0	275.0	5225.0	165.0	39637.5					30%
Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	**2.65**	**7.26**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
6b C-Band A-G: Radar Alt.														15.82	
Airborne			20000.0	30000.0		**4035713.0**		**1008928.3**		**8071811.6**	**13.17**	**13.17**	**83.22**		
Air Transport	12606	25			110.0	1386660.0	27.5	346665.0	16.5	2642499.7					50%
Business&Regional	17648	25			77.0	1358896.0	19.3	339724.0	11.6	2589649.7					20%
General Aviation	0	25			11.0	0.0	2.8	0.0	1.7	0.0					0%
UAV - Big	5352	25			71.5	382668.0	17.9	95667.0	10.7	714643.8					20%
UAV - Small	0	25			13.2	0.0	3.3	0.0	2.0	0.0					0%
Military Transport	3799	25			121.0	459679.0	30.3	114919.8	18.2	1076489.5					30%
Military Non-transport	2714	25			165.0	447810.0	41.3	111952.5	24.8	1048528.8					10%
Space Vehicles	0	25			1100.0	0.0	275.0	0.0	165.0	0.0					0%
Ground	1600	25	0.0	30000.0	130.0	**208000.0**	135.0	**216000.0**	55.0	**2200000.0**	**2.65**	**2.65**	**16.78**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
7 Optical A-G														102.90	
Airborne			200000.0	70000.0		**29868150.6**		**7467037.7**		**58946019.3**	**96.55**	**96.55**	**93.83**		
Air Transport	20169	25			270.0	5445630.0	67.5	1361407.5	40.5	10377817.1					80%
Business&Regional	70590	25			189.0	13341510.0	47.3	3335377.5	28.4	25425651.9					80%
General Aviation	68033	25			27.0	1836891.0	6.8	459222.8	4.1	3691500.5					5%
UAV - Big	20070	25			175.5	3522285.0	43.9	880571.3	26.3	6577971.2					75%
UAV - Small	14799	25			32.4	479487.6	8.1	119871.9	4.9	614780.6					5%
Military Transport	10131	25			297.0	3008907.0	74.3	752226.8	44.6	7046113.4					80%
Military Non-transport	5428	25			405.0	2198340.0	101.3	549585.0	60.8	5147323.1					20%
Space Vehicles	13	25			2700.0	35100.0	675.0	8775.0	405.0	64861.4					20%
Ground	100	25	200000.0	35000.0	8100.0	**810000.0**	3000.0	**300000.0**	2000.0	**5000000.0**	**6.35**	**6.35**	**6.17**		
Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 282 – Int. Alternatives Subsystem Costs–Factored AC Model#2 [Part 3 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
8	Hybrid RF/Optical A-G														**141.25**	
	Airborne			240000.0	90000.0		**40930428.6**		**10232607.2**		**80777878.3**	**132.27**	**132.27**	**93.65**		
	Air Transport	20169	25			370.0	7462530.0	92.5	1865632.5	55.5	14221453.1					80%
	Business&Regional	70590	25			259.0	18282810.0	64.8	4570702.5	38.9	34842560.0					80%
	General Aviation	68033	25			37.0	2517221.0	9.3	629305.3	5.6	5058722.9					5%
	UAV - Big	20070	25			240.5	4826835.0	60.1	1206708.8	36.1	9014256.8					75%
	UAV - Small	14799	25			44.4	657075.6	11.1	164268.9	6.7	842477.2					5%
	Military Transport	10131	25			407.0	4123317.0	101.8	1030829.3	61.1	9655785.0					80%
	Military Non-transport	5428	25			555.0	3012540.0	138.8	753135.0	83.3	7053739.1					20%
	Space Vehicles	13	25			3700.0	48100.0	925.0	12025.0	555.0	88884.1					20%
	Ground	100	25	120000.0	45000.0	9100.0	**910000.0**	4000.0	**400000.0**	3000.0	**7500000.0**	**8.98**	**8.98**	**6.35**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
9	Terminal K to W Band Network (e.g., KU Band QualComm+)														**11.54**	
	Airborne			20000.0	30000.0		**2713239.0**		**678309.8**		**5448784.9**	**8.89**	**8.89**	**77.04**		
	Air Transport	21429	25			30.0	642870.0	7.5	160717.5	4.5	1225159.0					85%
	Business&Regional	44119	25			21.0	926499.0	5.3	231624.8	3.2	1765670.3					50%
	General Aviation	68033	25			3.0	204099.0	0.8	51024.8	0.5	410166.7					5%
	UAV - Big	16056	25			19.5	313092.0	4.9	78273.0	2.9	584708.6					60%
	UAV - Small	0	25			3.6	0.0	0.9	0.0	0.5	0.0					0%
	Military Transport	7598	25			33.0	250734.0	8.3	62683.5	5.0	587176.1					60%
	Military Non-transport	8141	25			45.0	366345.0	11.3	91586.3	6.8	857887.2					30%
	Space Vehicles	32	25			300.0	9600.0	75.0	2400.0	45.0	18017.0					50%
	Ground	300	25	20000.0	30000.0	1500.0	**450000.0**	5166.0	**1549800.0**	80.0	**600000.0**	**2.65**	**2.65**	**22.96**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
10	DTV VHF/UHF Network														**14.82**	
	Airborne			0.0	10000.0		**3887949.5**		**971987.4**		**7438538.7**	**12.31**	**12.31**	**83.06**		
	Air Transport	15127	25			25.0	378175.0	6.3	94543.8	3.8	720681.7					60%
	Business&Regional	52943	25			17.5	926502.5	4.4	231625.6	2.6	1765670.3					60%
	General Aviation	680331	25			2.5	1700827.5	0.6	425206.9	0.4	3418056.0					50%
	UAV - Big	8028	25			16.3	130455.0	4.1	32613.8	2.4	243628.6					30%
	UAV - Small	147989	25			3.0	443967.0	0.8	110991.8	0.5	569241.3					50%
	Military Transport	3799	25			27.5	104472.5	6.9	26118.1	4.1	244656.7					30%
	Military Non-transport	5428	25			37.5	203550.0	9.4	50887.5	5.6	476604.0					20%
	Space Vehicles	0	25			250.0	0.0	62.5	0.0	37.5	0.0					0%
	Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**2500000.0**	**2.51**	**2.51**	**16.94**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
11a	Cellular Network: Aircell														**18.49**	
	Airborne			0.0	10000.0		**5336302.0**		**1334075.5**		**10302980.3**	**16.98**	**16.98**	**91.83**		
	Air Transport	21429	25			20.0	428580.0	5.0	107145.0	3.0	816772.6					85%
	Business&Regional	75002	25			14.0	1050028.0	3.5	262507.0	2.1	2001093.0					85%
	General Aviation	1156563	25			2.0	2313126.0	0.5	578281.5	0.3	4648556.2					85%
	UAV - Big	22746	25			13.0	295698.0	3.3	73924.5	2.0	552224.7					85%
	UAV - Small	251580	25			2.4	603792.0	0.6	150948.0	0.4	774168.2					85%
	Military Transport	10764	25			22.0	236808.0	5.5	59202.0	3.3	554555.2					85%
	Military Non-transport	13569	25			30.0	407070.0	7.5	101767.5	4.5	953208.0					50%
	Space Vehicles	6	25			200.0	1200.0	50.0	300.0	30.0	2402.3					10%
	Ground	300	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	200.0	**1500000.0**	**1.51**	**1.51**	**8.17**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 283 – Int. Alternatives Subsystem Costs–Factored AC Model#2 [Part 4 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
11b	Cellular Network: LTE+														23.24	
	Airborne			0.0	10000.0		**5336302.0**		**1334075.5**		**10302980.3**	**16.98**	**16.98**	**73.07**		
	Air Transport	21429	25			20.0	428580.0	5.0	107145.0	3.0	816772.6					85%
	Business&Regional	75002	25			14.0	1050028.0	3.5	262507.0	2.1	2001093.0					85%
	General Aviation	1156563	25			2.0	2313126.0	0.5	578281.5	0.3	4648556.2					85%
	UAV - Big	22746	25			13.0	295698.0	3.3	73924.5	2.0	552224.7					85%
	UAV - Small	251580	25			2.4	603792.0	0.6	150948.0	0.4	774168.2					85%
	Military Transport	10764	25			22.0	236808.0	5.5	59202.0	3.3	554555.2					85%
	Military Non-transport	13569	25			30.0	407070.0	7.5	101767.5	4.5	953208.0					50%
	Space Vehicles	6	25			200.0	1200.0	50.0	300.0	30.0	2402.3					10%
	Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	**6.26**	**26.93**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
11c	Cellular Network: AWS														23.24	
	Airborne			0.0	10000.0		**5336302.0**		**1334075.5**		**10302980.3**	**16.98**	**16.98**	**73.07**		
	Air Transport	21429	25			20.0	428580.0	5.0	107145.0	3.0	816772.6					85%
	Business&Regional	75002	25			14.0	1050028.0	3.5	262507.0	2.1	2001093.0					85%
	General Aviation	1156563	25			2.0	2313126.0	0.5	578281.5	0.3	4648556.2					85%
	UAV - Big	22746	25			13.0	295698.0	3.3	73924.5	2.0	552224.7					85%
	UAV - Small	251580	25			2.4	603792.0	0.6	150948.0	0.4	774168.2					85%
	Military Transport	10764	25			22.0	236808.0	5.5	59202.0	3.3	554555.2					85%
	Military Non-transport	13569	25			30.0	407070.0	7.5	101767.5	4.5	953208.0					50%
	Space Vehicles	6	25			200.0	1200.0	50.0	300.0	30.0	2402.3					10%
	Ground	500	25	0.0	10000.0	0.0	**0.0**	0.0	**0.0**	500.0	**6250000.0**	**6.26**	**6.26**	**26.93**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
12	LEO SATCOM Network (e.g., Iridium Next+)														84.63	
	Airborne			0.0	10000.0		**20577102.0**		**5144275.5**		**39460894.1**	**65.19**	**65.19**	**77.03**		
	Air Transport	21429	25			150.0	3214350.0	37.5	803587.5	22.5	6125794.8					85%
	Business&Regional	44119	25			105.0	4632495.0	26.3	1158123.8	15.8	8828351.4					50%
	General Aviation	272132	25			15.0	4081980.0	3.8	1020495.0	2.3	8203334.5					20%
	UAV - Big	24084	25			97.5	2348190.0	24.4	587047.5	14.6	4385314.1					90%
	UAV - Small	147989	25			18.0	2663802.0	4.5	665950.5	2.7	3415448.0					50%
	Military Transport	10764	25			165.0	1776060.0	41.3	444015.0	24.8	4159164.2					85%
	Military Non-transport	8141	25			225.0	1831725.0	56.3	457931.3	33.8	4289435.9					30%
	Space Vehicles	19	25			1500.0	28500.0	375.0	7125.0	225.0	54051.1					30%
	Ground	13	25	0.0	5000.0	4000.0	**52000.0**	11000.0	**143000.0**	1500.0	**487500.0**	**0.69**	**0.69**	**0.81**		
	Satellite	66	6.25	0.0	10000.0	40000.0	**10560000.0**	6000.0	**1584000.0**	4000.0	**6600000.0**	**18.75**	**18.75**	**22.16**		
	spares	15														
13	GEO SATCOM Network with global/regional /spot beams														65.30	
	Airborne			0.0	10000.0		**19186987.5**		**4796746.9**		**39021786.7**	**63.02**	**63.02**	**96.50**		
	Air Transport	22690	25			225.0	5105250.0	56.3	1276312.5	33.8	9729203.5					90%
	Business&Regional	35295	25			157.5	5558962.5	39.4	1389740.6	23.6	10594021.6					40%
	General Aviation	136066	25			22.5	3061485.0	5.6	765371.3	3.4	6152500.9					10%
	UAV - Big	2676	25			146.3	391365.0	36.6	97841.3	21.9	730885.7					10%
	UAV - Small	0	25			27.0	0.0	6.8	0.0	4.1	0.0					0%
	Military Transport	8865	25			247.5	2194087.5	61.9	548521.9	37.1	5137791.0					70%
	Military Non-transport	8141	25			337.5	2747587.5	84.4	686896.9	50.6	6434153.9					30%
	Space Vehicles	57	25			2250.0	128250.0	562.5	32062.5	337.5	243230.1					90%
	Ground	3	25	0.0	5000.0	4000.0	**12000.0**	11000.0	**33000.0**	3000.0	**225000.0**	**0.28**	**0.28**	**0.42**		
	Satellite	3	12.5	0.0	10000.0	150000.0	**900000.0**	100000.0	**600000.0**	6666.7	**500000.0**	**2.01**	**2.01**	**3.08**		
	spare	1														

Figure 284 – Int. Alternatives Subsystem Costs–Factored AC Model#2 [Part 5 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
14	MEO SATCOM Network (e.g., GlobalStar+)														64.20	
	Airborne			0.0	20000.0		**17992553.6**		**4498138.4**		**35988435.8**	**58.50**	**58.50**	**91.12**		
	Air Transport	22690	25			160.0	3630400.0	40.0	907600.0	24.0	6918544.7					90%
	Business&Regional	44119	25			112.0	4941328.0	28.0	1235332.0	16.8	9416908.1					50%
	General Aviation	136066	25			16.0	2177056.0	4.0	544264.0	2.4	4375111.7					10%
	UAV - Big	21408	25			104.0	2226432.0	26.0	556608.0	15.6	4157927.5					80%
	UAV - Small	29598	25			19.2	568281.6	4.8	142070.4	2.9	728628.9					10%
	Military Transport	10131	25			176.0	1783056.0	44.0	445764.0	26.4	4175474.6					80%
	Military Non-transport	10855	25			240.0	2605200.0	60.0	651300.0	36.0	6100531.1					40%
	Space Vehicles	38	25			1600.0	60800.0	400.0	15200.0	240.0	115309.1					60%
	Ground	8	25	0.0	5000.0	4000.0	**32000.0**	11000.0	**88000.0**	1900.0	**380000.0**	**0.51**	**0.51**	**0.79**		
	Satellite	20	8.33	0.0	20000.0	50000.0	**3000000.0**	25000.0	**1500000.0**	1355.0	**677500.0**	**5.20**	**5.20**	**8.10**		
	spares	6														
15	VHF A-A Hopping for Long Range A-G Com.														22.80	
	Airborne			0.0	20000.0		**6616420.0**		**1654105.0**		**13696782.2**	**21.99**	**21.99**	**96.45**		
	Air Transport	21429	25			100.0	2142900.0	25.0	535725.0	15.0	4083863.2					85%
	Business&Regional	22060	25			70.0	1544200.0	17.5	386050.0	10.5	2942783.8					25%
	General Aviation	0	25			10.0	0.0	2.5	0.0	1.5	0.0					0%
	UAV - Big	5352	25			65.0	347880.0	16.3	86970.0	9.8	649676.2					20%
	UAV - Small	0	25			12.0	0.0	3.0	0.0	1.8	0.0					0%
	Military Transport	10764	25			110.0	1184040.0	27.5	296010.0	16.5	2772776.1					85%
	Military Non-transport	8956	25			150.0	1343400.0	37.5	335850.0	22.5	3145586.3					33%
	Space Vehicles	54	25			1000.0	54000.0	250.0	13500.0	150.0	102096.6					85%
	Ground **Enroute GS**	729	25	0.0	20000.0	82.0	**59778.0**	100.0	**0.0**	40.0	**729000.0**	**0.81**	**0.81**	**3.55**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
16	UHF A-A Hopping for Long Range A-G Com.														24.99	
	Airborne			0.0	30000.0		**7278062.0**		**1819515.5**		**15066460.4**	**24.19**	**24.19**	**96.81**		
	Air Transport	21429	25			110.0	2357190.0	27.5	589297.5	16.5	4492249.5					85%
	Business&Regional	22060	25			77.0	1698620.0	19.3	424655.0	11.6	3237062.2					25%
	General Aviation	0	25			11.0	0.0	2.8	0.0	1.7	0.0					0%
	UAV - Big	5352	25			71.5	382668.0	17.9	95667.0	10.7	714643.8					20%
	UAV - Small	0	25			13.2	0.0	3.3	0.0	2.0	0.0					0%
	Military Transport	10764	25			121.0	1302444.0	30.3	325611.0	18.2	3050053.7					85%
	Military Non-transport	8956	25			165.0	1477740.0	41.3	369435.0	24.8	3460145.0					33%
	Space Vehicles	54	25			1100.0	59400.0	275.0	14850.0	165.0	112306.2					85%
	Ground	650	25	0.0	20000.0	95.0	**61750.0**	100.0	**65000.0**	40.0	**650000.0**	**0.80**	**0.80**	**3.19**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
17	L-Band A-A Hopping for Long Range A-G Com.														27.11	
	Airborne			0.0	30000.0		**7608883.0**		**1902220.8**		**15751299.5**	**25.29**	**25.29**	**93.31**		
	Air Transport	21429	25			115.0	2464335.0	28.8	616083.8	17.3	4696442.7					85%
	Business&Regional	22060	25			80.5	1775830.0	20.1	443957.5	12.1	3384201.4					25%
	General Aviation	0	25			11.5	0.0	2.9	0.0	1.7	0.0					0%
	UAV - Big	5352	25			74.8	400062.0	18.7	100015.5	11.2	747127.6					20%
	UAV - Small	0	25			13.8	0.0	3.5	0.0	2.1	0.0					0%
	Military Transport	10764	25			126.5	1361646.0	31.6	340411.5	19.0	3188692.5					85%
	Military Non-transport	8956	25			172.5	1544910.0	43.1	386227.5	25.9	3617424.3					33%
	Space Vehicles	54	25			1150.0	62100.0	287.5	15525.0	172.5	117411.1					85%
	Ground	1200	25	0.0	20000.0	120.0	**144000.0**	125.0	**150000.0**	50.0	**1500000.0**	**1.81**	**1.81**	**6.69**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		

Figure 285 – Int. Alternatives Subsystem Costs–Factored AC Model#2 [Part 6 of 7]

#	Candidate Technology	Number of Units	Lifetime (Years)	Technology Maturation & Standards Cost Score		Equipment Cost Score		Deployment Cost Score		Ops. & Maintenance Cost Score		Total System Cost Score				Percentage of AC in Fleet Model Being Run in Sheet
				Maturation Cost ($K)	Standards Cost ($K)	Average Per Unit ($K)	Total ($K)	Average Per Unit ($K)	Total ($K)	Per Unit Per Year ($K)	Total ($K)	Non-Factored ($B)	Total Cost of Candidate ($B)	Percentage of Total Cost	Total Cost for Candidate ($B)	
Column	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17
18	X-Band														85.59	
	Airborne			0.0	30000.0		**26663449.2**		**6665862.3**		**52032561.9**	**85.39**	**85.39**	**99.77**		
	Air Transport	17648	25			115.0	2029520.0	28.8	507380.0	17.3	3867658.7					70%
	Business&Regional	61767	25			80.5	4972243.5	20.1	1243060.9	12.1	9475763.8					70%
	General Aviation	952463	25			11.5	10953324.5	2.9	2738331.1	1.7	22012280.8					70%
	UAV - Big	18732	25			74.8	1400217.0	18.7	350054.3	11.2	2614946.6					70%
	UAV - Small	207184	25			13.8	2859139.2	3.5	714784.8	2.1	3665914.2					70%
	Military Transport	8865	25			126.5	1121422.5	31.6	280355.6	19.0	2625982.1					70%
	Military Non-transport	18997	25			172.5	3276982.5	43.1	819245.6	25.9	7673324.3					70%
	Space Vehicles	44	25			1150.0	50600.0	287.5	12650.0	172.5	96691.5					70%
	Ground	100	25	0.0	0.0	230.0	**23000.0**	135.0	**13500.0**	65.0	**162500.0**	**0.20**	**0.20**	**0.23**		
	Satellite	0	N/A	0.0	0.0	0.0	**0.0**	0.0	**0.0**	0.0	**0.0**	**0.00**	**0.00**	**0.00**		
19	GEO + HEO SATCOM Network														70.41	
	Airborne			0.0	12000.0		**20039742.5**		**5009935.6**		**40756088.4**	**65.82**	**65.82**	**93.48**		
	Air Transport	22690	25			235.0	5332150.0	58.8	1333037.5	35.3	10161612.6					90%
	Business&Regional	35295	25			164.5	5806027.5	41.1	1451506.9	24.7	11064867.0					40%
	General Aviation	136066	25			23.5	3197551.0	5.9	799387.8	3.5	6425945.3					10%
	UAV - Big	2676	25			152.8	408759.0	38.2	102189.8	22.9	763369.5					10%
	UAV - Small	0	25			28.2	0.0	7.1	0.0	4.2	0.0					0%
	Military Transport	8865	25			258.5	2291602.5	64.6	572900.6	38.8	5366137.3					70%
	Military Non-transport	8141	25			352.5	2869702.5	88.1	717425.6	52.9	6720116.3					30%
	Space Vehicles	57	25			2350.0	133950.0	587.5	33487.5	352.5	254040.3					90%
	Ground	5	25	0.0	5000.0	4000.0	**20000.0**	11000.0	**55000.0**	3500.0	**437500.0**	**0.52**	**0.52**	**0.74**		
	Satellite	6	12.5	0.0	12000.0	170000.0	**2040000.0**	85000.0	**1020000.0**	6666.7	**1000000.0**	**4.07**	**4.07**	**5.78**		
	spare	3														

Figure 286 – Int. Alternatives Subsystem Costs–Factored AC Model#2 [Part 7 of 7]

23.4 Cost Comparisons Across a Range of Performance Characteristics

This subsection provides comparisons of the cost sensitivity for NAS communication systems across a range of performance characteristics that include bandwidth, safety, reliability /availability, and security.

23.4.1 Bandwidth

This subsection plots the bandwidth (user data rate) versus cost sensitivity for the various A-A and A-G candidates assuming Aircraft Fleet Model #1. Figure 287 contains the A-A candidates plot. Figure 288, Figure 289, and Figure 290 contain the A-G candidates plots grouped into terrestrial-based (non-cellular) candidates, cellular/DTV candidates, and SATCOM candidates, respectively.

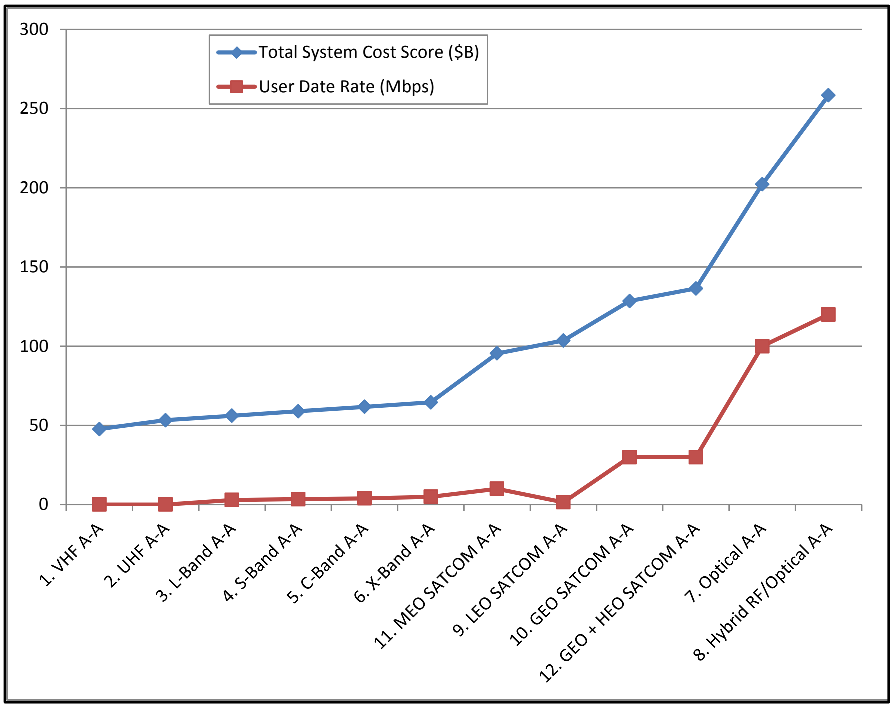


Figure 287 – A-A Candidates Cost Score vs. Bandwidth – AC Model #1

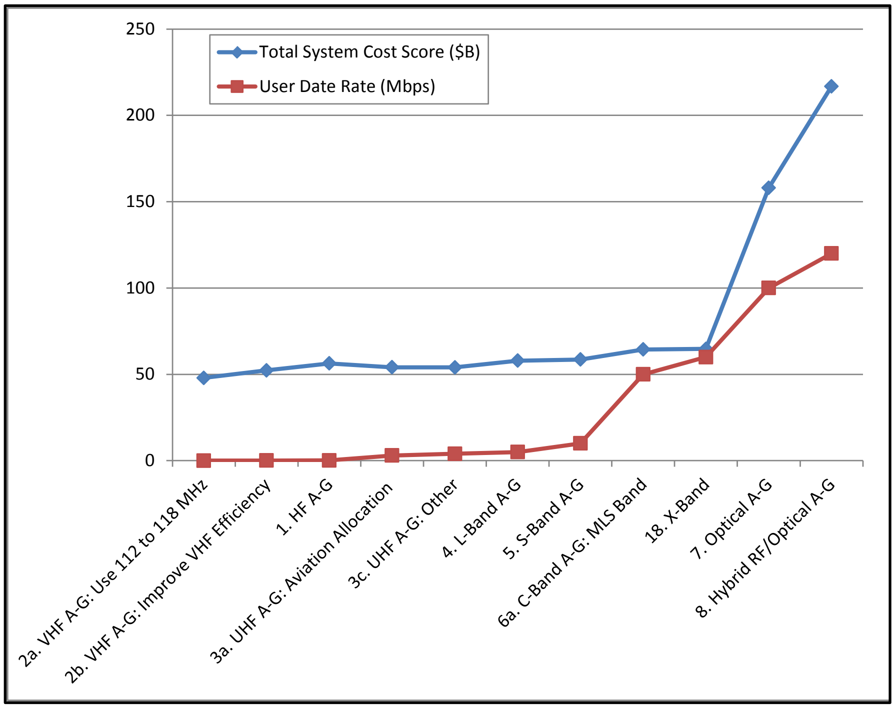


Figure 288 – A-G Candidates Cost Score vs. Bandwidth – AC Model #1

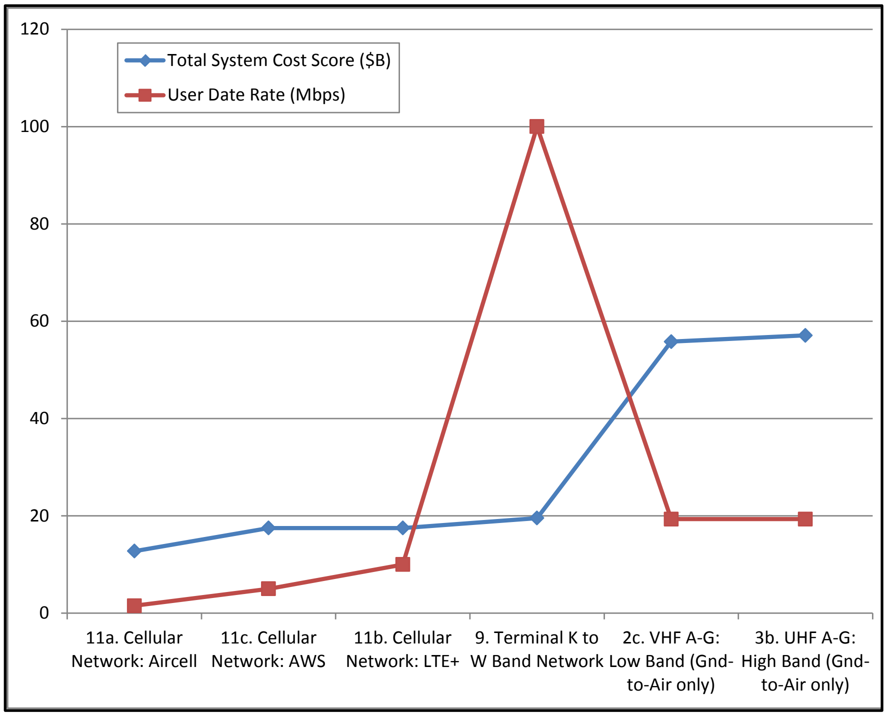


Figure 289 – A-G Cellular / DTV Candidates Cost Score vs. Bandwidth – AC Model #1

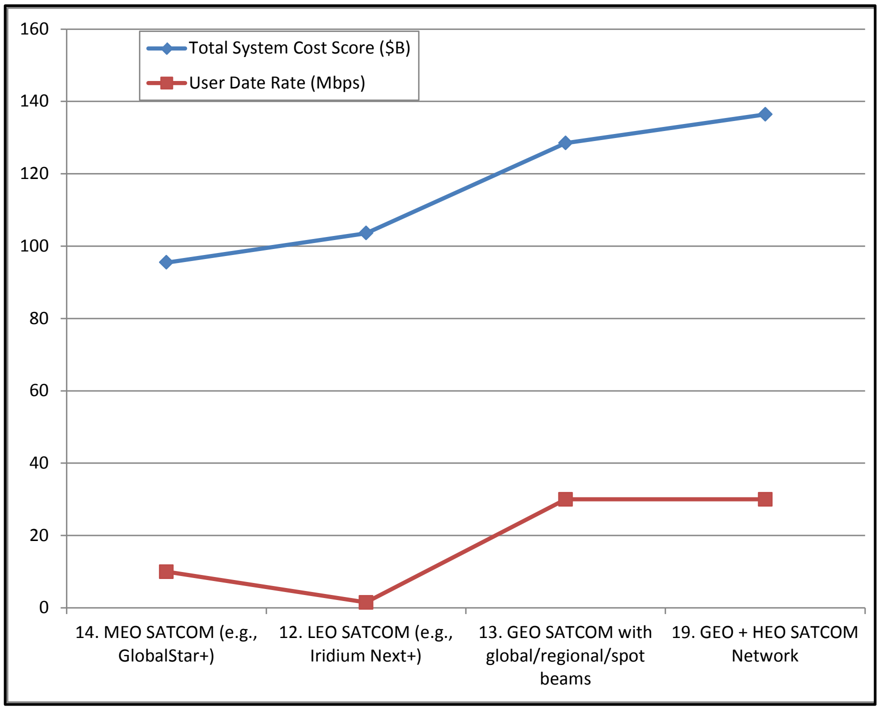


Figure 290 – A-G SATCOM Candidates Cost Score vs. Bandwidth – AC Model #1

23.4.2 Safety

The cost models herein have assumed that the safety design assurance levels associated with airborne, ground, and satellite equipment are analogous to certification/approvals done today.

Thus, for instance, it is assumed that airborne communications equipment is implemented at software (SW) and hardware (HW) design assurance level C as defined in RTCA/DO-178() and RTCA/DO-254(), respectively for SW and HW. Similarly, for most ground and satellite equipment (except as noted below), the software and hardware for the equipment is built commensurate with design assurance process specified in RTCA/DO-278() Level C. It is assumed that service history would be used to approve several of the A-G communications candidates where design processes commensurate with DO-278() Level C could not be readily established. It is envisioned that this would be the case for the DTV VHF/UHF Network and Cellular Network candidates (A-G Candidates #2c, #3b, #10, #11a, #11b, and #11c).

If the safety requirements are increased such that level B hardware and software design assurance is required, the equipment costs are estimated to grow by 15% over the Level C costs to incorporate the additional non-recurring development and certification costs. This will also impact the operations and maintenance costs as the cost for spare equipment and replacement parts will also be increased. If level A hardware and software design assurance is required, the equipment costs are estimated to grow by 20% over level C equipment. Applications such as UAS Control Non-Payload Communications (CNPC) are envisioned to require higher levels of design assurance than level C.

23.4.3 Service Reliability / Availability

The cost score for the candidates has assumed a single string avionics system (e.g., single antenna and single radio). The reliability of single string avionics equipment varies by communications candidate and by aircraft type (e.g., typically Air Transport equipment is more reliable / available per flight hour than General Aviation equipment). To meet the enhanced reliability / availability required for some applications, dual or triple redundant airborne communication equipment will be needed. Dual redundant equipment installations nominally increase the airborne costs by approximately 75% and triple redundant equipment nominally increases the airborne costs by 150%.

The satellite and ground station reliability / availability requirements were assumed to be commensurate with today's requirements, nominally 0.99999 for terrestrial communications and 0.999 to 0.99999 for oceanic/remote/polar communications. With future increased traffic density and reduced separation, it is envisioned that in some airspaces (e.g., those with very high aircraft density) or to support some specific applications for specific aircraft (e.g., UAS CNPC data link) that there will be even higher reliability / availability requirements. Increasing the availability requirements to add an additional "9" can greatly increase the cost nominally 150% to 300% or more depending upon the system(s) and assumptions. Multiple candidate technologies may be used to achieve higher levels of communications availability, rather than demanding such high levels for each candidate.

23.4.4 Security

The baseline cost model has been based upon an estimated (assumed) 25% to 30% growth in equipment costs associated with satisfying a wide range of future communications requirements, including future communications security requirements.

A small part of this cost growth was envisioned to address future communications security requirements. One particular area of concern is the large potential operational and maintenance cost impact to address security-related requirements (e.g., security-related key management / keying communications equipment). At this point in time, the future communication security requirements have not been well established to fully assess how onerous they will be to implement and operate. UAS related operations for remotely piloted vehicles may drive security requirements to be even higher than those for manned aircraft. As a first order estimate, it is envisioned that security-related requirements could increase equipment and operational & maintenance costs by 5% to 10%.

23.5 Summary Discussion of Cost Results

Section 23 has provided the results from a relative cost comparison scoring of the twelve A-A and nineteen A-G communications candidates. The relative cost scores were estimated using a 25-year communication system life cycle with two different aircraft fleet models. Note that the cost model was also run with a number of other aircraft fleet models, the results of which are not presented in this report, but nevertheless show similar relative total cost relationships among the communications candidates as that presented herein for the two aircraft fleet models.

For the A-A communications candidates, the cost assessment results indicate that the LOS communications candidates, including the VHF, UHF, L-Band, etc. alternatives, tend to be in the lowest tier of costs. The middle cost tier tends to be the SATCOM candidates, followed by the highest cost tier includes the free space optical candidates. The SATCOM candidates tend to be higher in cost than the LOS candidates, the latter of which for A-A communications do not need any ground network. The optical communication candidates have higher predicted costs associated with the avionics equipment, deployment, and operation & maintenance.

For the A-G communications candidates, the cost assessment results indicate that communications candidates that leverage commercial communication links like cellular networks potentially have the lowest relative costs, followed by the dedicated LOS A-G communication links (like VHF, UHF, etc.), followed by the SATCOM alternatives, and lastly by those candidates that utilize free space optical communications.

In addition to the relative costs associated with implementing individual communication candidates, the cost model has also been exercised to estimate the relative costs when implementing an integrated communication system across the NAS that utilizes a number of the communication candidates to meet the needs across all the flight domains. It is believed that a combination of various communication technologies will be needed to address the diverse aeronautical communications requirements, since no one single communications technology has been identified that meets all the future NAS communication requirements across all the operational flight domains. Integrations that leverage the lower cost communications candidate technologies tend to have lower cost scores than integrations that utilize the higher cost technologies.

24 PHASE 3 – INTERIM STUDY FINDINGS

The section of the report summarizes the interim study findings and provides a conclusion to the third phase of the study.

24.1 Summary of Phase 3 Interim Study Findings

1) NAS modernization architects and planners should be very conscious of the cost impact of CNS infrastructure elements including future A-A and A-G communication systems.
2) Airborne system costs are a very substantial portion of the entire system infrastructure cost for future communications systems resulting from the large number of aircraft that need equipment built, installed, operated, and maintained to broadly implement a given communications candidate.
3) It is typically cost beneficial for reducing the total system costs to increase ground and satellite system costs if it results in a reduction in airborne system costs. This is normally the case because of the large number of aircraft that need to be equipped, operated, and maintained versus the relatively small number of ground and satellite systems.
4) Future NAS communications costs can be substantially reduced by taking advantage of commercial communications networks (e.g., cellular), rather than building custom aviation-only communications networks.
5) The operational improvements enabled by various future NAS CNS systems improvements or upgrades must have their schedules aligned to when the users can expect to receive benefits or else they will be resisted because of the very substantial costs being borne by the aircraft operators.
   - An aligned schedule synchronizes the different avionics modifications programs (e.g., CNS) to reduce the number of installations, thereby minimizing aircraft out-of-service costs, and achieving synergy between related programs needed to achieve operational objectives.
   - Multiple installations are almost always more expensive than a single installation because the labor required for one larger installation is typically less expensive than the labor for two or more smaller installations and other associated costs (e.g., aircraft out of service cost for retrofit aircraft).

24.2 Interim Study Conclusion

This concludes Phase 3 of the study (presented in Sections 21 to 24 of this report) which was originally documented in the third in a series of five interim reports that were completed during the execution of this study to identify and evaluate air-to-air and air-to-ground candidates for meeting the long-term evolving needs of the National Airspace System during the modernization time horizon of 50 years. Subsequent sections of this document describe the results from phases 4 and 5 of the study.

Phase 4 of the study is documented in Sections 25 to 28. These sections: a) identify, describe, and prioritize a set of long-term ATM applications including identifying which applications could be supported by the communications candidates, and b) provide use case analyses for three of the highest priority applications including Delegated Interval / Interval Management, Delegated Separations, and Airborne Self-Separation.

Phase 5 of the study is documented in Sections 29 to 32. These sections identify criteria for prioritizing the communication candidates and describe the use of the criteria to prioritize the candidates from most promising to least promising.

25 DESCRIPTION AND PRIORITIZATION OF ATM APPLICATIONS

This section of the report describes a broad range of communications-enabled ATM applications that may potentially be utilized in NextGen and beyond National Airspace System.

The ATM applications and their descriptions were identified based upon work completed in the aviation industry by RTCA, EUROCAE, NASA, JPDO, FAA, the ADS-B IN Aviation Rulemaking Committee (ARC), and a wide range of other organizations and companies.

The process for prioritization of the ATM applications leveraged the process that has been developed by the RTCA NextGen Advisory Committee (NAC) that they used for prioritizing near-term NextGen ATM applications. This section of the report first begins with an overview of the application prioritization process and results from the NAC's prioritization of near-term NextGen ATM applications, and then describes and prioritizes a set of longer-term NextGen and beyond communications enabled applications.

This section includes two major subsections including:

- Near-term prioritization of NextGen comm-enabled ATM applications by the NextGen Advisory Committee (NAC) (Section 25.1)
- Long-term prioritization of NextGen and beyond comm-enabled ATM applications (Section 25.2)

25.1 Near-Term Prioritization of NextGen Comm-Enabled ATM Applications

A summary of the ATM applications prioritization process developed by the RTCA NextGen Advisory Committee (NAC) and results from their prioritization of a set of near-term applications is provided in this section. This summarizes the work of the NAC as documented in the "*NextGen Prioritization Report"* that was developed by the RTCA NextGen Advisory Committee (September 2013).

As stated in the NAC report, "tough times call for tough choices." Because resources are always limited, it is always good business practice to drive investment decisions based on priorities. Unlike many of the previous air traffic management modernization programs, NextGen and beyond ATM applications typically will require significant investment not only on the part of the government, but also by those who operate in the airspace system. The investment required by operators to enable many of the future applications typically includes standardization activities, aircraft equipment (e.g., CNS equipment and human-machine interfaces, like displays and controls), aircraft equipment installation and maintenance, and flight crew training, and may require changes to AOC ground systems.

The NAC claimed that their prioritization process was analytic, transparent, repeatable, and defensible. Their approach entailed: 1) defining a set of guiding principles (see Section 25.1.1), 2) defining a set of evaluation criteria and weightings (see Section 25.1.2), 3) identifying a list of potential NextGen applications/capabilities (Section 25.1.3), and 4) evaluating each of the various applications/capabilities using the defined guiding principles for evaluation, criteria, and weightings (see Section 25.1.4). A summary of their report is provided in the following subsections.

25.1.1 NAC Prioritization Guiding Principles

The following guiding principles were identified by the RTCA NAC for prioritizing ATM applications/capabilities *[reference: NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013]*.

The guiding principles (paraphrased by the authors of this report) include:

- Delivering tangible/measurable benefits is crucial to encouraging the investments needed to enable a future ATM application/capability.
- Applications should enhance safety.
- It is better to fund future ATM applications/capabilities at a level required to deliver benefits and drive to 100% completion of a single capability than to cut x% from everything and/or delay everything.
- Application funding must include all necessary resources including equipment, personnel, procedures, training, etc.
- The highest priority initiatives need to have all the necessary resources allocated for success, and include participation of the key stakeholders, especially air traffic controllers.
- Those ATM applications/capabilities with a validated operational concept and a positive business case that are in a critical stage of implementation should be considered for continued investment.
- Timing matters – Operator’s business case for investment in applications/ capabilities are predicated on commitment on the part of the FAA to deliver capabilities by defined dates.
- Right size the investments – deploy the applications/capabilities at locations where measurable benefits can be achieved.
- It is important to have “scalability” of capabilities across the NAS.
- Metrics is an overarching issue. It is critical to define goals, establish baseline measures of performance, and track and report progress on the metrics in a public forum.

25.1.2 NAC Prioritization Criteria and Weightings

To ensure a transparent and defensible outcome, the NAC reached consensus on the following prioritization criteria and weightings, including the associated criteria definitions and rating scales.

1) Monetizable Benefits [46.2%]
2) Non-Monetizable Benefits [12.8%]
3) Implementation Readiness (including risk mitigation) [28.3%]
4) “Other Considerations” (i.e., enhance global harmonization, increase confidence, critical infrastructure element of NextGen) [12.7%]

These criteria are defined with rating scales in the subsections below.

25.1.2.1 NAC Benefits (Monetizable)

Monetizable benefits are those that can readily be estimated to have a monetary (or cash) value. Monetizable benefits were assessed by the NAC using the sub criteria of capacity, efficiency, ATC system productivity, and environmental impact. The benefits ratings scale ranged from "showstopper" (a very poor rating whereby the monetizable "benefits" are negative) to "very high" as indicated in Figure 218 (page 411).

25.1.2.2 NAC Benefits (Non-Monetizable)

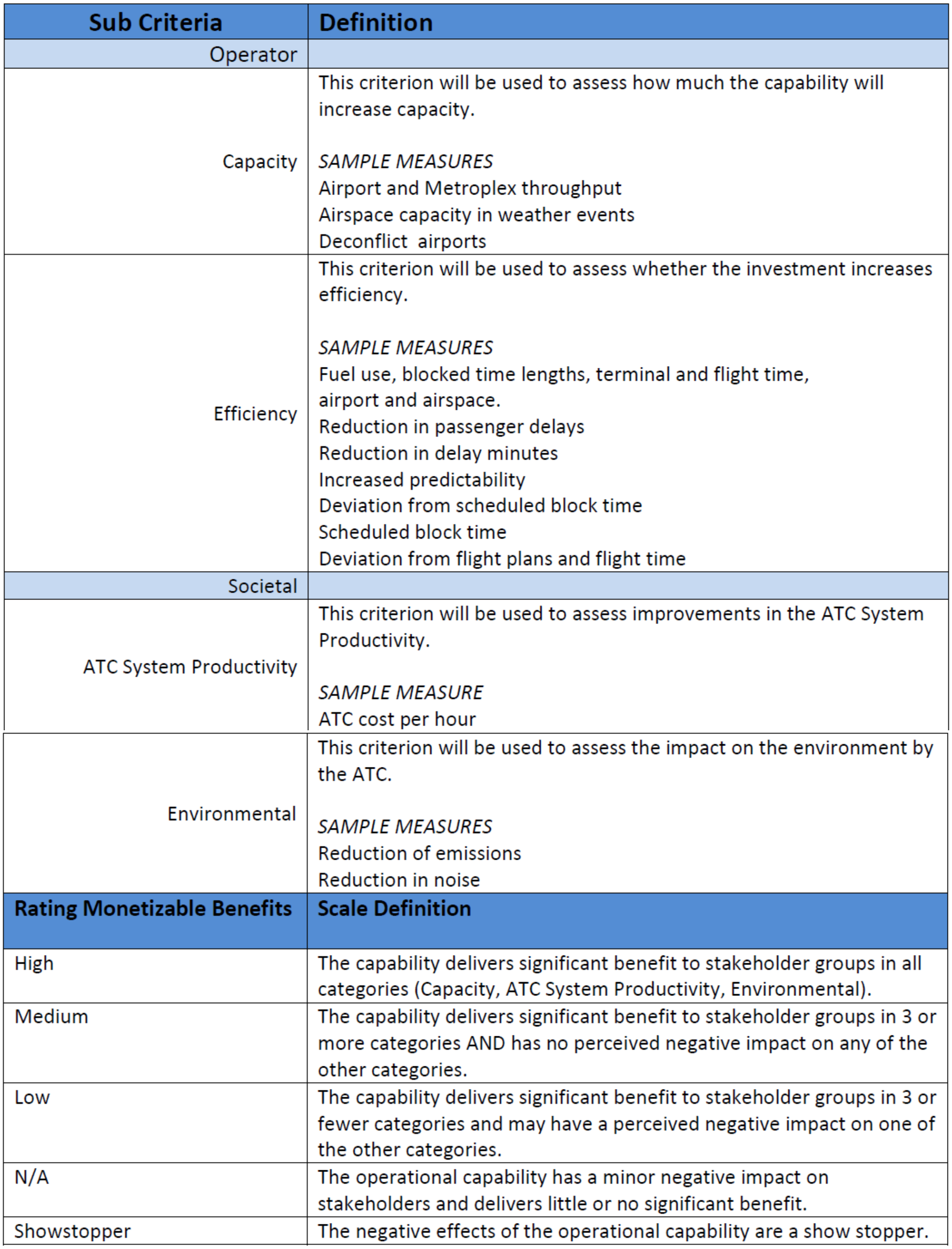
Non-monetizable benefits are those that are difficult to estimate the monetary (or cash) value. Non-monetizable benefits were assessed by the NAC according to the sub criteria of access, flexibility, safety, and security. The non-monetizable benefits ratings scale ranged from "very low" to "very high" as indicated in Figure 292 (page 412).

25.1.2.3 NAC Implementation Readiness

Implementation readiness is an assessment of whether the needed elements are in place to achieve a given operational capability. The implementation readiness was assessed by the NAC according to the sub criteria of standards and approvals, policy/concept of operations, systems, institutional, roles & operational complexity, community perceived noise and emission impact, and time to completion. The implementation readiness ratings scale ranged from "very low" to "very high" as indicated in Figure 293 (page 413).

25.1.2.4 NAC "Other Considerations" Prioritization Criterion

The "other considerations" prioritization criterion established by the NAC included assessment of the global harmonization, confidence building, and foundational critical infrastructure. Further definition and the rating scale for "other considerations" is provided in Figure 294 (page 414).

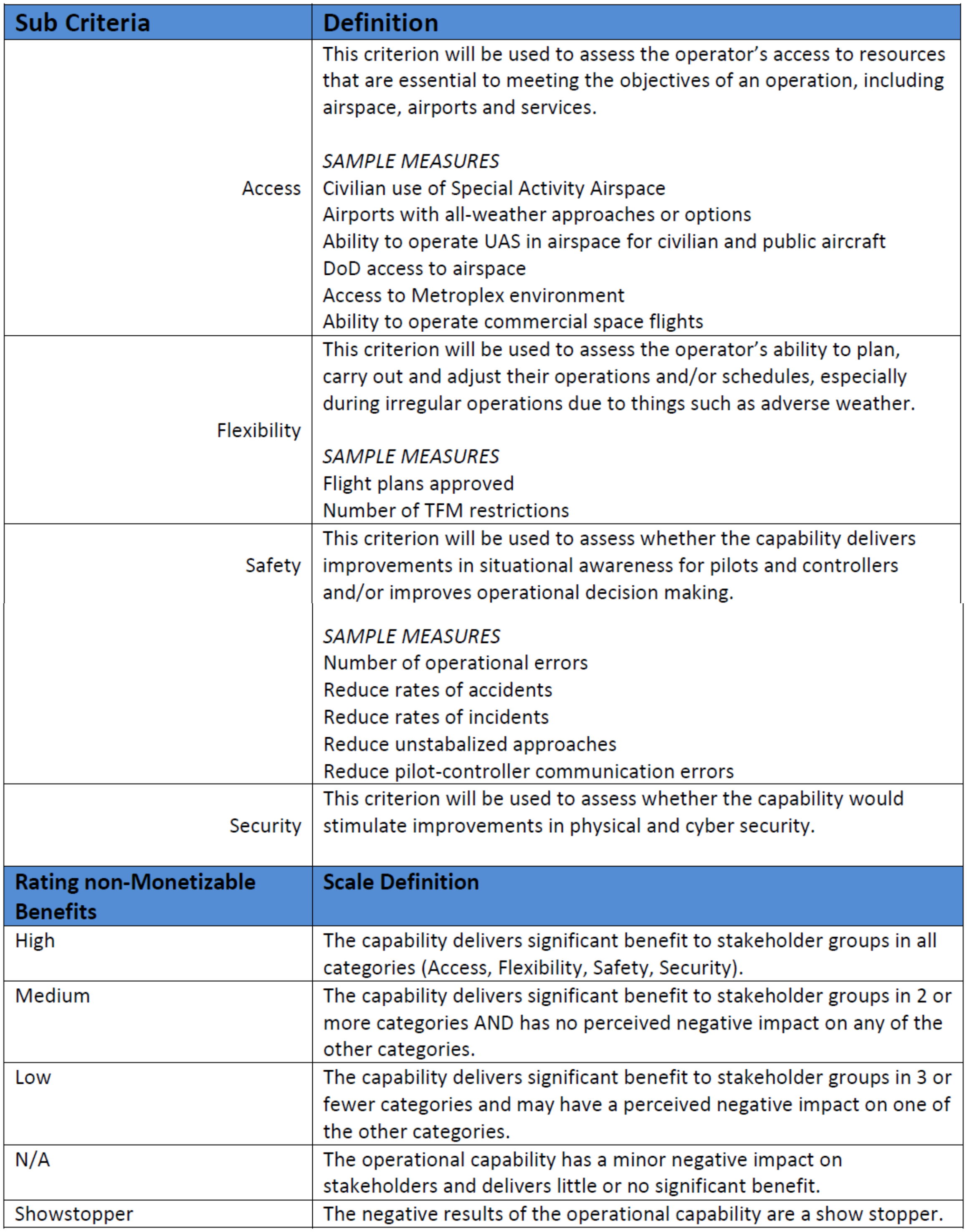


Sub Criteria	Definition
Operator	
Capacity	This criterion will be used to assess how much the capability will increase capacity. *SAMPLE MEASURES* Airport and Metroplex throughput Airspace capacity in weather events Deconflict airports
Efficiency	This criterion will be used to assess whether the investment increases efficiency. *SAMPLE MEASURES* Fuel use, blocked time lengths, terminal and flight time, airport and airspace. Reduction in passenger delays Reduction in delay minutes Increased predictability Deviation from scheduled block time Scheduled block time Deviation from flight plans and flight time
Societal	
ATC System Productivity	This criterion will be used to assess improvements in the ATC System Productivity. *SAMPLE MEASURE* ATC cost per hour
Environmental	This criterion will be used to assess the impact on the environment by the ATC. *SAMPLE MEASURES* Reduction of emissions Reduction in noise

Rating Monetizable Benefits	Scale Definition
High	The capability delivers significant benefit to stakeholder groups in all categories (Capacity, ATC System Productivity, Environmental).
Medium	The capability delivers significant benefit to stakeholder groups in 3 or more categories AND has no perceived negative impact on any of the other categories.
Low	The capability delivers significant benefit to stakeholder groups in 3 or fewer categories and may have a perceived negative impact on one of the other categories.
N/A	The operational capability has a minor negative impact on stakeholders and delivers little or no significant benefit.
Showstopper	The negative effects of the operational capability are a show stopper.

Figure 291 – NAC Monetizable Benefits Definition and Rating Scale

[Reference: NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013.]

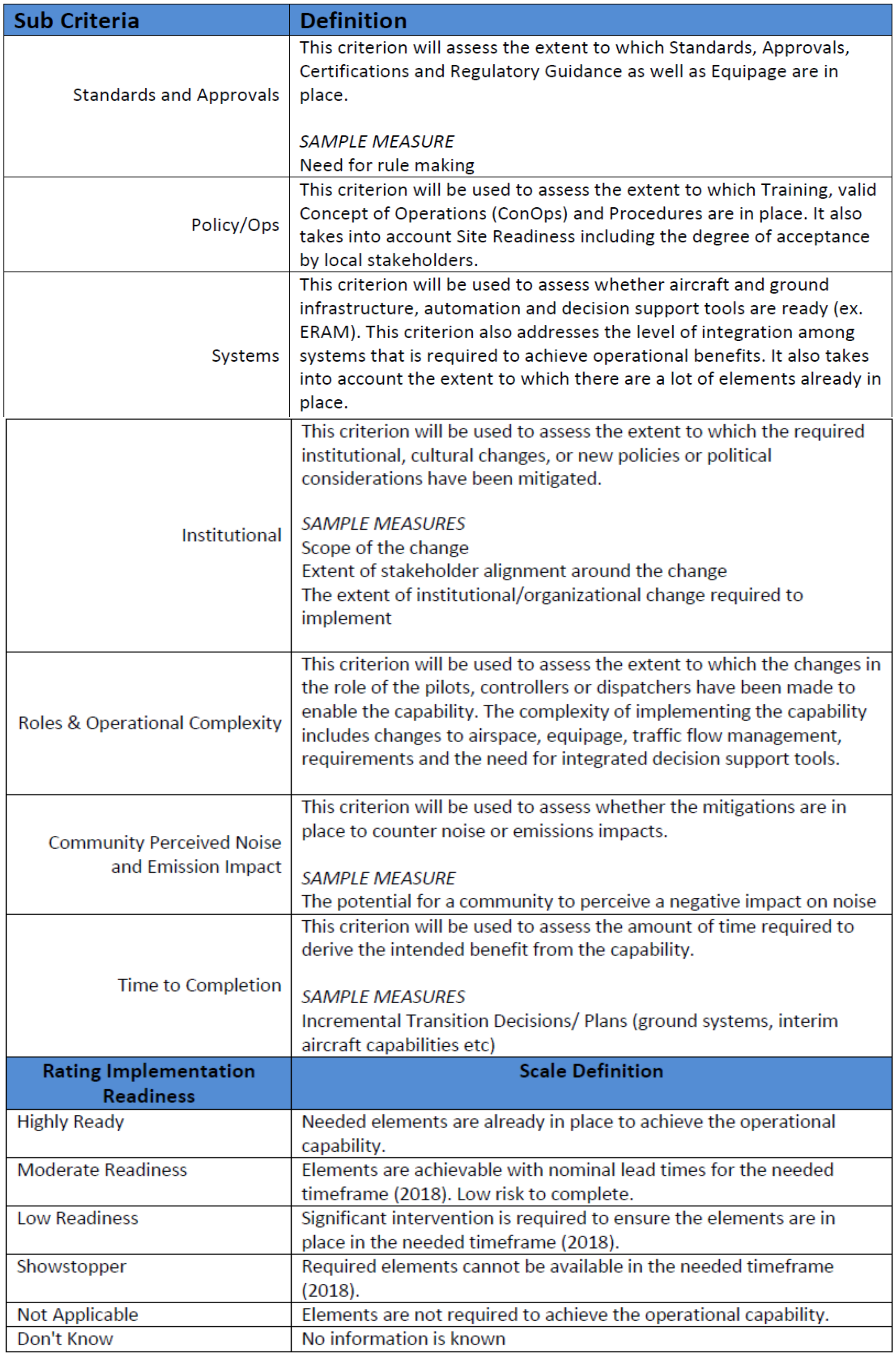


Sub Criteria	Definition
Access	This criterion will be used to assess the operator's access to resources that are essential to meeting the objectives of an operation, including airspace, airports and services. *SAMPLE MEASURES* Civilian use of Special Activity Airspace Airports with all-weather approaches or options Ability to operate UAS in airspace for civilian and public aircraft DoD access to airspace Access to Metroplex environment Ability to operate commercial space flights
Flexibility	This criterion will be used to assess the operator's ability to plan, carry out and adjust their operations and/or schedules, especially during irregular operations due to things such as adverse weather. *SAMPLE MEASURES* Flight plans approved Number of TFM restrictions
Safety	This criterion will be used to assess whether the capability delivers improvements in situational awareness for pilots and controllers and/or improves operational decision making. *SAMPLE MEASURES* Number of operational errors Reduce rates of accidents Reduce rates of incidents Reduce unstabalized approaches Reduce pilot-controller communication errors
Security	This criterion will be used to assess whether the capability would stimulate improvements in physical and cyber security.

Rating non-Monetizable Benefits	Scale Definition
High	The capability delivers significant benefit to stakeholder groups in all categories (Access, Flexibility, Safety, Security).
Medium	The capability delivers significant benefit to stakeholder groups in 2 or more categories AND has no perceived negative impact on any of the other categories.
Low	The capability delivers significant benefit to stakeholder groups in 3 or fewer categories and may have a perceived negative impact on one of the other categories.
N/A	The operational capability has a minor negative impact on stakeholders and delivers little or no significant benefit.
Showstopper	The negative results of the operational capability are a show stopper.

Figure 292 – NAC Non-monetizable Benefits Definition and Rating Scale

[Reference: NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013.]



Sub Criteria	Definition
Standards and Approvals	This criterion will assess the extent to which Standards, Approvals, Certifications and Regulatory Guidance as well as Equipage are in place. *SAMPLE MEASURE* Need for rule making
Policy/Ops	This criterion will be used to assess the extent to which Training, valid Concept of Operations (ConOps) and Procedures are in place. It also takes into account Site Readiness including the degree of acceptance by local stakeholders.
Systems	This criterion will be used to assess whether aircraft and ground infrastructure, automation and decision support tools are ready (ex. ERAM). This criterion also addresses the level of integration among systems that is required to achieve operational benefits. It also takes into account the extent to which there are a lot of elements already in place.
Institutional	This criterion will be used to assess the extent to which the required institutional, cultural changes, or new policies or political considerations have been mitigated. *SAMPLE MEASURES* Scope of the change Extent of stakeholder alignment around the change The extent of institutional/organizational change required to implement
Roles & Operational Complexity	This criterion will be used to assess the extent to which the changes in the role of the pilots, controllers or dispatchers have been made to enable the capability. The complexity of implementing the capability includes changes to airspace, equipage, traffic flow management, requirements and the need for integrated decision support tools.
Community Perceived Noise and Emission Impact	This criterion will be used to assess whether the mitigations are in place to counter noise or emissions impacts. *SAMPLE MEASURE* The potential for a community to perceive a negative impact on noise
Time to Completion	This criterion will be used to assess the amount of time required to derive the intended benefit from the capability. *SAMPLE MEASURES* Incremental Transition Decisions/ Plans (ground systems, interim aircraft capabilities etc)

Rating Implementation Readiness	Scale Definition
Highly Ready	Needed elements are already in place to achieve the operational capability.
Moderate Readiness	Elements are achievable with nominal lead times for the needed timeframe (2018). Low risk to complete.
Low Readiness	Significant intervention is required to ensure the elements are in place in the needed timeframe (2018).
Showstopper	Required elements cannot be available in the needed timeframe (2018).
Not Applicable	Elements are not required to achieve the operational capability.
Don't Know	No information is known

Figure 293 – NAC Implementation Readiness Definition and Rating Scale

[Reference: NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013.]

Sub Criteria	Definition
Global Harmonization	This criterion will be used to assess whether the capability will enhance global harmonization. It will also take into account the degree of interoperability of procedures needed.
Rating Global Harmonization	**Scale Definition**
High Impact	It is a capability called out in an ICAO Aviation System Block Upgrade (ASBU) and helps maintain US leadership in aviation.
No Impact	The capability does not require harmonization.
Negative Impact	Implementation of this capability would be contradictory to the direction of the rest of the global aviation community.
Confidence Building	This criterion will be used to assess whether the capability increases the aviation stakeholders' confidence in industry and FAA's ability to deliver on commitments (early delivery of benefits) leading to higher probability of positive business case for equipage.
Rating Confidence Building	**Scale Definition**
Strong Positive Impact	Will greatly increase likelihood of a positive return on investment related to this or subsequent related capabilities.
Moderate Positive Impact	Will modestly increase likelihood of a positive return on investment related to this or subsequent related capabilities.
Minimal Positive Impact	Will only minimally increase likelihood of a positive return on investment related to this or subsequent related capabilities.
Neutral / No Impact	Will not increase likelihood of a positive return on investment related to this or subsequent related capabilities.
Negative Impact	Will be perceived as having a negative return on investment related to this or subsequent related capabilities.
Foundational Critical Infrastructure	This criterion will be used to assess the degree to which this capability provides a foundational critical infrastructure component of NextGen or is required to be compliant with mandates.
Rating Foundational Critical Infrastructure	**Scale Definition**
Essential	To future benefits-yielding NextGen capabilities or to cost-cutting measures.
Very Important	To future benefits-yielding capabilities or to cost-cutting measures.
Moderately Important	To future benefits-yielding capabilities or to cost-cutting measures.
Marginally Important	To future benefits-yielding capabilities or to cost-cutting measures.
No Impact on NextGen	Or considered not essential to ability to deliver NextGen benefits at reasonable cost or to cost cutting measures.

Figure 294 – NAC "Other Considerations" Definition and Rating Scale

[Reference: NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013.]

25.1.3 NAC Identified NextGen Applications/Capabilities

Working with the FAA, the NAC identified a large number of NextGen-related initiatives as possible applications/capabilities to prioritize. The list was scrutinized and reduced by the NAC into a shorter consolidated list of capabilities as provided in Figure 201. This consolidated list was developed starting from a much longer list of NextGen Operational Improvements (OIs) documented in a number of FAA documents. The consolidation was carried out to enable the following outcomes: 1) to produce a more manageable number of capabilities to prioritize, 2) to ensure meaningful recommendations at an appropriate level of fidelity, and 3) to produce a prioritized list that can more easily be utilized and incorporated back into the FAA planning processes.

Figure 295 – NAC Consolidated List of Nearer-Term Applications

Capability Portfolio	#	Consolidated Application / Capability	Description
Surface Operations	1	Data sharing	Share data on the movement of traffic on the surface.
	2	Situational Awareness – ADS-B / ADS-R / TIS-B	Display surface traffic on ATC and aircraft displays.
	3	Revised Pre-Departure Clearance (PDC) via DataComm	Deliver revised PDC to pilot pre-flight via DataComm.
Surface / Terminal Ops.	4	Surface/Terminal Alerting (ADS-B IN)	Automated Terminal Proximity Alert (ATPA) provides situational awareness and alerts to controllers. ADS-B IN Traffic Situational Awareness on the Airport Surface.
Low Visibility Approaches, Landing, and Takeoff	5	GNSS Landing System (GLS) I	GLS I – precision approaches
	6	GLS II/III	GLS II-III – precision approaches
	7	Enhanced Flight Vision System (EFVS)	Enable use of enhanced flight vision systems to conduct approach and landing in low visibility conditions.
	8	Advanced EFVS	Use of EFVS for lower than standard approach minima operations and takeoff.
Multiple Runway Ops.	9	Separation standards reduced (CSPO)	Reduced lateral separation for runways closer than 4300 feet and 2500 feet. SATNAV or ILS for parallel runway operations.
PBN	10	Optimization of Airspace and Procedures in the Metroplex (OAPM)	Expedite the optimization of airspace and procedures in the metroplex areas to improve air traffic flow for the entire region. 21 metroplex geographic areas have been identified that have multiple airports in close proximity serving large metropolitan areas. The optimization considers a number of factors including safety, efficiency, capacity, access, and environment impact.
	11	Performance Based Navigation (PBN)	Large scale airspace redesign to optimize airspace for PBN (e.g., RNAV and RNP).
	12	Advanced PBN	Dynamic PBN procedures / Advanced RNP.
Time-Based Flow Management (TBFM)	13	Metering/Merging/Spacing (Enroute and Terminal) (Ground-based)	Ground automation-based time-based metering, merging, and spacing
	14	Interval Management (IM) (ADS-B)	IM in cruise phase of flight Terminal IM, single stream of aircraft
	15	Advanced Flight deck Interval Management (FIM)	Terminal IM for multiple streams of aircraft

Capability Portfolio	#	Consolidated Application / Capability	Description
Collaborative ATM	16	Flight Planning Feedback	Ability for operators to get feedback on NAS constraints during fight planning Collaborative trajectory/flight planning
	17	Airborne Rerouting - TFM	Traffic Manager ability to propose reroutes and amend for weather or other constraints
	18	Modeling, improved predictions	Enhanced modeling for better demand/capacity balance
	19	Collaborative Decision Making	Collaborative arrival, departure, and enroute planning
Separation Management	20	Separation Services (reduced separation) (ADS-B Out)	Expanded use of 3-NM separation standards Reduce aircraft separation standards Increased access to low altitude, non-radar airspace
	21	Terminal Controller Proximity Alerting	Alerts controllers when compression between subsequent aircraft is likely to result in unsafe separation
	22	In Trail Procedures (ITP) (ADS-B)	Enable aircraft equipped with ADS-B and appropriate on-board automation to climb and descend through altitudes where current non-ADS-B separation standards would prevent desired altitude changes
	23	Oceanic DataComm (ATN Services)	Extend Data Communications services beyond satellite and FANS 1/A to aircraft having the ATN baseline 1 application package
	24	Advanced ATOP Applications	Numerous enhancement to the Advanced Technologies & Oceanic Procedures (ATOP) system
	25	Enhanced Conflict Detection	Enhanced conflict probe for enroute controller (A/C to A/C and A/C to airspace)
	26	CPDLC, Weather Reroute (DataComm, FANS 1/A)	Basic CPDLC and reroutes around weather for DataComm-equipped aircraft (FAN 1/A, VDL 2)
	27	DataComm ATN B2 Services	DataComm ATN B2 services (CPDLC, 4DT, FIS)
	28	New DataComm Applications	New DataComm Applications with ATN B2 (Advanced PBN, Advanced FIM, ATC Winds)
	29	Enroute PBN	Automation to reduce conformance bounds used in conflict detection algorithms for AC with RNAV/RNP based on performance criteria adapted for the route and AC capabilities, allowing the system to take advantage of reduced separation while maintaining safe operations
	30	Wake Re-Categorization & Wake Separation	Improve throughput at capacity constrained airports while maintaining or improving wake safety. Revise separation based on wake information.
	31	Oceanic User Requests	Enable aircraft to stay closer to preferred route.
On-Demand NAS Info	32	NAS information to stakeholders (Near-Term)	Provide information to stakeholders on status of NAS resources.
	33	NAS information to stakeholders (Far-Term)	Provide more sophisticated and more real-time NAS status information.
Weather	34	Common Weather Info Database	Access to common aviation weather picture, using global and open standards
Core Infrastructure	35	SWIM Ground	Provides policies and standards to support NAS data management with integrity and controlled access & use.
	36	SWIM Air	Airborne Access to SWIM (AAtS) enables in-flight AC access to information available through SWIM. AAtS extends these capabilities to the cockpit through third party vendors, providing Internet access on the flight deck, for example, on an Electronic Flight Bag (EFB).

[Reference: NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013.]

25.1.4 NAC Near-Term Application/Capability Prioritization Rankings Summary

The NAC evaluated the NextGen applications/capabilities using the criteria and weightings as described in the subsections above. This evaluation led to prioritizing the applications into 4 Tiers as presented in Figure 296 and Figure 297 (on pages 418 and 419), with the tiers ranked in order of priority with Tier 1 being the highest priority and Tier 4 being the lowest priority. *Note that the RTCA NextGen Prioritization Report actually rated the applications into 4 tiers, named as: 1) Tier 1a, 2) Tier 1b, 3) Tier 2, and 4) other. For clarity, this document has simply numbered these as Tier 1 to 4, respectively, with an exact one-to-one mapping.*

The first tier (Tier 1) prioritization included applications/capabilities that were deemed to be of high benefit and high readiness for implementation such that airspace users could start receiving benefits as soon as possible.

The second tier (Tier 2) included applications that were deemed to be of high benefit and low or medium readiness for implementation. The NAC recommended that Tier 1 and Tier 2 capabilities should be allocated full resources to get these capabilities in the ATM system.

Tier 3 capabilities were those deemed to be of medium benefit and high readiness. These capabilities should remain on track budget permitting, but if prioritization needed to be made, these capabilities could be delayed.

Tier 4 capabilities were deemed to be prioritized below Tiers 1, 2, and 3 because of lower relative scores in at least one of either the benefits and/or readiness for implementation.

A scatter diagram is provided in Figure 298 (page 420) that illustrates the results of the scoring for each of the applications, as a function of the two highest weighted evaluation criteria. The monetizable benefits score was plotted on the x-axis and implementation readiness score was plotted on the y-axis. Demarcation lines on this plot illustrate the quantifiable breakpoints between the four tiers, with a single exception that capability #10 (PBN-OAPM) falls outside the demarcation lines drawn for Tier 1. The NAC prioritized the PBN-OAPM capability was grouped in Tier 1 rather than Tier 2 or 3 because of its very high implementation readiness score.

It should be further noted that the NAC NextGen application/capability prioritization presented in this section based upon the published RTCA NextGen Prioritization Report is very similar to the RTCA NextGen Task Force 5 recommendations *[reference: NextGen Mid-Term Implementation Task Force Report, RTCA, September 9, 2009]*.

Rank	Capability / Application Name	#	Score	Ranking Criteria
Tier 1	PBN	11	0.815	Capabilities that are deemed to be high benefit and high readiness. These should be considered highest priority, and be given full resources to achieve or IOC dates or accelerate those dates. Budget cuts should not affect these capabilities. It is important to note that several of these are interdependent and lead to service improvements. For example, PBN will not achieve the projected benefit in congested terminal airspace without the merging and spacing tools or CSPO work being completed.
	Multiple Runway Operations – Separation standards reduced (CSPO)	9	0.749	
	Surface Ops - Data Sharing	1	0.711	
	TBFM - Metering/ Merging/ Spacing (Enroute and Terminal) (Ground-based)	13	0.706	
	Separation Management - Wake Re-Categorization & Wake Separation	30	0.673	
	PBN - OAPM	10	0.648	
Tier 2	CATM - Flight Planning Feedback	16	0.633	Capabilities that are deemed to be high benefit and low or medium readiness. These capabilities should also be given full resources to achieve or IOC dates or accelerate those date. In the case of Tier 2, attention should be given to address and resolve all technical and non-technical issues, and the capabilities should be accelerated if possible. Budget cuts should not affect these capabilities.
	CATM - CDM	19	0.626	
	Separation Management (reduced separation) (ADS-B Out)	20	0.633	
	Separation Management - CPDLC, Weather Reroute (DataComm, FANS 1/A)	26	0.628	
	Separation Management - Enroute PBN	29	0.608	
Tier 3	Surface/Ops - Revised PDC via DataComm	3	0.621	Capabilities that are deemed to be of medium benefit and high readiness. These capabilities should remain on track budget permitting, but if budget cuts dictate, they could be delayed. To be considered for the Tier 3 list (consensus on things that should continue, resources permitting), an initiative must have scored relatively high, but below the cutoff point defined by the NextGen Advisory Committee.
	CATM - Airborne Rerouting - TFM	17	0.600	
	Separation Management - Terminal Controller Proximity Alerting	21	0.601	
	Separation Management - In Trail Procedures (ITP) (ADS-B)	22	0.597	
	Separation Management - Enhanced Conflict Detection	25	0.561	
	Separation Management - Oceanic User Requests	31	0.562	
	On Demand NAS Info- Near Term	32	0.628	
	Core Infrastructure - SWIM Ground Based	35	0.618	

Figure 296 – NAC Prioritized List of Near-Term Apps. Tiers & Scores (Part 1 of 2)

[Reference: Results based upon NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013. See Figure 201 *for a description of the applications.]*

Rank	Capability / Application Name	#	Score	Ranking Criteria
Tier 4	Surface Ops - Situational Awareness ADS-B	2	0.512	All other capabilities that were not prioritized as Tier 1, Tier 2, or Tier 3.
	Surface/Terminal - Surface/Terminal Alerting (ADS-B IN)	4	0.439	
	Low Vis Approaches - GLS I	5	0.571	
	Low Vis Approaches - GLS II and III	6	0.510	
	Low Vis Approaches - EFVS	7	0.495	
	Low Vis Approaches - Advanced EFVS	8	0.457	
	PBN - Advanced PBN	12	0.478	
	TBFM - Interval Management (IM) (ADS-B)	14	0.530	
	TBFM - Advanced Flight Deck Interval Management (FIM)	15	0.517	
	CATM - Modeling, improved predictions	18	0.503	
	Separation Management - Oceanic DataComm (ATN Services)	23	0.489	
	Separation Management - Advanced ATOP	24	0.510	
	Separation Management - DataComm ATN B2 Services	27	0.534	
	Separation Management - New DataComm Applications	28	0.503	
	On Demand NAS Info - Far Term	33	0.543	
	Weather - Common Weather Info DB	34	0.551	
	Core Infrastructure - SWIM Airborne Based	36	0.496	

Figure 297 – NAC Prioritized List of Nearer-Term Apps. Tiers & Scores (Part 2 of 2)

[Reference: Results based upon NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013. See Figure 201 *for a description of the applications.]*

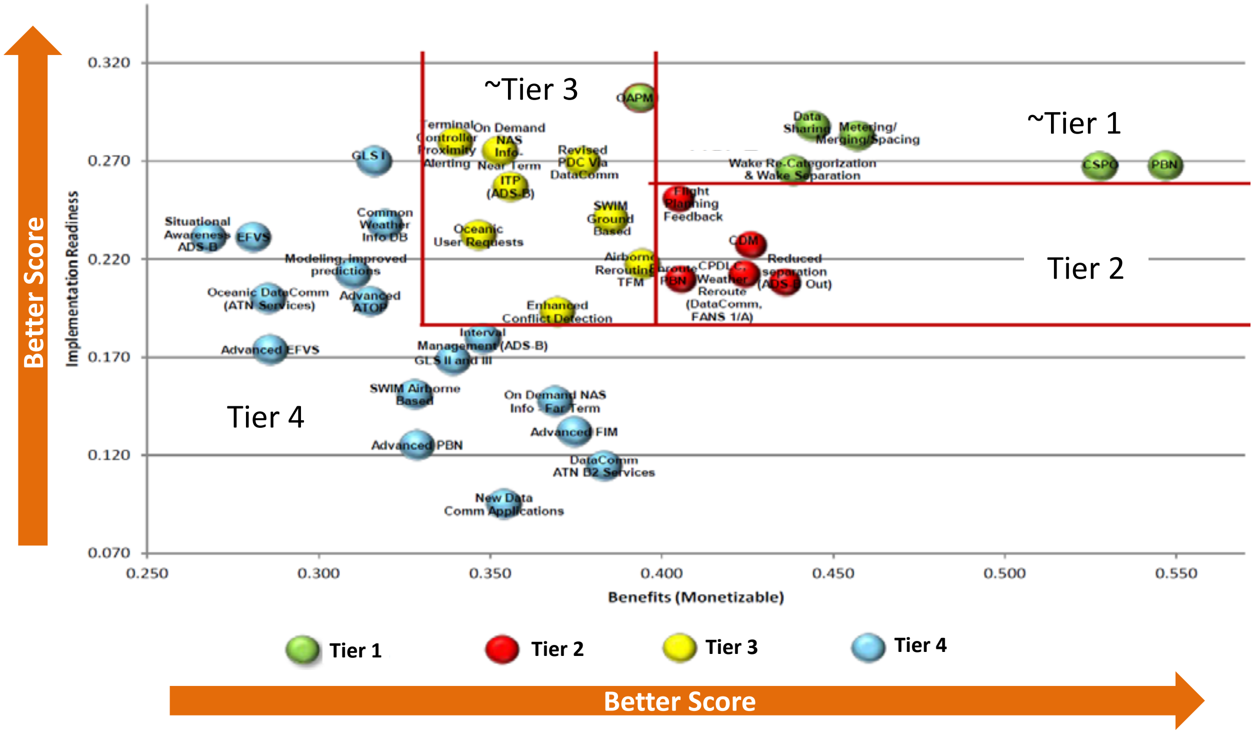


Figure 298 – NAC Scatter Plot of Applications Priority Scorings and Tiers

[Reference: Diagram with modifications from the NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013. See Figure 201 *for a description of the applications.]*

25.2 Long-Term Prioritization of NextGen Comm-Enabled ATM Applications

Over 50 NextGen and beyond long-term applications or capabilities have been identified, prioritized, and analyzed as part of the process to assess the ability of the various A-A and A-G communication candidates to support a wide range of possible future ATM operational needs. The subsections below provide a description of each application and provide a relative prioritization of these applications.

25.2.1 Application Descriptions

Figure 299 lists and describes 52 NextGen and beyond long-term ATM applications or capabilities that are enabled by A-A and/or A-G communications. This list of applications was partitioned into eight groupings, including: 1) Surface Operations, 2) Surface / Terminal Area Operations, 3) Time Based Flow Management (TBFM), 4) Collaborative Air Traffic Management (CATM), 5) Separation, 6) Performance-Based Navigation (PBN), 7) Weather and NAS Flight Information Services, and 8) Other Applications / Multiple Flight Phases.

Figure 299 – List of NAS Long-Term ATM Applications / Capabilities

Application Grouping	#	Application / Capability	Description
Surface Operations	1	Data sharing	Share data on the movement of traffic on the surface.
	2	Surface Situational Awareness – ADS-B / ADS-R / TIS-B	Display surface traffic on aircraft and ATC displays. *(The on-aircraft SURF application is described in RTCA DO-322 and the on-ground ATC ADS-B airport surface situational awareness application is described in RTCA DO-321.)*
	3	Revised PDC via DataComm	Deliver revised pre-departure clearance (PDC) to pilot pre-flight via DataComm.
	4	Improved Efficiency of Taxiing Operations	During periods of high traffic density and poor visibility, the on-ground surface traffic management and on-aircraft capabilities will allow for highly efficient taxi operations in all conditions, including very low visibility operations. Systems will use ADS-B surveillance, high accurate/high integrity aircraft/surface vehicle positioning systems (e.g., differential GNSS) and airport databases, ATC / Flight Crew / Vehicle Operator displays, and automation.
Surface / Terminal Area Ops.	5	Ground-based Runway and/or Taxiway Alerting	Automated surface and terminal proximity alerting provides situational awareness and alerts to controllers (and potentially also directly to pilots) for potential incursions.
	6	Simultaneous Runway Operations	Application that enables two or more aircraft to simultaneously be conducting operations on the runway (e.g., one aircraft completing the rollout from landing, and a second aircraft beginning the takeoff roll).
	7	Closely Spaced Parallel Runway Operations (CSPO)	On aircraft ADS-B-enabled application that enables independent (or only dependent in some cases) takeoff and landing operations in all weather conditions with runways in close lateral proximity.
	8	Converging and Intersecting Runway Operations	Application at ATC controlled airports that optimize takeoff and landing operations in all weather conditions with converging and intersecting runways.
	9	Aircraft based Surface/Terminal Area Situational Awareness with Indications & Alerts (SURF IA)	On aircraft ADS-B IN Traffic Situational Awareness with Indications and Alerts (SURF IA as described in RTCA DO-323) on the airport surface.
	10	Optimized Profile Descent (OPD) / Continuous Descent Approach (CDA)	Aircraft approach designed to reduce fuel consumption and noise compared to conventional descents. Instead of approaching an airport in an altitude stair-step down fashion, OPD allows for a constant-angle descent to landing. A continuous descent approach starts ideally from the top of descent (i.e., at cruise altitude) and allows the aircraft to fly its individual optimal vertical profile down to the runway threshold. Some airports apply constraints to this individual optimal profile.

Application Grouping	#	Application / Capability	Description
Surface / Terminal Area Ops. (continued)	11	Optimized Climb	Optimized climbs is an application that enables aircraft to attain initial cruise flight altitude at their aircraft optimized air speed / engine climb thrust settings though out the climb.
	12	Tailored Arrivals and Departures	Standard arrival/departure procedures have been established at certain airports to simplify clearance delivery procedures, among a broad number of constraints including traffic, terrain, and noise abatement. Such procedures may be modified or tailored (via aircraft to ground negotiation) to allow the flights to arrive/depart with greater efficiency while still saying clear of surrounding flights and other constraints while integrating into the arrival flow at the prescribed time and location.
	13	Wake Turbulence Mitigation for Arrivals / Departures	Improve arrival and departure efficiency / throughput with reduced inter-aircraft spacings, especially at capacity constrained airports, while maintaining or improving wake safety. Revise the aircraft separation needed based on better wake characterization and information (e.g., based on environmental conditions and aircraft type and configuration).
	14	GNSS/GBAS Cat. I/II/III Precision Approach	Precision approaches using GNSS augmented with GBAS. Reference the latest revision of RTCA DO-253.
	15	Multiple Glide Slope Angle Approaches	GNSS (or other) positioning/approach guidance technology can be used provide aircraft with different approach angles and paths to mitigate wake concerns for subsequent aircraft, allowing aircraft on approach to be much closer in-trail to one another enabling more landings per hour to be conducted. One such application is where successive aircraft have a slightly higher approach glide path (up to a maximum) to stay above the wake created by leading aircraft since wakes tend to fall over time. For example, the first aircraft in an approach stream may be on a 2 degree glide path, followed by aircraft each at subsequently higher glide paths (e.g., 2.5, 3, 3.5, and 4 degrees) up to a maximum glide path angle.
TBFM	16	Metering/Merging/Spacing (Enroute and Terminal)	Ground automation-based time-based metering, merging, and spacing.
	17	Ground-Based Interval Management (GIM) (ADS-B)	Ground-based interval management tools to support better longitudinal aircraft spacings.
	18	Delegated Interval (DI) / Interval Management	Interval management application that enables ATC to delegate a spacing task to the flight crew / aircraft for achieving or maintaining longitudinal spacing from one or more designated aircraft. Displays along track guidance, turn guidance, control, indications, and alerts to support achieving more precise inter aircraft spacing. (See Section 27.1.)

Application Grouping	#	Application / Capability	Description
CATM	19	Flight Planning Feedback	Ability for operators to get known NAS constraints during fight planning process for collaborative flight planning.
	20	Dynamic Aircraft Rerouting - TFM	Traffic manager that analyzes the NAS state and identifies conflicts and inefficiencies. As appropriate, proposes reroutes for weather and other constraints. One such application is Dynamic Weather Reroute (DWR).
	21	Enhanced NAS Modeling, Prediction, and Planning	Enhanced modeling & prediction of conditions for better demand/capacity balancing, planning, and scheduling.
	22	Collaborative Decision Making (CDM)	Collaborative arrival, departure, & enroute planning and negotiation prior to finalizing clearances / trajectory.
Separation	23	Delegated Separation (DS) [One-to-One and One-to-"Many"]	Airborne application to support flight crew with safely separating from a limited number (one or more) of ATC specifically designated aircraft. (See Section 27.2.)
	24	Airborne Self Separation (e.g., Autonomous Flight Rules)	Airborne application that uses on-board systems and procedures to prevent loss of separation (Conflict Detection and Resolution) and provide advisory information for trajectories that may cause a conflict (Conflict Prediction) from all other aircraft known by the airborne equipment. (See Section 27.3.)
	25	In Trail Procedures (ITP) Domestic	Enable aircraft equipped with ADS-B and appropriate on-board equipment to climb/descend through altitudes in enroute domestic airspace where separation standards would otherwise prevent the desired altitude changes.
	26	In Trail Procedures (ITP) Oceanic / Remote / Polar	Enable aircraft equipped with ADS-B and appropriate on-board equipment to climb/descend through altitudes in oceanic/ remote/ polar airspace where separation standards would otherwise prevent the desired altitude changes.
	27	Reduced Domestic Separation Services (reduced separation)	Enable reduced separation standards in domestic airspace (e.g., 3 NM or less) based upon improved CNS systems. Reduced aircraft separation standards reduce airspace constraints.
	28	Reduced Oceanic / Remote / Polar Separation Services (reduced separation)	Enable reduced oceanic / remote / polar separation standards based upon improved CNS systems. Reduced aircraft separation standards reduce airspace constraints.

Application Grouping	#	Application / Capability	Description
Performance Based Navigation (PBN) / Reduced Aircraft Separation	29	Advanced PBN (e.g., Dynamic RNP)	New Advanced PBN procedures, like Dynamic RNP (DRNP). DRNP involved the generation of dynamic RNP routes by initially ATC that can be uplinked to affected aircraft. In the future, the dynamic RNP routes will be generated and negotiated among aircraft, AOC, and ATC (as appropriate). The premise is that such a capability will enable the maintenance of traffic in terms flow or capacity when the airspace is constrained as a result of a broad number of factors [e.g., including but not limited to weather, high traffic density, the presence or release of special activity airspace] by being able to dynamically adjust routes to deal with constraints.
	30	PBN including airspace redesign to take greater advantage of RNAV and RNP	Performance Based Navigation (PBN) includes applications that provide more accurate and predictable flight paths with enhanced safety and efficiency. For example, RNP Authorization Required (AR) can improve access to and from airports with approaches and departures that can curve to/from the runway. Such procedures can separate traffic flows, which is especially important in high aircraft density airspace.
	31	Reduced Oceanic/Remote RNP	Further reduce oceanic/remote RNP operations, in combination with better CNS systems (e.g., C=DataComm, N=GNSS, S=ADS-B for A-A and Satellite-Based ADS-B for A-G in Oceanic/Remote Regions) for enhanced efficiency and safety.
	32	Reduced Domestic RNP	Reduced domestic RNP operations (in combination with better CNS systems) will enhance efficiency and safety.
	33	Enroute PBN	Automation to reduce conformance bounds used in conflict detection algorithms for AC with RNAV/RNP based on performance criteria adapted for the route and AC capabilities, allowing the system to take advantage of reduced separation while maintaining safe operations.
Weather and NAS Flight Info Services	34	Flight Information Services (FIS)	Provide information to stakeholders on the real-time status and planned/predicted outages of NAS resources.
	35	Weather Information Services (WIS)	A service provided for the purpose of providing to the weather/environmental information pertinent to the safe and efficient conduct of flights. It can include, for example, information on meteorological information and possible other hazards to flight.
	36	Weather Technology in the Cockpit (WTIC)	Data Link Weather information has existed at various levels for many years and will continue to improve. In the future, external weather sources will be merged with on-aircraft weather sensor information. Weather predictions will become more accurate and probabilistic, and be in a form that is more readily consumed by decision support tools for better managing and optimizing the efficiency, safety, ride quality, and other business case trajectory elements of the flight.

Application Grouping	#	Application / Capability	Description
Other Apps / Multiple Flight Phases	37	Data Link Clearances	ATC delivery of clearances (e.g., taxi, departure, landing, altitude, route, etc.) and flight crew acknowledgement via DataComm.
	38	AOC / FOC Communications	Data communications between aircraft crew and aeronautical / flight operational control centers.
	39	Airborne Access to SWIM (AAtS)	Airborne Access to SWIM (AAtS) enables in-flight aircraft access to information available through SWIM. AAtS extends these capabilities to the cockpit through communication vendors that provide connectivity over non-aeronautical data links. Providing SWIM Information / Internet access on the flight deck for a wide range of flight deck uses. Appropriate policies and standards support NAS data management, secure its integrity, and control its access and use.
	40	4D Trajectory Based Operations (TBO)	Trajectory-based operations, in contrast to today's clearance-based operations, enables aircraft to fly negotiated more optimized business case flight paths, taking operator preferences and airspace constraints into greater consideration. TBO concept of operation represents a shift from the communications and workload intensive aspects of ATC tactical clearances (e.g., vectors, altitudes, holds, etc.), to trajectory-based control. Aircraft will fly negotiated trajectories and ATC will become trajectory managers. Precise management of trajectories dramatically reduces the volume of airspace needed for a given flight and this translates into having the ability to accommodate more flights per unit of airspace (i.e., increased capacity) and a reduced need for ATC intervention.
	41	Gate-to-Gate TBO	TBO will migrate from limited trajectory operations in enroute cruise through arrivals, linking enroute trajectories to top of descent, and then through OPDs to approach and landing. Additionally Ground 3DT (lateral, longitudinal, and time) TBO are used in surface movement with introduction of surface movement management tools for sequencing aircraft for departures with consideration to arrival flows.
	42	ADS-B (Air-to-Air)	Aircraft-to-aircraft exchange of surveillance information enables a broad range of on aircraft applications for achieving improvements in airspace capacity, efficiency, safety, security, and environmental friendliness.
	43	ADS-B / TIS-B / ADS-R (Air-to-Ground & Ground-to-Air)	Aircraft-to-ground (and ground-to-aircraft) exchange of surveillance information. This enables a broad range of on aircraft and on ground applications for achieving improvements in airspace capacity, efficiency, safety, security, and environmental friendliness. Better surveillance enables improved aircraft traffic operations and automation processing.

Application Grouping	#	Application / Capability	Description
Other Apps. / Multiple Flight Phases (continued)	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Information	Aircraft may exchange sensed information, including for example weather and environmental sensed information (e.g., wind, weather radar info, icing conditions, etc.).
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Information	Aircraft may provide information to a ground consumer, including, for example, sensed weather & environmental information (e.g., wind, weather radar info, icing conditions, lightning, temperature, etc.). The ground may combine information provided by aircraft with other information available for a better current and predicted state of the weather and other conditions.
	46	UAS in the NAS	Seamless integration of UAS into the NAS, enabling UAS that are remotely piloted, supervisory controlled (high level of automation), and fully autonomous. Such a capability is vast, and potentially can include very small to very large UAS vehicles.
	47	ACAS-X	On aircraft Airborne Collision Avoidance System – Next Generation (ACAS-X). A future aircraft collision avoidance and resolution system that supports providing traffic advisories, alerts, and resolutions suitable for all aircraft in all operating environments based upon utilizing surveillance information from a multitude of surveillance sources including transponder-based, ADS-B, ADS-R, TIS-B, radar, optical, etc. This application is intended to be a more capable next generation TCAS replacement system suitable for a wide range of aircraft performance capabilities with reduced nuisance alerts.
	48	Traffic Situational Awareness with Alerts (TSAA)	TSAA provides traffic advisories and alerts (without resolution advisories) to assist the pilot with acquisition and avoidance of traffic in all operating environments.
	49	Continuous Cruise Climb / Descent	Continuous climb is an aircraft operating technique allowing (by airspace design) an aircraft during the cruise phase of flight to execute a flight profile optimized to the performance of the aircraft.
	50	Traffic Aware Strategic Aircrew Request (TASAR)	Airborne application that continuously searches for high-value route adjustments, taking into account all known information, including, for example, weather and other environmental hazards, terrain, fuel burn, wind-corrected flying time, traffic conflicts, sector congestion, special use airspace, and FAA route restrictions.
	51	Dynamic Weather Reroute	Ground automation system that continuously searches for high-value aircraft route adjustments, taking into account weather and other environmental hazards, wind-corrected flying time, traffic conflicts, sector congestion, special use airspace, and FAA route restrictions.
	52	New DataComm Applications	New DataComm Applications with ATN B2+ Services (CPDLC, Advanced PBN, Advanced FIM, TBO, etc.). Provides clearances, terminal information, and supports CDM, trajectory operations, TBO, etc.

25.2.2 Prioritization Criteria, Weightings, and Rating Scales

This section describes the prioritization criteria, weightings, and rating scales used to prioritize the long-term NextGen Comm-Enabled ATM Applications identified in Section 25.2.1. The criteria, weightings, and rating scales are closely aligned with those defined by the RTCA NextGen Advisory Committee in their prioritization report *[reference: NextGen Prioritization Report, RTCA NextGen Advisory Committee, September 2013]* which is overviewed in Section 25.1 of this report. However, one additional rating criterion was added, called "cost" and the relative importance of today's "implementation readiness" was de-weighted given the longer term nature of the study as is described below.

<u>Prioritization Criteria and Weightings</u>: The following five prioritization criteria and weightings were used for the prioritization of the long-term ATM applications:

1) Benefits (Monetizable) [45%]
2) Benefits (Non-Monetizable) [15%]
3) Cost [25%]
4) Implementation Readiness [5%]
5) Other Considerations (global harmonization, confidence in delivering benefits, critical element needed for a broad set of NextGen improvements) [10%]

These criteria are defined with rating scales in the subsections below.

25.2.2.1 Benefits (Monetizable)

Monetizable benefits are those that can readily be estimated to have a monetary (or cash) value to the capacity, efficiency, ATC system productivity, and/or environmental impact to operate the ATM system. Monetizable benefits were relatively assessed using the rating scale defined in Figure 300.

Rating Scale	Score	Scale Definition
Very High	5	The application delivers very significant monetizable benefits to the ATM stakeholders in all categories (capacity, efficiency, ATC system productivity, environmental impact).
High	4	The application delivers significant monetizable benefits to the ATM stakeholders 3 or more categories and has no negative monetizable benefit impact on any of the other categories.
Medium	3	The application delivers modest monetizable benefits to the ATM stakeholders in at least 2 categories and has no or little negative monetizable benefit impact on any of the other categories.
Low	2	The application delivers low monetizable benefits to the ATM stakeholders in at least 2 categories and has no or little negative monetizable benefit impact on any of the other categories.
Very Low / None	1	The application delivers little or no monetizable benefits.
Negative	0	The application has negative monetizable benefits.

Figure 300 – Monetizable Benefits Rating Scale

25.2.2.2 Benefits (Non-Monetizable)

Non-monetizable benefits are those that are difficult to estimate the monetary (or cash) value. Non-monetizable benefits were assessed against access, flexibility, safety, and security (as defined in Section 25.1.2.2) with the rating scale as defined in Figure 301.

Rating Scale	Score	Scale Definition
Very High	5	The application delivers very significant non-monetizable benefits to the ATM stakeholders in all categories including access, flexibility, safety, and security (see Section 25.1.2.2).
High	4	The application delivers significant non-monetizable benefits to the ATM stakeholders 3 or more categories and has no perceived negative non-monetizable benefits impact on any of the other categories.
Medium	3	The application delivers modest non-monetizable benefits to the ATM stakeholders in at least 2 categories and has no or little negative non-monetizable benefits impact on any of the other categories.
Low	2	The application delivers low non-monetizable benefits to the ATM stakeholders in at least 2 categories and has no or little negative non-monetizable benefits impact on any of the other categories.
Very Low / None	1	The application delivers little or no non-monetizable benefits.
Negative	0	The application has negative non-monetizable benefits.

Figure 301 – Non-monetizable Benefits Rating Scale

25.2.2.3 Cost

The cost prioritization evaluation criterion is an estimate of the relative amount of cost needed to enable the application. The cost scale ranged from “very low” to “insurmountable” and was assessed relatively against the set of applications analyzed. The cost was assessed using the rating scale defined in Figure 302.

Rating Scale	Score	Scale Definition
Very Low	5	The application requires relatively little to no investment to enable. Relative cost is assessed across the set of applications/capabilities being analyzed.
Low	4	The application requires a relatively low investment to enable.
Medium	3	The application requires a relatively medium level of investment to enable.
High	2	The application requires a relatively high level of investment to enable.
Very High	1	The application requires a very high level of investment to enable.
Insurmountable	0	The cost required to enable the application is considered to be too significant to overcome.

Figure 302 – Cost Rating Scale

25.2.2.4 Implementation Readiness

Implementation readiness is an assessment that the needed elements are in place to achieve a given operational capability. The implementation readiness was assessed against having: a) defined standards and approval processes; b) defined policy/concept of operations; c) necessary systems elements; d) necessary institutional elements; f) defined/harmonized changes in roles of pilots, ATC, AOC, and automation; g) simple or complex operational changes to the airspace, equipage, traffic flow management, automation, and decision support tools; and f) the length of time to completion (see Section 25.1.2.3). The rating scale for this implementation readiness assessment is defined in Figure 303.

Rating Scale	Score	Scale Definition
Very Highly Ready	5	The needed elements (including standards, approval process, policy, systems, institutional, roles, and airspace changes) are already in place to achieve the operational capability.
Highly Ready	4	The needed elements are nearly in place to achieve the operational capability.
Moderate Readiness	3	Elements are moderately in place, and the remaining elements can be available within 10 years.
Low Readiness	2	A few elements are in place, and the remaining elements can be available within 20 years.
Very Low / No Readiness	1	Little to no elements are in place to enable the capability.

Figure 303 – Implementation Readiness Rating Scale

25.2.2.5 “Other Considerations” Prioritization Criterion

The “other considerations” prioritization criterion is aligned with the criterion defined by the NAC for “other considerations” (see Section 25.1.2.4). It includes an assessment of the global harmonization, confidence that the benefits will be realized, and whether the application/capability is a foundational critical element needed for a broad set of NextGen improvements. The rating scale for the “other considerations” assessment for the long range ATM applications is indicated in Figure 304.

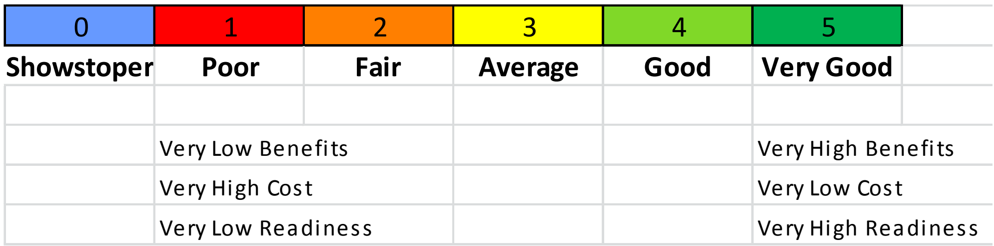
Rating Scale	Score	Scale Definition
Very High	5	The application/capability is internationally harmonized, has a very high likelihood of positive return on investment (ROI) or very large improvement in safety/security, and is very highly critical to the future NextGen / SESAR vision.
High	4	The application/capability is internationally harmonized, has a high likelihood of positive ROI or large improvement in safety/security, and is highly recognized as part of the future NextGen / SESAR vision.
Medium	3	The application/capability is likely to gain international harmonization, has a medium likelihood of positive ROI or modest improvement in safety/security, and is recognized as part of the future NextGen / SESAR vision.
Low	2	The application/capability has low international harmonization, has a low likelihood of positive ROI or little improvement in safety/security, and has little recognition as part of the future NextGen / SESAR vision.
Very Low/None	1	The application/capability has very low or no international harmonization, has very low likelihood of positive ROI or very little to no improvement in safety/security, and has very little or no recognition as part of the future NextGen / SESAR vision.

Figure 304 – Other Considerations Rating Scale

25.2.3 Priority Ranking

The long-term NextGen applications were subjectively assessed relative to each other using the 5 evaluation criteria with the associated rating scales as described in the Section 25.2.2. Then, these 5 individual ratings for each application were multiplied by the weighting factors associated with each evaluation criterion and summed to yield a resulting relative "total score" for each application. Figure 306 provides the results from this evaluation and scoring for all 52 applications. *Note that Figure 305 provides the legend used to color code the application assessment scores presented in Figure 306 and Figure 307.* Commensurate with the "relative" scoring in this prioritization assessment, the average score for the ratings associated with all of the evaluation criteria are approximately "3" (the average rating).

This evaluation has led to prioritizing the applications into 3 Tiers as presented in Figure 307 based upon their relative total score. The tiers are a ranked priority grouping of the applications with "Tier 1" being the highest priority grouping, "Tier 2" being the middle priority grouping, and "Tier 3" being the lowest priority grouping.



🟦 0	🟥 1	🟧 2	🟨 3	🟩 4	🟩 5
Showstoper	**Poor**	**Fair**	**Average**	**Good**	**Very Good**
	Very Low Benefits				Very High Benefits
	Very High Cost				Very Low Cost
	Very Low Readiness				Very High Readiness

Figure 305 – Legend Score to Color Coding used in Figure 306 and Figure 307

	#	Application / Capability	Relative Ratings					Total Score	Ranking
			$ Benefits	Non-$ Benefits	Cost	Implementation Readiness	Other Considerations		
Surface Operations	1	Data Sharing	3	3	3	2	1	2.75	43
	2	Surface SA (SURF in aircraft, APT for ATC)	1	2	4	5	5	2.50	48
	3	Revised PDC via DataComm	2	2	4	4	4	2.80	41
	4	Improved Efficiency of Taxiing Operations	2	2	4	3	3	2.65	47
Surface / Terminal Area Operations	5	Ground-based Runway and/or Taxiway Alerting	1	4	4	3	3	2.50	49
	6	Simultaneous Runway Operations	4	2	3	2	2	3.15	22
	7	Closely Spaced Parallel Runway Operations (CSPO)	4	2	3	4	4	3.45	14
	8	Converging and Intersecting Runway Operations	2	1	3	2	2	2.10	52
	9	Surface SA with Indications & Alerts (SURF IA)	1	4	3	3	4	2.35	51
	10	Optimized Profile Descent (OPD)	4	1	3	3	3	3.15	23
	11	Optimized Climb	4	1	3	2	3	3.10	30
	12	Tailored Arrivals and Departures	4	3	4	4	4	3.85	3
	13	Wake Turbulence Mitigation for Arrivals / Departures	2	3	4	3	3	2.80	42
	14	GNSS/GBAS Cat. I/II/III Precision Approach	2	3	3	4	4	2.70	45
	15	Multiple Glide Slope Angle Approaches	4	2	3	2	2	3.15	24
TBFM	16	Metering/Merging/Spacing (Enroute and Terminal)	3	3	4	4	3	3.30	16
	17	Ground-Based Interval Management (GIM) (ADS-B)	3	2	3	4	3	2.90	38
	18	Delegated Interval (DI) / Interval Management	4	4	3	4	4	3.75	5
CATM	19	Flight Planning Feedback	3	3	3	2	2	2.85	40
	20	Dynamic Aircraft Rerouting - TFM	4	4	3	2	2	3.45	15
	21	Enhanced NAS Modeling, Prediction, and Planning	3	3	4	2	2	3.10	31
	22	Collaborative Decision Making (CDM)	4	3	2	3	3	3.20	20
Separation	23	Delegated Separation (DS)	5	4	3	3	3	4.05	1
	24	Airborne Self Separation (e.g., AFR)	5	5	1	1	2	3.50	13
	25	In Trail Procedures (ITP) Domestic	2	2	4	3	4	2.75	44
	26	In Trail Procedures (ITP) Oceanic / Remote / Polar	3	2	4	4	4	3.25	18
	27	Reduced Separation for Domestic Airspace	4	3	2	2	3	3.15	25
	28	Reduced Separation for Oceanic / Remote / Polar	4	3	4	3	3	3.70	6
PBN / Reduced AC Separation	29	Advanced PBN	4	4	3	3	3	3.60	11
	30	PBN including Airspace Redesign	5	3	2	3	3	3.65	8
	31	Reduced Oceanic/Remote RNP	3	3	5	4	4	3.65	10
	32	Reduced Domestic RNP	3	3	4	3	3	3.25	19
	33	Enroute PBN	3	3	3	4	4	3.15	27
Wx & Flt. Info.	34	Flight Information Services (FIS)	2	2	5	5	5	3.20	21
	35	Weather Information Services (WIS)	2	3	4	5	5	3.10	32
	36	Weather Technology in the Cockpit (WTIC)	2	3	3	4	4	2.70	46
Other Apps. / Multiple Flight Phases	37	Data Link Clearances	3	3	3	4	4	3.15	28
	38	AOC / FOC Communications	3	3	3	4	4	3.15	29
	39	Airborne Access to SWIM (AAtS)	3	3	3	4	3	3.05	33
	40	4D Trajectory Based Operations (TBO)	5	4	2	2	2	3.65	9
	41	Gate-to-Gate TBO	4	4	2	1	1	3.05	34
	42	ADS-B Air-to-Air	4	4	3	5	4	3.80	4
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	5	4	2	5	3	3.90	2
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	2	3	3	2	2	2.40	50
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	3	3	3	3	3	3.00	36
	46	UAS in the NAS	5	5	1	2	2	3.55	12
	47	ACAS-X	3	5	3	3	3	3.30	17
	48	Traffic Situational Awareness with Alerts (TSAA)	1	3	5	5	5	2.90	39
	49	Continuous Cruise Climb/Descent	4	2	3	2	2	3.15	26
	50	Traffic Aware Strategic Aircrew Request (TASAR)	2	2	5	4	3	2.95	37
	51	Dynamic Weather Reroute	4	3	4	3	3	3.70	7
	52	New DataComm Applications	3	4	3	2	2	3.00	35
		Average Score	*3.17*	*2.98*	*3.23*	*3.17*	*3.12*	*3.15*	
			Weight1	**Weight2**	**Weight3**	**Weight4**	**Weight5**		
		Weighting Factors for Evaluation Criteria	0.45	0.15	0.25	0.05	0.10		

Figure 306 – Priority Assessment of the Identified NAS Long-term ATM Applications

			Relative Ratings						
	#	Application / Capability	$ Benefits	Non-$ Benefits	Cost	Implemen-tation Readiness	Other Considera-tions	Total Score	Ranking
Tier 1	23	Delegated Separation (DS)	5	4	3	3	3	4.05	1
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	5	4	2	5	3	3.90	2
	12	Tailored Arrivals and Departures	4	3	4	4	4	3.85	3
	42	ADS-B Air-to-Air	4	4	3	5	4	3.80	4
	18	Delegated Interval (DI) / Interval Management	4	4	3	4	4	3.75	5
	28	Reduced Separation for Oceanic / Remote / Polar	4	3	4	3	3	3.70	6
	51	Dynamic Weather Reroute	4	3	4	3	3	3.70	7
	30	PBN including Airspace Redesign	5	3	2	3	3	3.65	8
	40	4D Trajectory Based Operations (TBO)	5	4	2	2	2	3.65	9
	31	Reduced Oceanic/Remote RNP	3	3	5	4	4	3.65	10
	29	Advanced PBN	4	4	3	3	3	3.60	11
	46	UAS in the NAS	5	5	1	2	2	3.55	12
	24	Airborne Self Separation (e.g., AFR)	5	5	1	1	2	3.50	13
	7	Closely Spaced Parallel Runway Operations (CSPO)	4	2	3	4	4	3.45	14
	20	Dynamic Aircraft Rerouting - TFM	4	4	3	2	2	3.45	15
Tier 2	16	Metering/Merging/Spacing (Enroute and Terminal)	3	3	4	4	3	3.30	16
	47	ACAS-X	3	5	3	3	3	3.30	17
	26	In Trail Procedures (ITP) Oceanic / Remote / Polar	3	2	4	4	4	3.25	18
	32	Reduced Domestic RNP	3	3	4	3	3	3.25	19
	22	Collaborative Decision Making (CDM)	4	3	2	3	3	3.20	20
	34	Flight Information Services (FIS)	2	2	5	5	5	3.20	21
	6	Simultaneous Runway Operations	4	2	3	2	2	3.15	22
	10	Optimized Profile Descent (OPD)	4	1	3	3	3	3.15	23
	15	Multiple Glide Slope Angle Approaches	4	2	3	2	2	3.15	24
	27	Reduced Separation for Domestic Airspace	4	3	2	2	3	3.15	25
	49	Continuous Cruise Climb/Descent	4	2	3	2	2	3.15	26
	33	Enroute PBN	3	3	3	4	4	3.15	27
	37	Data Link Clearances	3	3	3	4	4	3.15	28
	38	AOC / FOC Communications	3	3	3	4	4	3.15	29
	11	Optimized Climb	4	1	3	2	3	3.10	30
	21	Enhanced NAS Modeling, Prediction, and Planning	3	3	4	2	2	3.10	31
	35	Weather Information Services (WIS)	2	3	4	5	5	3.10	32
	39	Airborne Access to SWIM (AAtS)	3	3	3	4	3	3.05	33
	41	Gate-to-Gate TBO	4	4	2	1	1	3.05	34
	52	New DataComm Applications	3	4	3	2	2	3.00	35
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	3	3	3	3	3	3.00	36
Tier 3	50	Traffic Aware Strategic Aircrew Request (TASAR)	2	2	5	4	3	2.95	37
	17	Ground-Based Interval Management (GIM) (ADS-B)	3	2	3	4	3	2.90	38
	48	Traffic Situational Awareness with Alerts (TSAA)	1	3	5	5	5	2.90	39
	19	Flight Planning Feedback	3	3	3	2	2	2.85	40
	3	Revised PDC via DataComm	2	2	4	4	4	2.80	41
	13	Wake Turbulence Mitigation for Arrivals / Departures	2	3	4	3	3	2.80	42
	1	Data Sharing	3	3	3	2	1	2.75	43
	25	In Trail Procedures (ITP) Domestic	2	2	4	3	4	2.75	44
	14	GNSS/GBAS Cat. I/II/III Precision Approach	2	3	3	4	4	2.70	45
	36	Weather Technology in the Cockpit (WTIC)	2	3	3	4	4	2.70	46
	4	Improved Efficiency of Taxiing Operations	2	2	4	3	3	2.65	47
	2	Surface SA (SURF in aircraft, APT for ATC)	1	2	4	5	5	2.50	48
	5	Ground-based Runway and/or Taxiway Alerting	1	4	4	3	3	2.50	49
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	2	3	3	2	2	2.40	50
	9	Surface SA with Indications & Alerts (SURF IA)	1	4	3	3	4	2.35	51
	8	Converging and Intersecting Runway Operations	2	1	3	2	2	2.10	52
		Average Score	*3.17*	*2.98*	*3.23*	*3.17*	*3.12*	*3.15*	
			Weight1	**Weight2**	**Weight3**	**Weight4**	**Weight5**		
		Weighting Factors for Evaluation Criteria	0.45	0.15	0.25	0.05	0.10		

Figure 307 – Prioritized Tiers of the Identified NAS Long-term ATM Applications

26 IDENTIFICATION OF COMM. CANDIDATES THAT MEET APPLICATION NEEDS

This section identifies the communication technology candidates that meet the needs of the long-term NextGen communications-enabled ATM applications identified in Section 25.2.1. Where appropriate, references have been provided to our previously submitted study reports that have identified and described the required communications performance (RCP) needed to meet the needs of each application in the various airspaces and the infrastructure required for each communication candidate.

26.1 Communication Candidates that Meet the Application Needs

The first NRA study report entitled “Data Communications Technologies Candidates” identified straw man RCP values necessary to support a broad range of ATM applications, including most of the long-term ATM applications identified in Section 25.2.1. The straw man RCP identified the required communications performance to support communications, navigation, and surveillance functions. *[Note, for example, that the RCP for a navigation function includes data communications associated with the GNSS local area augmentation function data broadcast, whereas the RCP for a surveillance function includes the data communications associated with ADS-B, ADS-R, and TIS-B.]*

This subsection identifies the A-A and A-G candidates that meet the application needs, based upon their capability [i.e., Actual Communications Performance (ACP)] to satisfy the required communications performance necessary to support the various applications. The communication technology candidates for A-A and A-G communications have been identified and described in the first Com50 study report, entitled “Data Communications Technologies Candidates.” This same study report identified the functional attributes and characteristics of the A-A and A-G communication technology candidates, which is a characterization of the ACP.

Figure 128 summarizes the A-A and A-G communication technology candidates by their ability to provide a quality of service commensurate with satisfying the required communications performance for some of the long-term NAS ATM applications identified as a function of the airspace environment. This figure is a notional simplification. Some candidates can support ATM applications in other airspace (e.g., MEO SATCOM can also support communications in surface and terminal airspace environments).

#	Communications Candidates	Airspace				
		Surface	Terminal	En Route	Oceanic/Remote	Polar
A-A	Air-to-Air (A-A) Communications Candidates					
1	VHF A-A	X	X	X	X	X
2	UHF A-A	X	X	X	X	X
3	L-Band A-A	X	X	X	X	X
4	S-Band A-A	X	X	X	X	X
5	C-Band A-A	X	X	X	X	X
6	X-Band A-A	X	X	X	X	X
7	Optical A-A	X	X	X	X	X
8	Hybrid RF/Optical A-A	X	X	X	X	X
9	LEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	X
10	GEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	
11	MEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	X
12	GEO + HEO SATCOM A-A (One Hop through Sat.)	X	X	X	X	X
A-G	Air-to-Ground (A-G) Communication Candidates					
1	HF A-G				X	X
2	VHF A-G	X	X	X		
3	UHF A-G	X	X	X		
4	L-Band A-G	X	X	X		
5	S-Band A-G	X	X	X		
6	C-Band A-G	X	X	X		
7	Optical A-G	X	X			
8	Hybrid RF/Optical A-G	X	X	X		
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)	X	X	X		
10	DTV VHF/UHF Network	X	X	X		
11	Cellular Network (e.g., Aircell)	X	X	X		
12	LEO SATCOM Network (e.g., Iridium Next+)	X	X	X	X	X
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)			X	X	
14	MEO SATCOM Network (e.g. GlobalStar+)			X	X	X
15	VHF A-A Hopping for long range A-G Com.				X	X
16	UHF A-A Hopping for long range A-G Com.				X	X
17	L-Band A-A Hopping for long range A-G Com.				X	X
18	X-Band A-G	X	X			
19	GEO + HEO SATCOM Network	X	X	X	X	X

Figure 308 – Notional Communication Candidates to Airspace Mapping

Figure 309 to Figure 313 identify the A-A and A-G candidates for which their Actual Communications Performance (ACP) is expected to be sufficient to satisfy the RCP necessary to support the identified long-term ATM applications. These figures are partitioned by applications intended to be used in the various different airspace domains, whereby: Figure 309 is for the airport surface airspace, Figure 310 (page 436) is for the surface/terminal area airspace, Figure 311 (page 437) is for the enroute domestic airspace, Figure 312 (page 438) is for the oceanic and remote airspace, and Figure 313 (page 438) is for polar airspace.

In all of these figures, the candidates numbers in the “Air-to-Air Candidate Mapping” columns refer to the A-A candidates as numbered and identified in Figure 128 and are colored in “**red**”. Similarly, the candidates numbers identified in the “Air-to-Ground Candidate Mapping” columns refer to the A-G candidates as numbered and identified in Figure 128 and are colored in “**blue**”.

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	**#**	**Application / Capability**	**RCP**	**Required Com. To Support Surv.**	**RCP**	**Required Com. To Support Surv.**	**Required Com. To Support Nav.**
Surface / APT	1	Data Sharing	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 18	---	---
	2	Surface SA (SURF in aircraft, APT for ATC)	---	1, 2, 3, 4, 5, 6	---	---	---
	3	Revised PDC via DataComm	---	---	2, 3, 4, 5, 6, 7, 8, 18	---	---
	4	Improved Efficiency of Taxiing Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	2, 3, 4, 5, 6, 18	---
	5	Ground-based Runway and/or Taxiway Alerting	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	9	Surface SA with Indications & Alerts (SURF IA)	---	1, 2, 3, 4, 5, 6	---	---	---
	19	Flight Planning Feedback	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 18, 19	---	---
	34	Flight Information Services (FIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	35	Weather Information Services (WIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	37	Data Link Clearances	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	38	AOC / FOC Communications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	41	Gate-to-Gate TBO	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	42	ADS-B Air-to-Air	---	1, 2, 3, 4, 5, 6	---	---	---
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	---	---	---	2, 3, 4, 5, 6, 18	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 18, 19	---	---
	46	UAS in the NAS	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	52	New DataComm Applications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---

Figure 309 – Surface / APT: Candidates that Meet Application Needs

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	#	Application / Capability	RCP	Required Com. To Support Surv.	RCP	Required Com. To Support Surv.	Required Com. To Support Nav.
Surface/ Terminal Area	2	Surface SA (SURF in aircraft, APT for ATC)	---	1, 2, 3, 4, 5, 6	---	---	---
	5	Ground-based Runway and/or Taxiway Alerting	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	6	Simultaneous Runway Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	7	Closely Spaced Parallel Runway Operations (CSPO)	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	8	Converging and Intersecting Runway Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	9	Surface SA with Indications & Alerts (SURF IA)	---	1, 2, 3, 4, 5, 6	---	---	---
	10	Optimized Profile Descent (OPD)	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	11	Optimized Climb	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	12	Tailored Arrivals and Departures	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	13	Wake Turbulence Mitigation for Arrivals / Departures	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	14	GNSS/GBAS Cat. I/II/III Precision Approach	---	---	2, 3, 4, 5, 6, 18	2, 3, 4, 5, 6, 18	2, 3, 4, 5, 6, 18
	15	Multiple Glide Slope Angle Approaches	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	16	Metering/Merging/Spacing	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	---	2, 3, 4, 5, 6, 18	---
	22	Collaborative Decision Making (CDM)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	34	Flight Information Services (FIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	35	Weather Information Services (WIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	37	Data Link Clearances	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	38	AOC / FOC Communications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	42	ADS-B Air-to-Air	---	1, 2, 3, 4, 5, 6	---	---	---
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	---	---	---	2, 3, 4, 5, 6, 18	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 18, 19	---	---
	46	UAS in the NAS	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	47	ACAS-X	---	1, 2, 3, 4, 5, 6	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3, 4, 5, 6	---	2, 3, 4, 5, 6, 18	---
	52	New DataComm Applications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---

Figure 310 – Surface / Terminal: Candidates that Meet Application Needs

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	#	Application / Capability	RCP	Required Com. To Support Surv.	RCP	Required Com. To Support Surv.	Required Com. To Support Nav.
Enroute Domestic	16	Metering/Merging/Spacing	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	2, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14, 19	---	---
	22	Collaborative Decision Making (CDM)	---	---	2, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	25	In Trail Procedures (ITP) Domestic	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	27	Reduced Separation for Domestic Airspace	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	29	Advanced PBN	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	30	PBN including Airspace Redesign	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	32	Reduced Domestic RNP	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	33	Enroute PBN	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	34	Flight Information Services (FIS)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	35	Weather Information Services (WIS)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	37	Data Link Clearances	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	38	AOC / FOC Communications	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	42	ADS-B Air-to-Air	---	1, 2, 3	---	---	---
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	---	---	---	2, 3, 4, 5, 6	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	46	UAS in the NAS	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	47	ACAS-X	---	1, 2, 3	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3	---	2, 3, 4, 5, 6	---
	49	Continuous Cruise Climb/Descent	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	50	Traffic Aware Strategic Aircrew Request (TASAR)	---	1, 2, 3	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	51	Dynamic Weather Reroute	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	52	New DataComm Applications	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---

Figure 311 – Enroute: Candidates that Meet Application Needs

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	**#**	**Application / Capability**	**RCP**	**Required Com. To Support Surv.**	**RCP**	**Required Com. To Support Surv.**	**Required Com. To Support Nav.**
Enroute Oceanic / Remote	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	22	Collaborative Decision Making (CDM)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	26	In Trail Procedures (ITP)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	28	Reduced Separation for Oceanic / Remote	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	29	Advanced PBN	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	30	PBN including Airspace Redesign	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	31	Reduced Oceanic/Remote RNP	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	34	Flight Information Services (FIS)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	35	Weather Information Services (WIS)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	37	Data Link Clearances	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	38	AOC / FOC Communications	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	42	ADS-B Air-to-Air	---	1, 2, 3	---	---	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	46	UAS in the NAS					
	47	ACAS-X	---	1, 2, 3	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3	---	1, 12, 13, 14, 15, 16, 17, 19	---
	49	Continuous Cruise Climb/Descent	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	50	Traffic Aware Strategic Aircrew Request (TASAR)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	---	---
	51	Dynamic Weather Reroute	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	52	New DataComm Applications	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---

Figure 312 – Oceanic/Remote: Candidates that Meet Application Needs

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	**#**	**Application / Capability**	**RCP**	**Required Com. To Support Surv.**	**RCP**	**Required Com. To Support Surv.**	**Required Com. To Support Nav.**
Polar	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	22	Collaborative Decision Making (CDM)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	26	In Trail Procedures (ITP)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	28	Reduced Separation for Oceanic / Remote	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	29	Advanced PBN	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	30	PBN including Airspace Redesign	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	31	Reduced Oceanic/Remote RNP	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	34	Flight Information Services (FIS)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	35	Weather Information Services (WIS)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	37	Data Link Clearances	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	38	AOC / FOC Communications	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	42	ADS-B Air-to-Air	---	1, 2, 3	---	---	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	46	UAS in the NAS					
	47	ACAS-X	---	1, 2, 3	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3	---	1, 12, 14, 15, 16, 17, 19	---
	49	Continuous Cruise Climb/Descent	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	50	Traffic Aware Strategic Aircrew Request (TASAR)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	---	---
	51	Dynamic Weather Reroute	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	52	New DataComm Applications	---	---	1, 12, 14, 15, 16, 17, 19	---	---

Figure 313 – Polar: Candidates that Meet Application Needs

26.2 Communications Infrastructure Required

Straw man RCP values necessary to support a broad range of long-range NextGen and beyond ATM applications were identified in Section 13. Based upon these RCP values (which include measures of performance including coverage volume, continuity, availability, integrity, latency, etc.), the communications infrastructure must provide an Actual Communications Performance (ACP) commensurate with meeting the RCP required for all applications that are intended to be utilized in a given airspace and be approved for such application use by the cognizant approval authority (e.g., the FAA).

The communications infrastructure required to implement each communication candidate was described previously in this report (see current and candidate architecture descriptions in Sections 16 and 17, respectively). The infrastructure identified is expected to meet needs of the long-term ATM applications. The A-A, G-A, and A-G communication infrastructure required to support the Delegated Interval / Interval Management, Delegated Separation, and Airborne Self-Separation applications is provided in Section 27.

27 USE CASE ANALYSES FOR SEVERAL ATM APPLICATIONS

This section of the report provides use case examples for the following applications:

- Delegated Interval / Interval Management (DI/IM) [see Section 27.1],
- Delegated Separation (DS) [see Section 27.2], and
- Airborne Self-separation (ASS) [see Section 27.3].

Each use case analysis includes subsections that describe the following aspects of the application:

1. a brief overview of the concept of operations,
2. a number of example operational scenarios,
3. a partitioning of the application into its constituent phases of operation (e.g., pre-initiation, initiation, execution, and termination),
4. use case activity diagrams that highlight the activities in the application where A-A and A-G (including G-A) communications take place,
5. a description of the communications information and infrastructure needed for the application, and
6. a subsection that comments on the use of the application for one-to-one and one-to-many aircraft interactions.

Note that the use case examples provided in this section are in the context of aircraft being flown by a flight crew of one or more pilots. In this context, the flight crew with support from automation is being delegated: a) a spacing task for DI/IM, b) a separation task to safely separate from one or a few specifically designated aircraft for DS, or c) a separation task to safely separate from all other aircraft for ASS. In the future, these use cases could be expanded to address DI, DS, and ASS in context of fully autonomous UAS.

27.1 Delegated Interval / Interval Management (DI/IM) Use Case Analysis

Delegated Interval which is also known as Interval Management (*hereafter referred to interchangeably in this document as with the acronyms of DI/IM, DI, or IM*) is a future concept of ATM operations whereby inter-aircraft spacing tasks are delegated from ATC to the aircraft flight crew with the support of automation. Such a delegation can potentially reduce controller workload and enable improved traffic flow management by improving the efficiency of merging and spacing aircraft, approach and landing aircraft, aircraft flow in domestic and oceanic/remote enroute airspace, as well as aircraft flow in departures.

RTCA DO-328 (also EUROCAE DO-195), entitled “Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management (FIM)” describes such an application, and is used as the basis for this use case analysis. As of this writing, DO-328 was released on 19 May 2011, and a revision (DO-328A) is in the process of being developed as well as a FIM airborne equipment MOPS. Also important to this use case analysis is the FAA’s Advanced Interval Management, Preliminary Concept of Operations document (version 1.0, dated March 27, 2014).

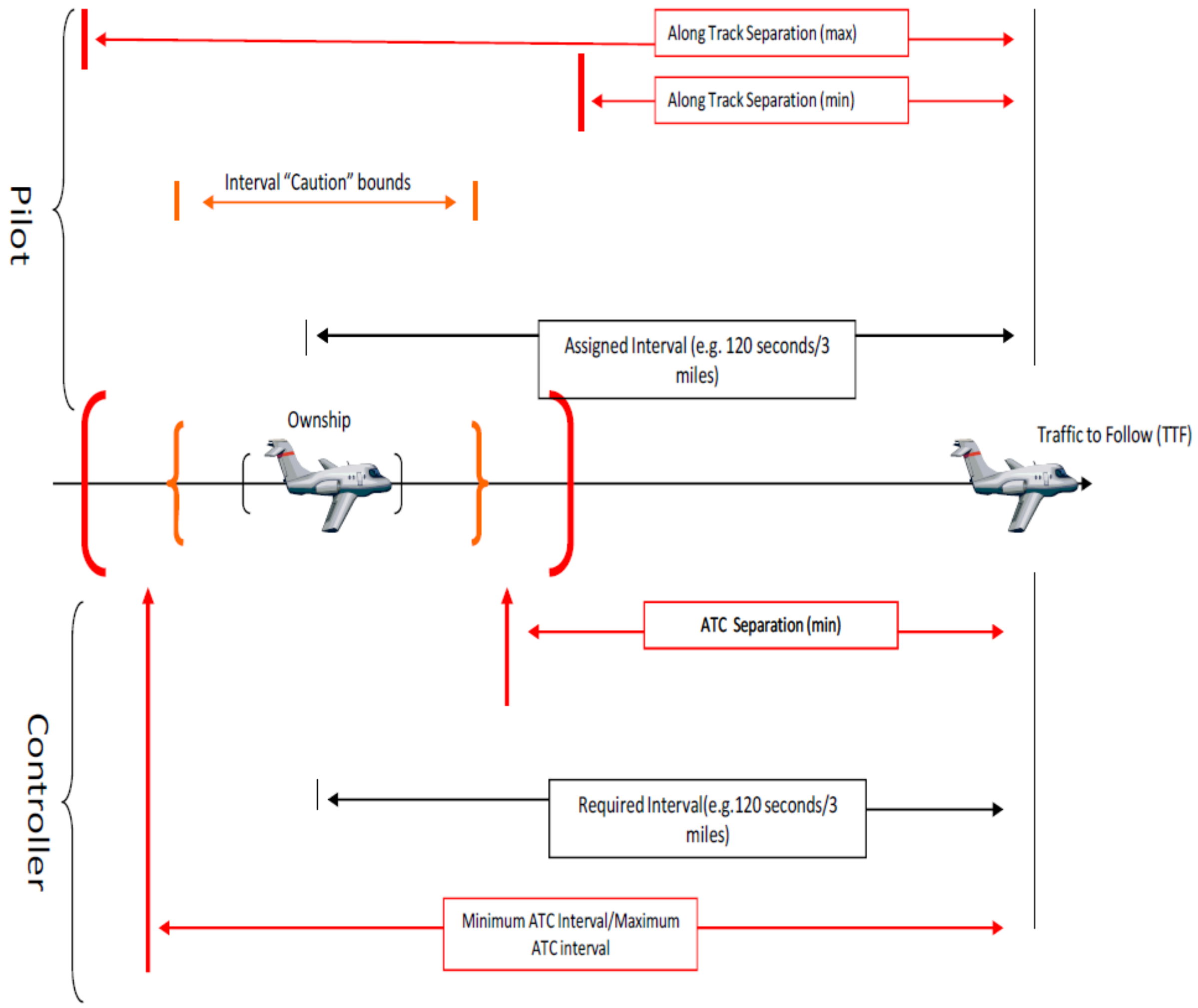


Figure 314 – DI / IM Operational Concept

[Reference: ADS-B IN Aviation Rulemaking Committee Report to the FAA, September 30, 2011.]

27.1.1 DI/IM Concept of Operations Overview

Delegated Interval / Interval Management includes a set of ground and flight deck capabilities that support a range of operations whose goal is efficient achievement and/or maintenance of precise inter-aircraft spacing. DI/IM is defined as the overall system that enables the improved means for managing traffic flows and aircraft spacing. This includes both the use of ground and airborne tools, where the Ground Interval Management (GIM) tools assist the controller in evaluating the traffic picture and determining appropriate clearances to merge and space aircraft efficiently and safely, and airborne Flight Deck Interval Management (FIM) tools allow the flight crew to conform to the IM clearance.

IM includes both the ground capabilities needed for the controller to issue an IM Clearance and the airborne capabilities needed for the flight crew to follow the IM Clearance.

The controller using ground IM tools will instruct the flight crew to achieve and/or maintain an Assigned Spacing Goal relative to typically one, but in some cases more than one, Target

Aircraft. The key addition to current operations with FIM is the provision of precise speed guidance within the flight deck to enable the flight crew to actively manage the spacing relative to the Target Aircraft. A one-time navigation instruction may also be used, wherein guidance to return to the original route is provided within the flight deck. During IM Operations, the controller retains responsibility for separation, while the flight crew is responsible for using the FIM Equipment to achieve and/or maintain the Assigned Spacing Goal that is set by the controller to meet the operational goals.

IM Operations can potentially be utilized during all flight phases. Figure 315 to Figure 321 illustrate example IM operations applied during a number of flight phases including cruise, departure, descent, and landing phases of flight.

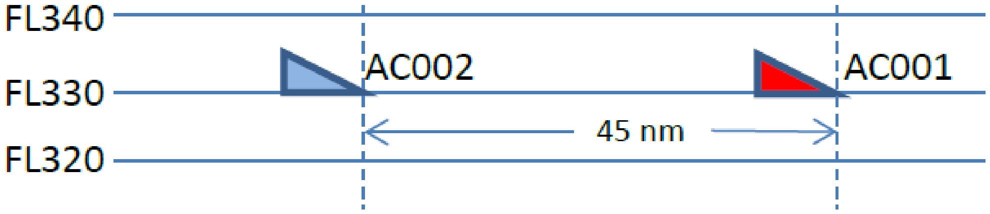


Figure 315 – IM Example Use During Cruise Flight – Same Track & Co-altitude

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

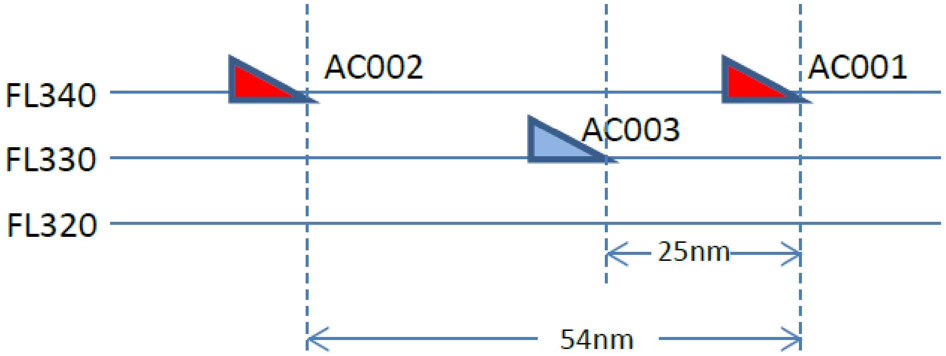


Figure 316 – IM Example Use During Cruise Flight – Different Tracks & Altitudes

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

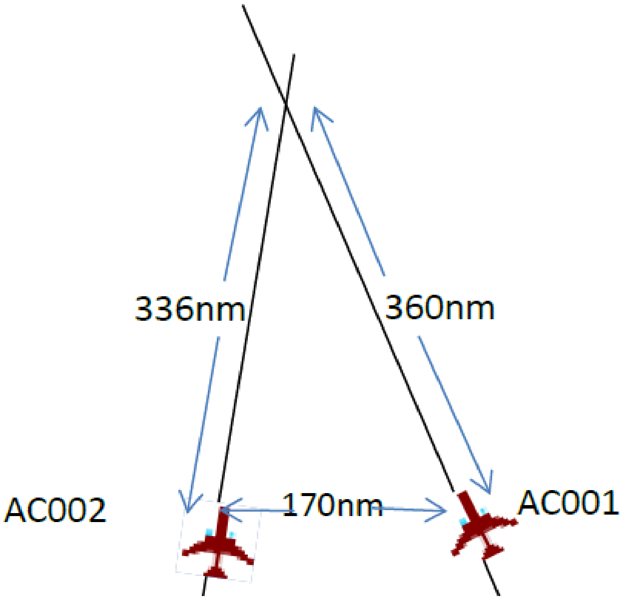


Figure 317 – IM Example Use During Cruise Crossing

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

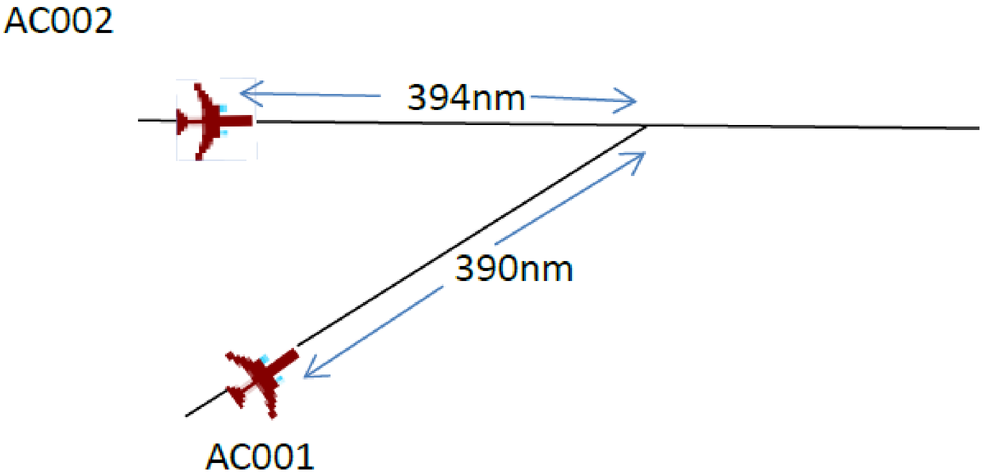


Figure 318 – IM Example Use During Cruise Merging

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

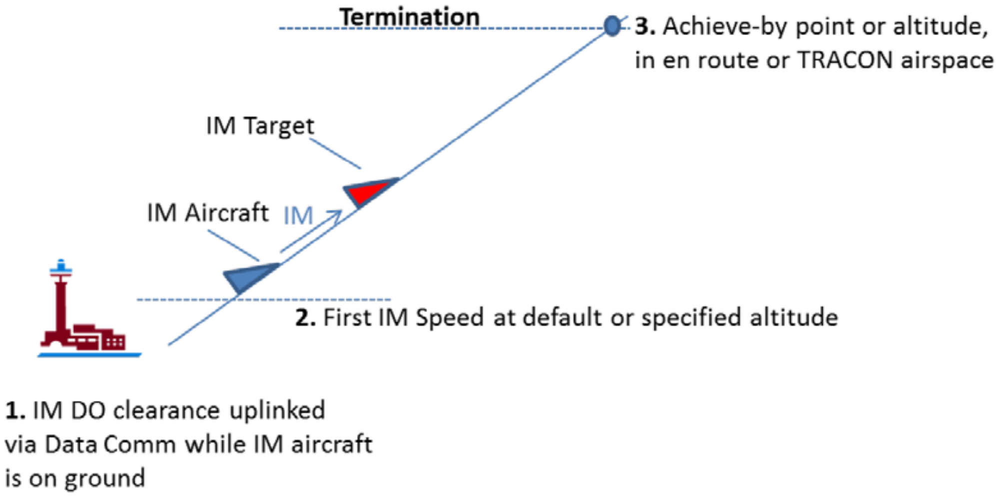


Figure 319 – IM Example Use During Initial Departure Climb

[Reference: Advanced IM, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

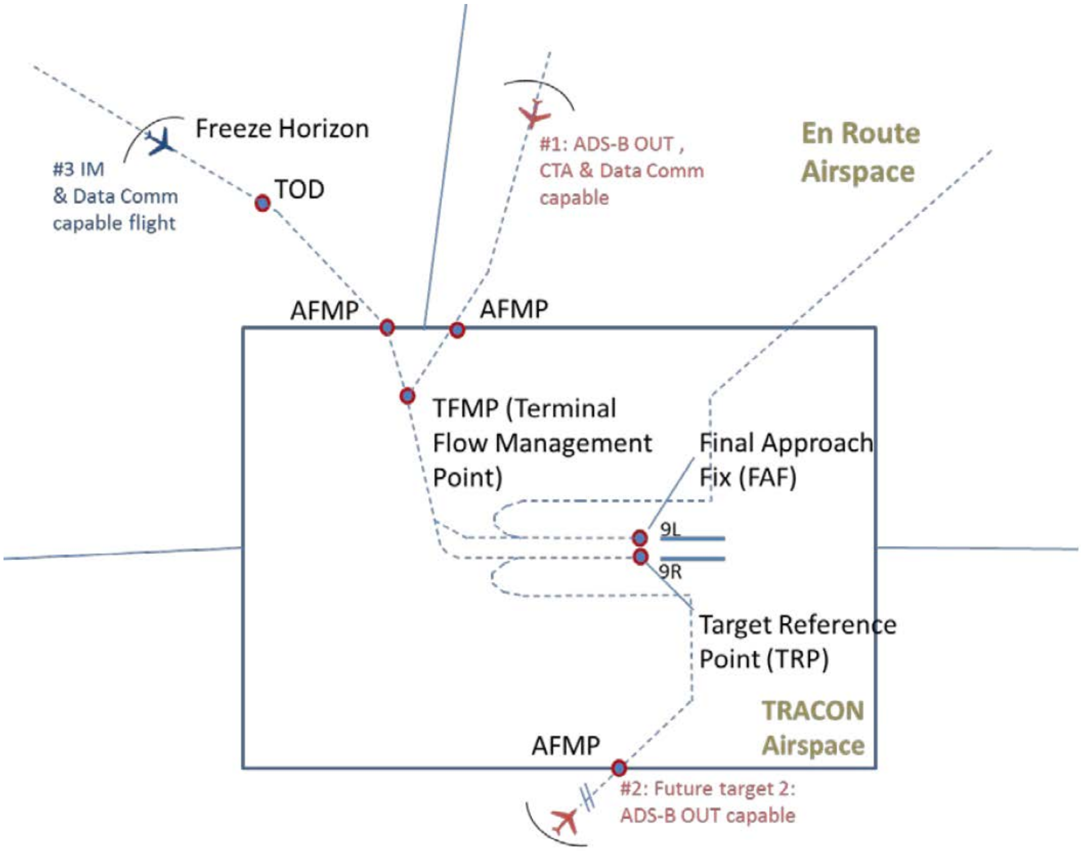


Figure 320 – IM Example Use During Descent and Approach Phases

[Reference: Advanced IM, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

Interval Management for paired approach (IM PA) is intended to recapture the capacity of visual operations at airports with closely spaced parallel runways less than 2500 feet apart (such as at San Francisco International Airport, SFO) when conditions deteriorate below visual approach or Simultaneous Offset Instrument Approach (SOIA) minima. IM PA does so by providing IM speeds that allow an IM Aircraft to safely maintain a position in the safety zone between the blunder risk and wake turbulence areas of a Target Aircraft arriving on the closely spaced parallel runway, as shown in Figure 321.

The safety zone is defined by parameters that depend on runway separation and geometry, and flight crews are alerted via FIM equipment when the aircraft is in danger of exceeding them. The safety zone parameters will be communicated from ATC to the IM Aircraft (e.g., using CPDLC).

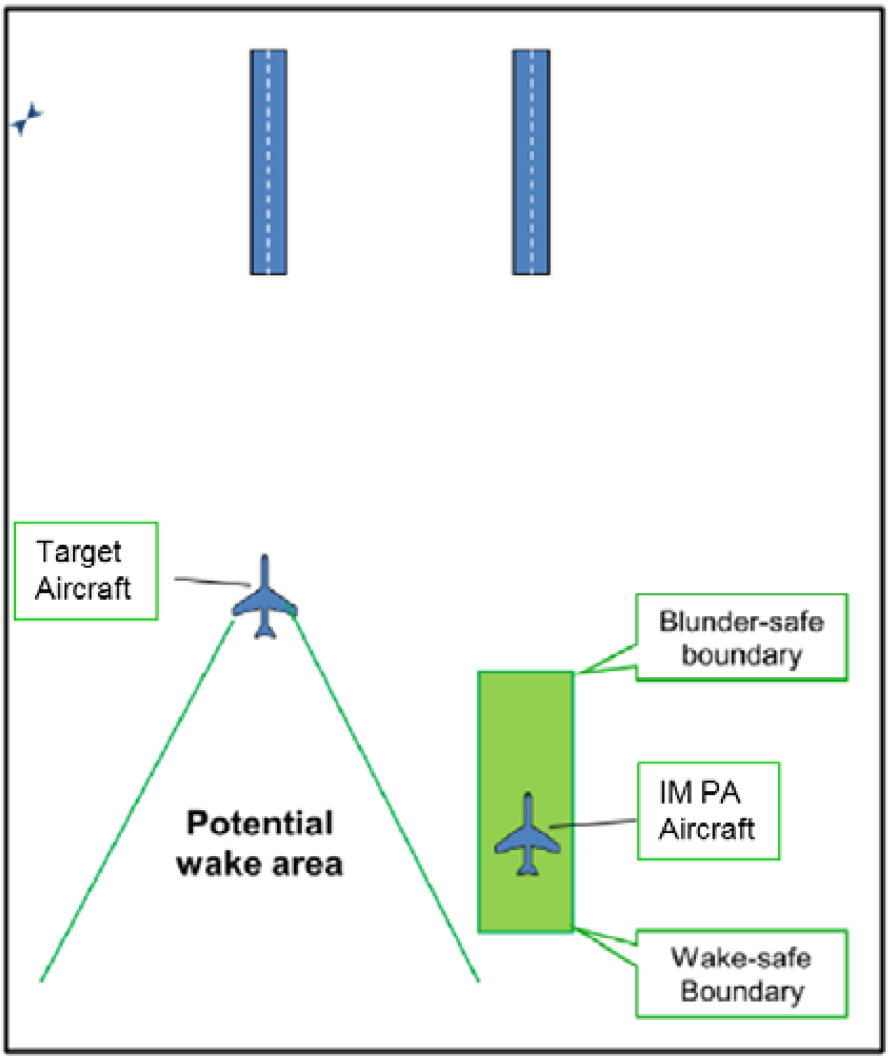


Figure 321 – IM Example Use During Paired Approach

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

27.1.2 IM Operational Scenarios

Seven operational scenarios were used by RTCA/EUROCAE as the basis for the developing the operational, performance, and safety requirements associated with FIM (as given in DO-328 and draft V1.01 of DO-328A). These same scenarios are used as the basis for the IM use case analysis provided in this document. The seven operational scenarios are summarized below. Additional information describing the scenarios can be found in RTCA/DO-328 and eventually in DO-328A or subsequent revisions.

27.1.2.1 IM Scenario #1: Sequencing and Merging – Remain Behind and Merge Behind

This scenario includes the aircraft sequencing and merging operation being supported by IM to achieve aircraft spacing while in-trail or proceeding direct to a common point and then in-trail. This scenario is applicable to various phases of flight, including departure, cruise, and descent.

There are three sub-scenarios to IM scenario #1 (labeled a, b, and c) as described below. This set of variations includes the following aspects of IM operations:

- achieving and/or maintaining a spacing interval;
- inserting non-ADS-B aircraft in the middle of a spacing pair;
- direct-to and common route intended flight path information;
- achieving at the merge point;
- achieve stage while on a common path; and
- maintaining and achieving while in climb, cruise, or descent.

In scenario #1a (see Figure 322), aircraft labeled “LED01” and “TRL02” merge on to the same route, whereby the trailing aircraft (TRL02) is instructed to achieve the Assigned Spacing Goal (ASG) of 90 seconds behind the lead aircraft (LED01) at the Achieve-by-Point (which happens to also be the Merge Point) and maintain the spacing until the Planned Termination Point.

In scenario #1b (see Figure 323), aircraft labeled “LED01” and “TRL02” merge on to the same route, whereby TRL02 is instructed to merge at the “Merge Point” and achieve 90 seconds spacing behind LED01 at the Achieve-by-Point (which happens to also be the Planned Termination Point). This sub-scenario differs from #1a in that the Achieve-by-Point is delayed from the Merge Point.

Scenario #1c (see Figure 324), is very similar to scenario #1a, except the aircraft labeled “TRL03” is instructed to achieve 195 seconds spacing behind LED01 at the Achieve-by-Point (which happens to also be the Merge Point). In this scenario, ATC has inserted a non-ADS-B aircraft labeled “MRG2” in the middle of the spacing pair.

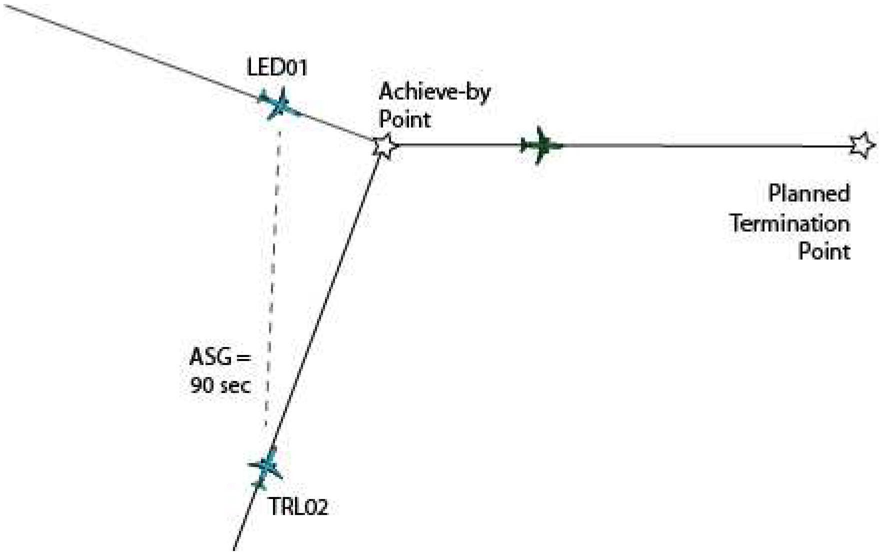


Figure 322 – IM Scenario #1a: Merge Behind

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

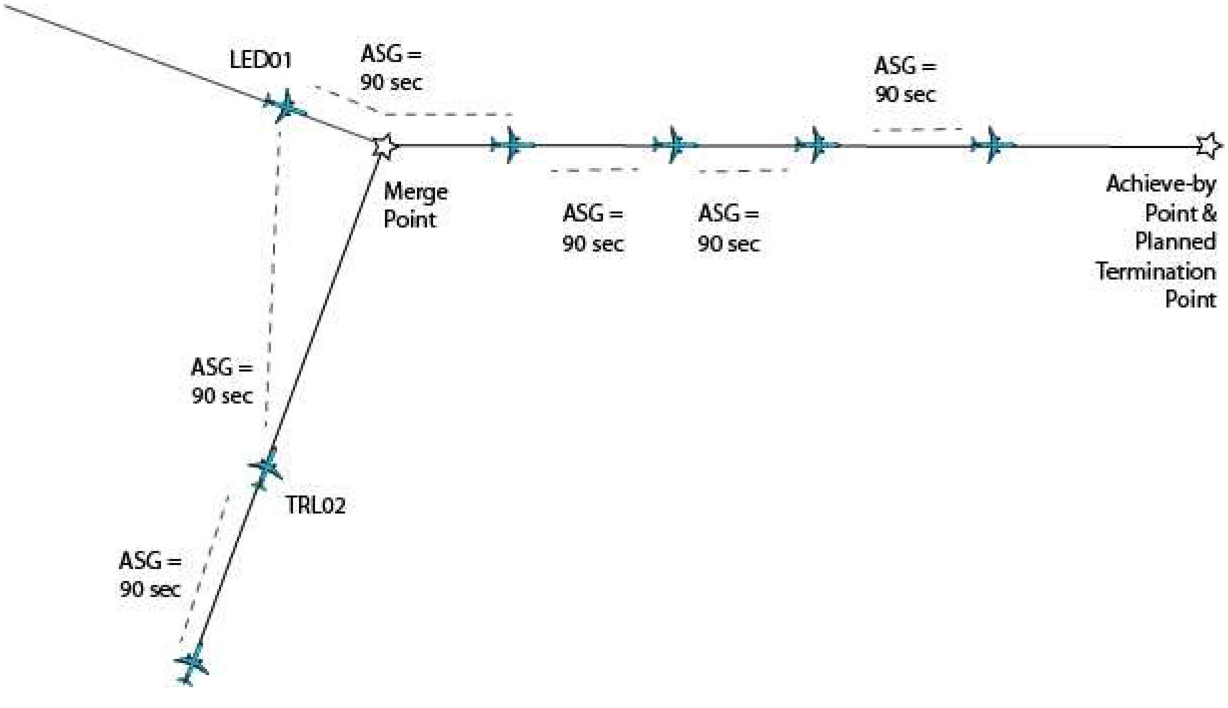


Figure 323 – IM Scenario #1b: Merge Behind with delayed Achieve-by-Point

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

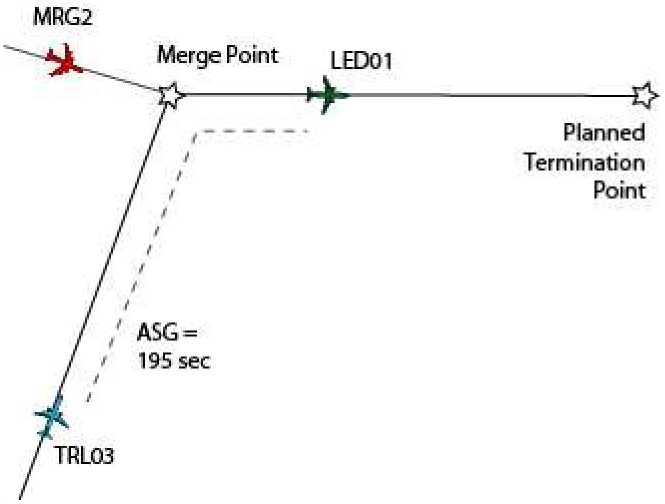


Figure 324 – IM Scenario #1c: Remain Behind with Intermediate Aircraft

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

27.1.2.2 IM Scenario #2: IM Turn Maneuvers

IM scenario #2 includes the use of IM Turn maneuvers for path shortening or path lengthening to make larger changes in the relative spacing between two aircraft. It is used to make changes to the initial spacing when speed changes alone would be insufficient, or to allow the flight path to be optimized for both speed and path length. The FIM Equipment calculates the turn point such that the IM Speed changes can subsequently be used to achieve the Assigned Spacing Goal at the Achieve-By Point.

In this scenario as depicted in Figure 325 and Figure 326, the controller wants the trailing aircraft (TRL02) to achieve 90 second spacing behind the lead aircraft (LED01) at the Achieve-by Point. The controller could initiate the IM Turn maneuver for two reasons:

1) they know (e.g., based on ground decision support tools) that TRL02 cannot achieve the Assigned Spacing Goal using speed adjustment alone. Some sort of path shortening (too far behind initially) or path lengthening (too close initially) is required in order to achieve the Assigned Spacing Goal, or
2) the controller has the flexibility to allow the flight crew to shorten their flight path while slowing down in order to increase the aircraft's efficiency.

There are two sub-scenarios to scenario #2 (labeled "a" and "b") as described below. This set of variations includes the following aspects of IM operations:

- IM Turn after a vector;
- IM Turn from the current route; and
- named route intended flight path for IM Aircraft and Target Aircraft.

In scenario #2a (Figure 325), the controller wants the trail aircraft (TRL02) to cross the Intercept / Achieve-by Point 90 seconds after the lead aircraft (LED01). The controller expects that TRL02 will not be able to slow down enough to achieve the desired spacing at Achieve-by Point. Therefore, the controller issues a 'turn right, heading 140' and instructs TRL02 to turn to

Achieve-by Point when able to achieve 90 seconds spacing behind LED01. Prior to the turn to the Achieve-by Point, the IM Speeds presented will direct the flight crew to slow their speed to assist in achieving the Assigned Spacing Goal. The FIM equipment onboard TRL02 notifies the flight crew when the turn to the Intercept / Achieve-by Point that will enable successful completion of the IM clearance. In scenario #2a, the Planned Termination Point is also at the Intercept / Achieve-by-Point.

In scenario #2b (Figure 326), the controller wants the trail aircraft (TRL02) to cross the Achieve-by Point 90 seconds after lead aircraft (LED01). The controller issues an IM clearance to TRL02 and the flight crew of TRL02 responds “unable, IM Speed too fast.” The controller instructs TRL02 to follow current route and turn to the Intercept Point when able to achieve 90 seconds spacing behind LED01 at the Achieve-by Point. The FIM equipment onboard TRL02 notifies the flight crew when the turn to the Intercept Point to enable successful completion of the IM clearance.

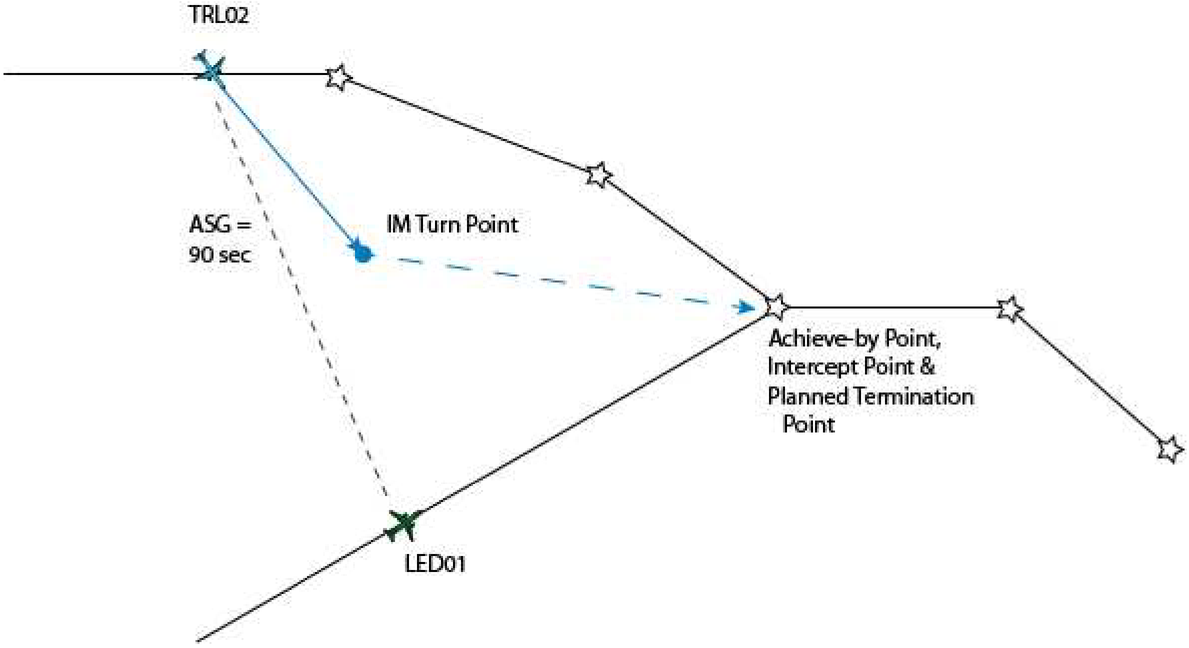


Figure 325 – IM Scenario #2a: Radar Vector then Turn

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

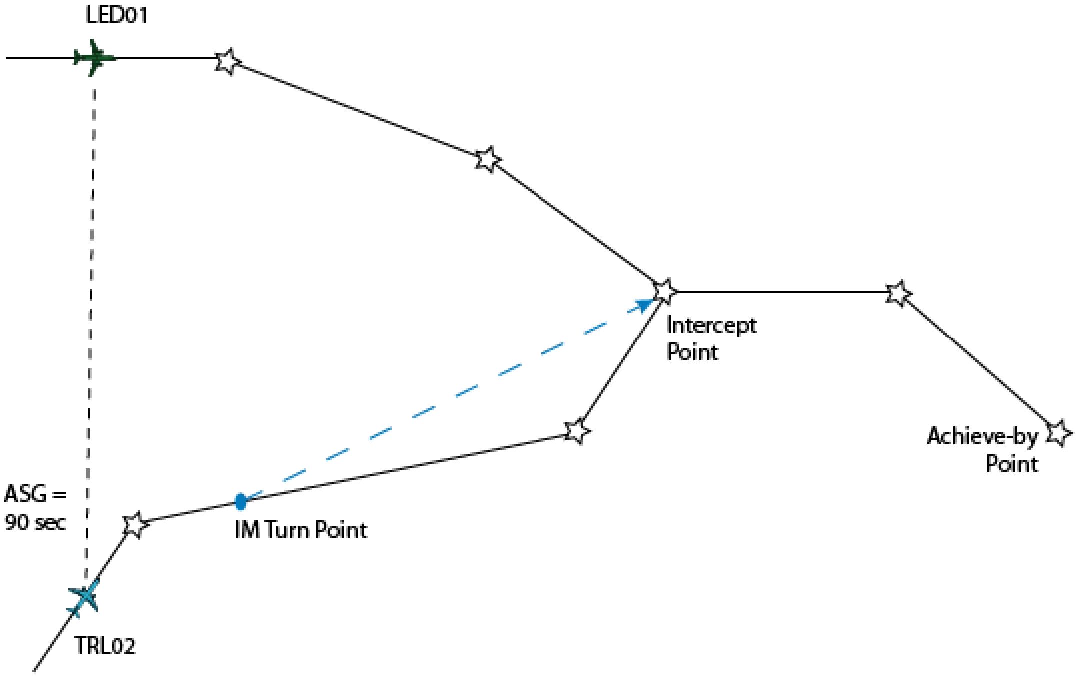


Figure 326 – IM Scenario #2b: Follow Route then Turn

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

27.1.2.3 IM Scenario #3: IM Arrival and Approach along an Optimized Profile Descent

IM scenario #3 is where aircraft are arriving into a busy terminal airspace with the goal of performing Continuous Descent Operations or Optimized Profile Descents (OPD). The controller uses a decision support tool to determine the assigned spacing goal at the Achieve-by Point that will provide acceptable, but tight, spacing all the way to the runway threshold.

There are three sub-scenarios to scenario #3 (labeled a, b, and c) as described below whereby controllers use a decision support tool to help them determine the preferred landing sequence, spacing pairs, and assigned spacing goals. This set of variations includes the following aspects of IM operations:

- IM speed management along constrained flight path;
- Named route intended flight path;
- Achieve-by-Point after the Merge Point; and
- Adjusting for differences in final approach speeds.

In scenario #3a (Figure 327), all aircraft have known routing to the runway. The trailing aircraft (TRL02) is merging behind the lead aircraft (LED01) at the Achieve-by-Point, prior to their tops of descent, and then will be in-trail for the rest of the arrival and approach. The controller's decision support tool takes account the different planned final approach speeds of LED01 and TRL02, the forecast winds and weather near the runway, and wake categories and determines that 112 second spacing will deliver the desired throughput while keeping the aircraft safely separated all the way to the runway.

In scenario #3b (Figure 328), all aircraft have known routing to the runway and are controlled to cross their Terminal Metering Points at scheduled times to pre-condition the merging traffic flows. The trail aircraft (TRL02) is merging behind the lead aircraft (LED01) at the Achieve-by-Point inside the Terminal Control Area, and then will be in-trail for the rest of the arrival and approach. The controllers' decision support tool takes into account the different planned final approach speeds of LED01 and TRL02, the forecast winds and weather near the runway, and wake categories and determines that 112 second spacing will deliver the desired throughput while keeping the aircraft safely separated all the way to the runway. The Achieve-by Point and Planned Termination Point are part of the published IM procedure.

In scenario #3c (Figure 329), all aircraft have known routing to the runway and were controlled to meet scheduled times of arrival at their Enroute Flow Management Points. TRL02 is merging behind LED01 at the Merge Point, inside the Terminal Control Area, and then will be in-trail for the rest of the arrival and approach procedure. The controller's decision support tool takes account the different planned final approach speeds of LED01 and TRL02, the forecast winds and weather near the runway, and wake categories and determines that a spacing of 5.4 NM at the Achieve-by-Point will deliver the aircraft at 4.2 NM at the runway based on the expected compression due to the aircraft slowing down. The use of distance in this IM Clearance is acceptable since the TRL02 will achieve it and then immediately terminate the IM Operation. The use of a distance interval might be more intuitive for controllers to use, while the use of a time in this scenario could improve the robustness of the scheduling of the arrivals.

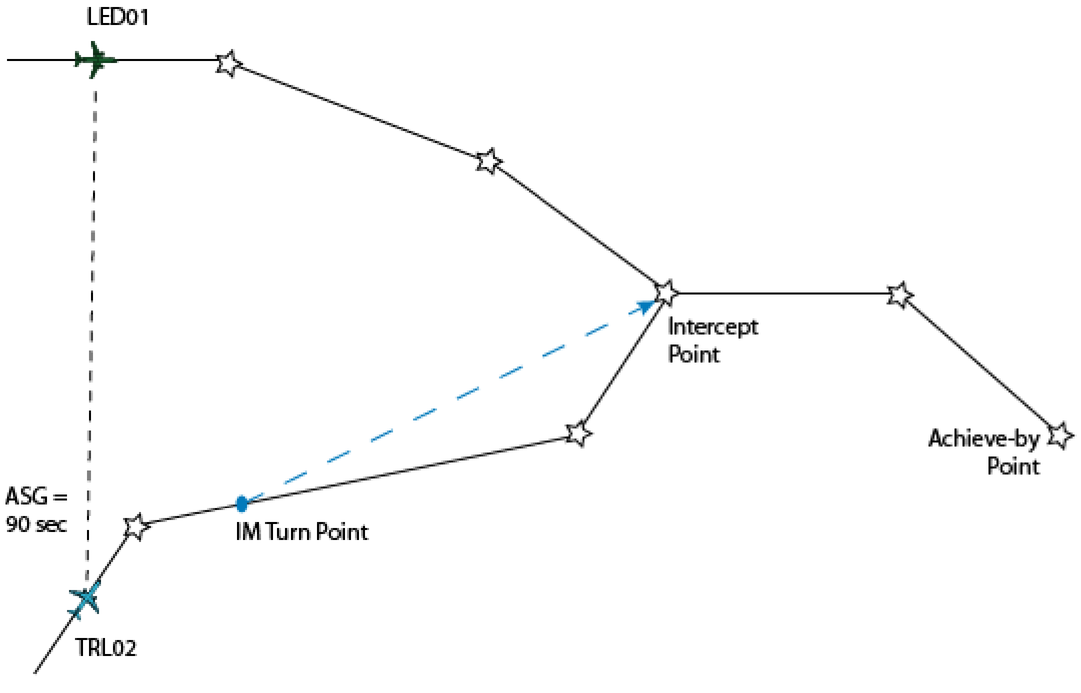


Figure 327 – IM Scenario #3a: Arrival & Approach with OPD & High Altitude Merge

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

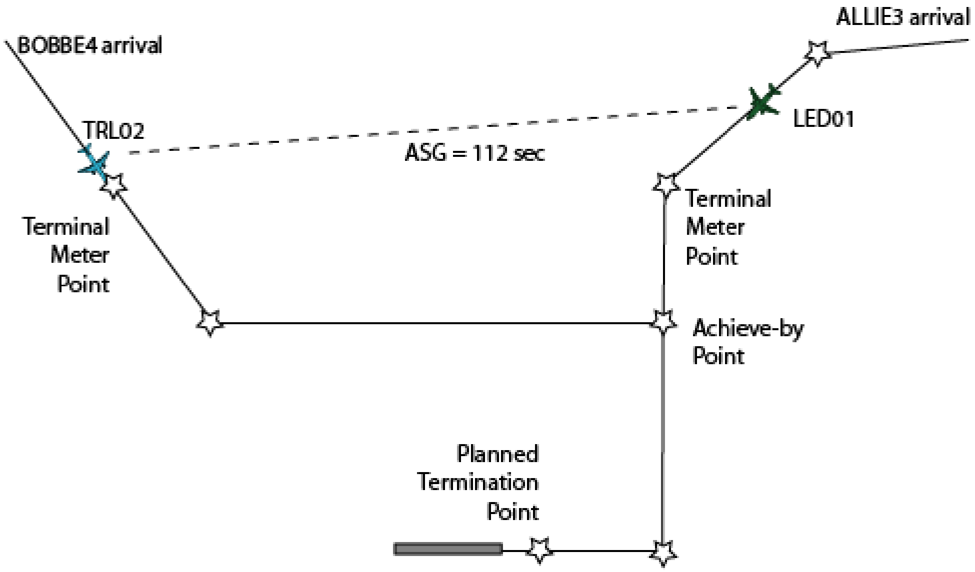


Figure 328 – IM Scenario #3b: Arrival & Approach with OPD & Terminal Area Merge

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

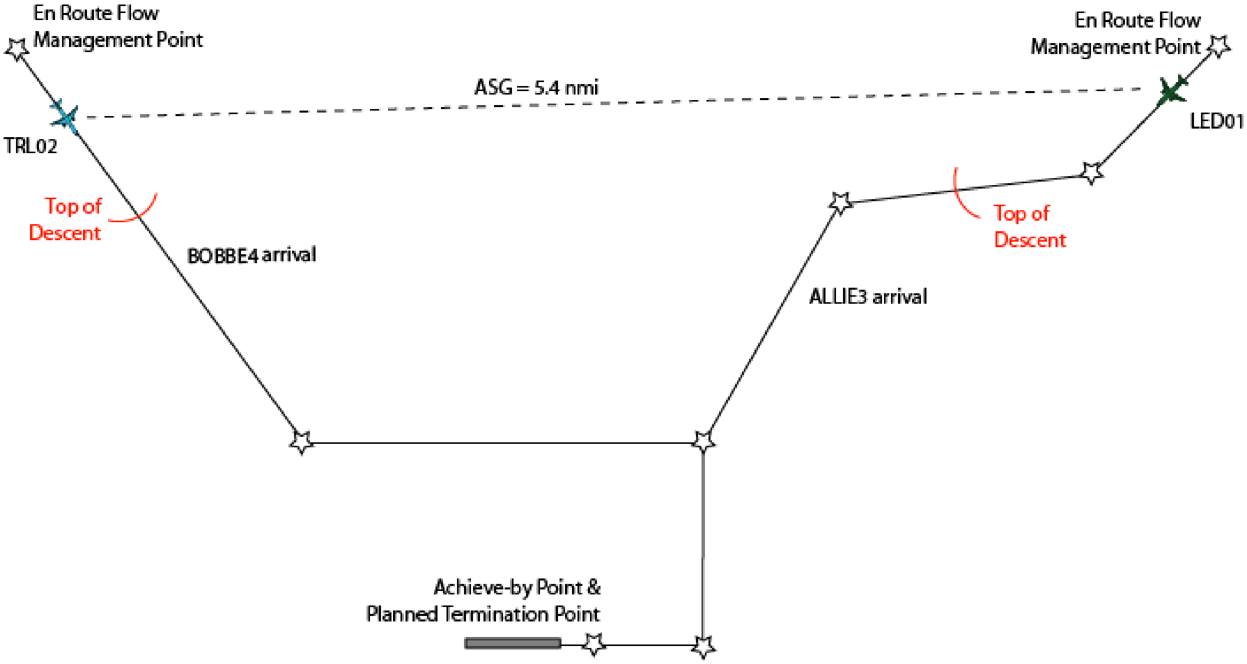


Figure 329 – IM Scenario #3c: Arrival & Approach with OPD to Final Approach Fix

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

27.1.2.4 IM Scenario #4: Final Approach Spacing

In this scenario, controllers are delivering aircraft to the airport using tactical vectors and altitude step-downs. In lieu of a specific speed assignment, the use of IM in this scenario will enable ATC to assign a spacing goal that could improve the precision of the interval between successive arrivals.

In scenario #4 (Figure 330), the lead aircraft (LED01) is arriving from the east and has just turned onto the base leg of the traffic pattern at 5000 ft. The trail aircraft (TRL02) is arriving from the west and is established on long final at 6000 ft. The controller vectors LED01 to a heading of 060 degrees to intercept the ILS to runway 9 and clears them to descend to 3000 ft. TRL02 is cleared to descend to 5000 ft. Once LED01 is established on the localizer, the controller will descend TRL02 to 3000 ft. The ILS approach has aircraft crossing waypoint “APPR1” at 3000 ft and the final approach fix at 1700 ft.

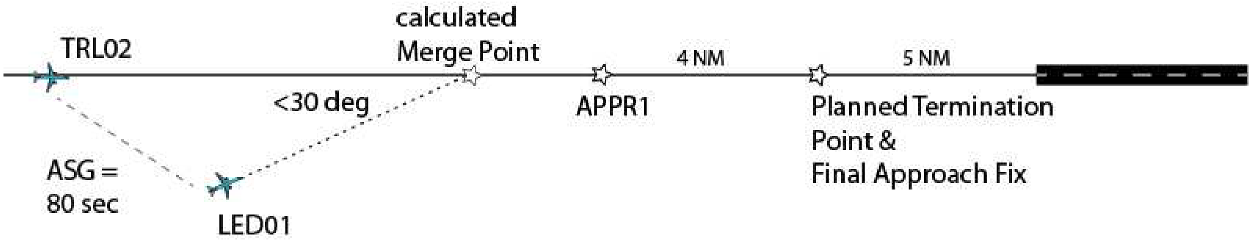


Figure 330 – IM Scenario #4: Final Approach Spacing

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 of RTCA DO-328A, April 2014.]

27.1.2.5 IM Scenario #5: Crossing Runways

In this scenario, the airport is using two crossing runways for arrivals. The goal is to interweave arrivals to the two runways to increase throughout. One aircraft can land on Runway 13 and after it crosses through the runway intersection, the next can land on Runway 22 and so on.

Figure 331 depicts the scenario, where the lead aircraft (LED01) is landing on Runway 13. The trail aircraft (TRL02) is instructed by the controller to maintain their current course and turn direct to FAF223 so that they arrive at the threshold of Runway 22, 40 seconds after LED01 crosses the threshold of Runway 13. The 40 seconds is enough time to ensure that LED01 is clear of the intersection between Runways 13 and 22.

This scenario includes the following aspects of IM operations:

- Non-Coincident routes; and
- Turn maneuver.

Aircraft LED01 and TRL02 are arriving at LGA such that LED01 will land on RWY13 followed by TRL02 landing on RWY22. LED01 is flying the RNP WESTY1 Arrival to RW13 and is on the leg that is direct to FAF133, which is on the extended final 3 miles from the FAF13. TRL02 is on the EASTY1 RNP to RWY22, and given an IM Turn instruction by ATC to turn direct to FAF223 to achieve an Assigned Spacing Goal of 40 seconds relative to LED01. The design of the arrival routes includes the identification of the Achieve-by-Point (RWY22), the Intercept Point (FAF223), and the Target Reference Point (RWY13) as well as the use of a Precise Assigned Spacing Goal of 40 seconds. The FIM Equipment on TRL02 predicts when TRL02 is expected to begin its turn to FAF223 so that the TRL02 aircraft will arrive at the runway threshold, RWY22, nominally 40 seconds after LED01 has reached the threshold of RWY13.

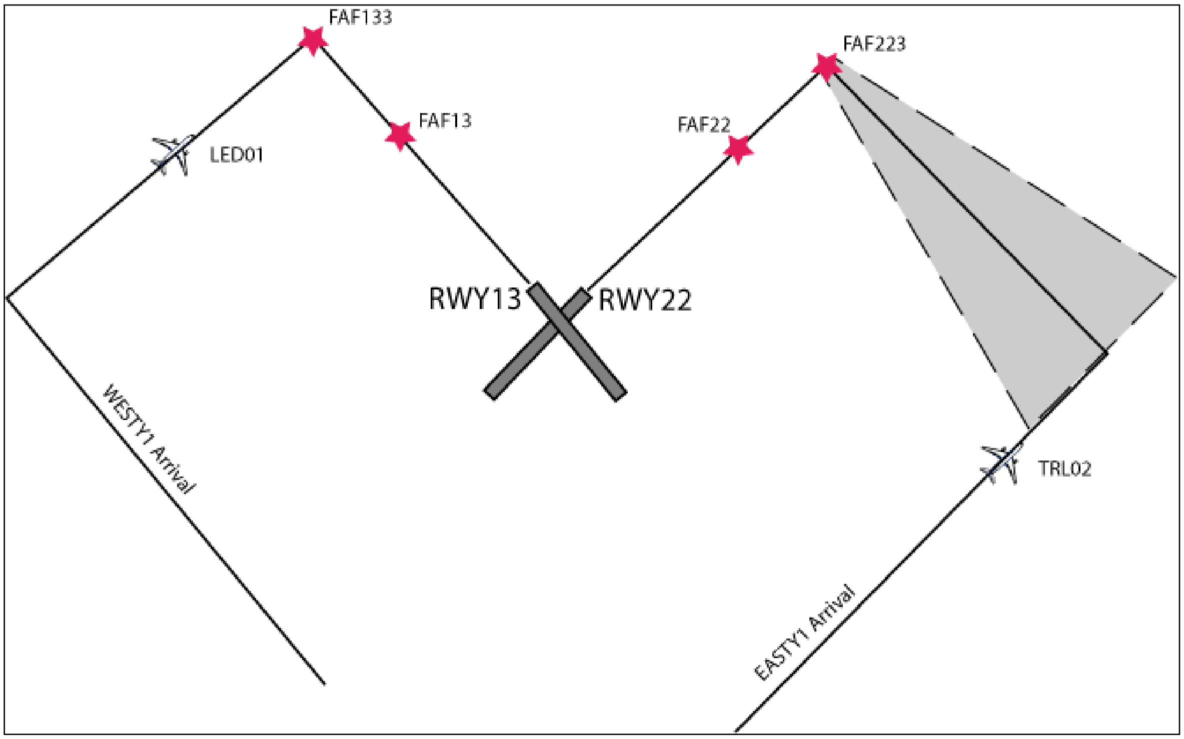


Figure 331 – IM Scenario #5: Crossing Runways

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, RTCA DO-328, May 19, 2011.]

27.1.2.6 IM Scenario #6: Departure Spacing

In this scenario (see Figure 332), the controller is using IM to provide spacing between lead aircraft LED01 and trailing aircraft TRL02 as they depart different airports, but are routed through the same departure fix.

This scenario includes the following aspects of IM operations:

- No closer than Assigned Spacing Goal; and
- Spacing during climb.

After TRL02 has departed airport KTWO and is climbing, the controller instructs it to cross PYD, a departure fix on its assigned departure route, at an Assigned Spacing Goal of no closer than 65 seconds behind LED01. TRL02 follows their departure route managing speed to achieve the Assigned Spacing Goal. After crossing waypoint PYD, the IM Operation is terminated, and the aircraft continue their way on different flight paths.

Figure 333 illustrates three different types of traffic geometries for initial departure climb. Going from the left to the right of this figure, part “A” depicts the IM and target aircraft on the same climbing path, part “B” depicts the IM and target aircraft on different initial climb paths and merging, and part “C” depicts climbing aircraft on parallel paths.

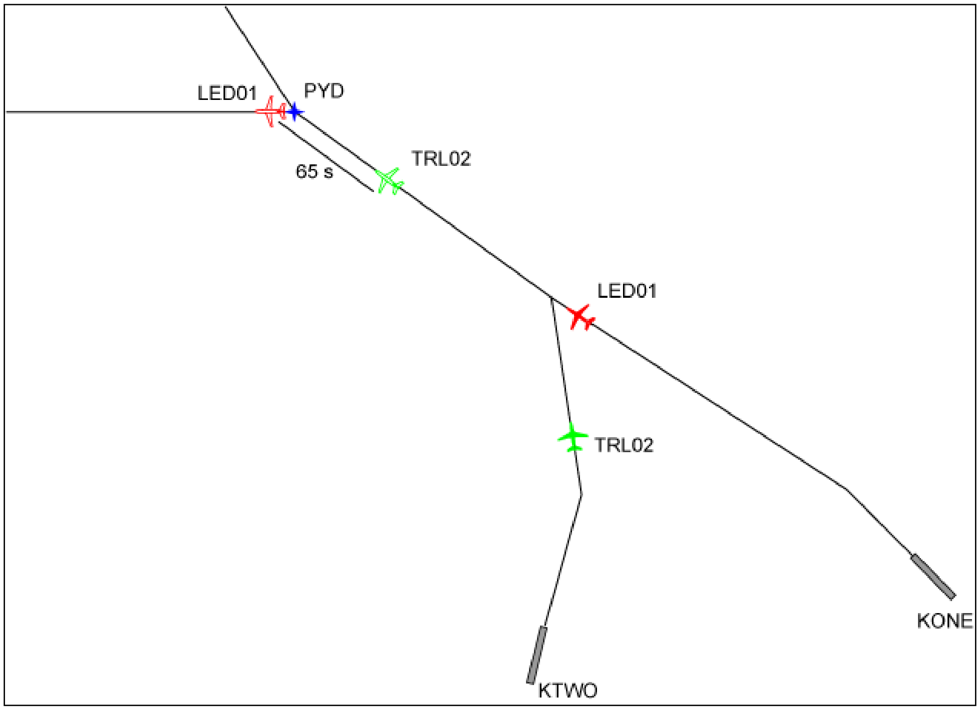


Figure 332 – IM Scenario #6: Departure Spacing

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, RTCA DO-328, May 19, 2011.]

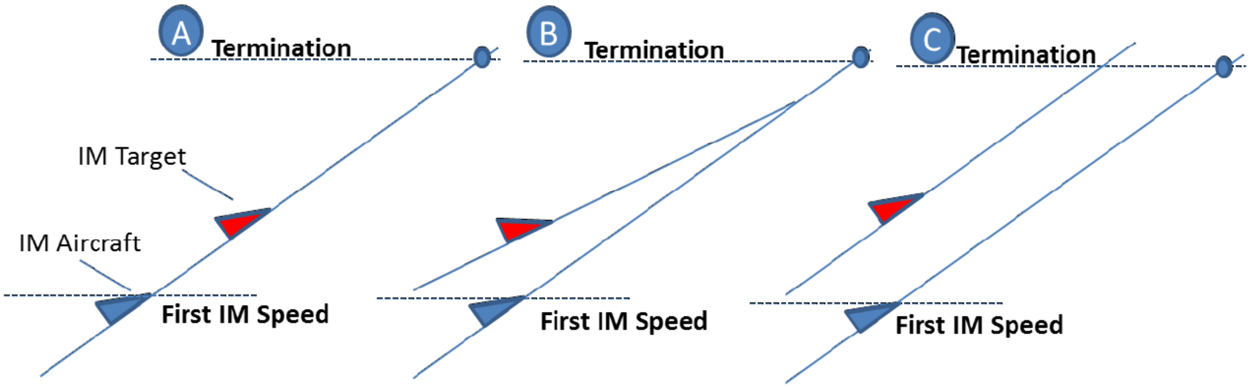


Figure 333 – Traffic Geometries for Three Types of IM Initial Departure Climb

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

27.1.2.7 IM Scenario #7: Dependent Runway Spacing

In this scenario (see Figure 334), dependent parallel operations are occurring at an airport. The controller provides a separation distance from both the in-trail aircraft and a stagger separation from aircraft on the parallel approach runway. The stagger separation is required once both aircraft are established on their final approach course. IM Operations using two targets can support the controller in meeting both of these goals.

This scenario includes the following aspects of IM operations:

- Two-target operations;
- Spacing to the runway threshold; and
- Non-coincident routes.

Aircraft TRL03, REF02, and LED01 are all arriving at an airport such that LED01 and TRL03 are landing in sequence on Runway 19R and REF02 is landing on 19L. There is a large enough gap in front of LED01 that LED01 is not performing IM Operations. Stagger operations at the airport are being used so an IM Clearance is given to TRL03 to achieve 130 seconds behind LED01 and 60 seconds relative to REF02 at the runway threshold.

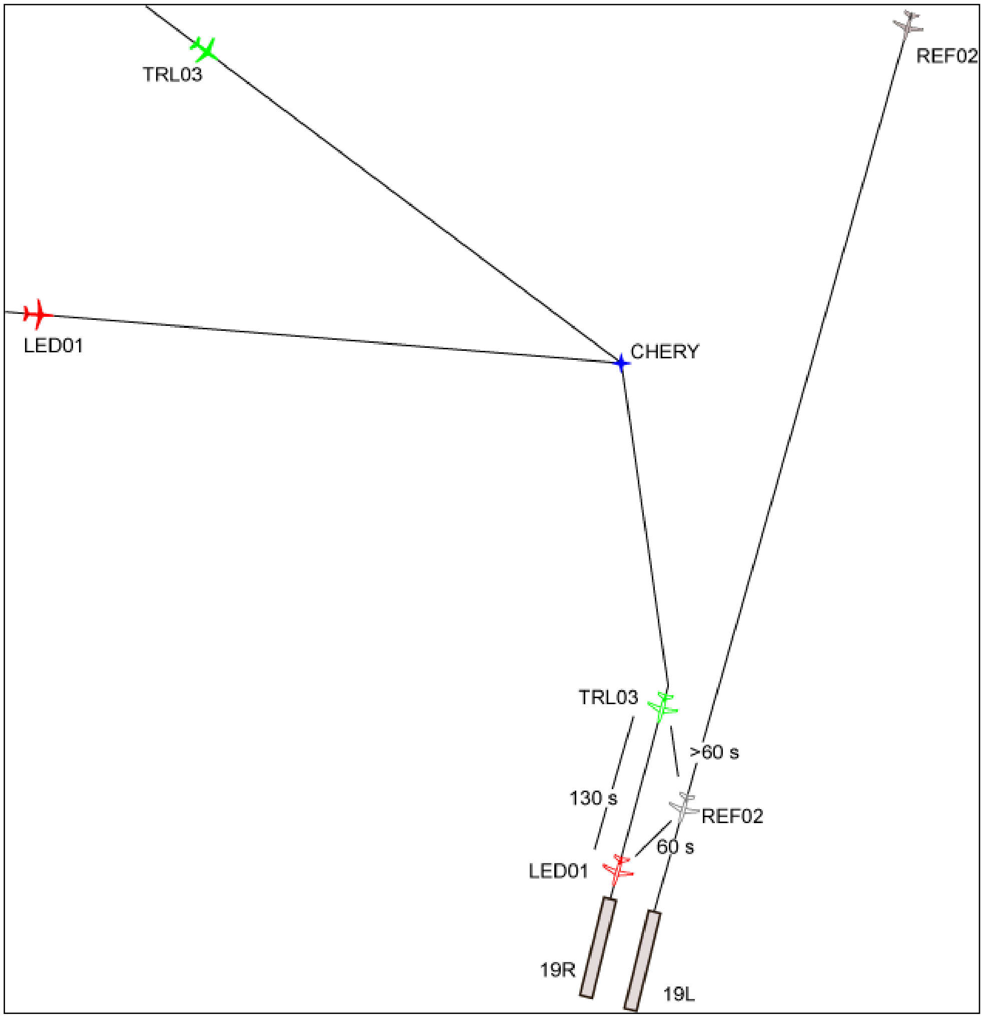


Figure 334 – IM Scenario #7: Dependent Runway Spacing

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, RTCA DO-328, May 19, 2011.]

27.1.3 IM Phases of Operation

For the purposes of this use case analysis, the IM application has been broken down into four phases of operation including:

1. Pre-initiation
2. Initiation
3. Execution
4. Termination

These four phases of IM operation are briefly described in the subsections below.

27.1.3.1 Pre-Initiation Phase

In the pre-initiation phase, the controller evaluates the traffic pattern and evaluates if an IM Operation is appropriate for ATM and, if so, what type of IM Clearance is most appropriate to meet the operational needs. The pre-initiation activities therefore include the determination by the controller (or associated ground tools) for the type of IM Clearance that will best support meeting the operational need, the appropriate IM special points (e.g., Achieve-by, Intercept, and Termination Points), and value of the spacing goals and tolerances to be used, given the desired operations and current operational environment.

27.1.3.2 Initiation Phase

The controller determines that the use of IM would be beneficial. After determining that the IM Operation can be successfully performed, including that the IM and Target Aircraft are able to participate, the controller instructs the IM Aircraft (by issuing an IM Clearance) to conduct the IM Operation. Before accepting the IM Clearance, the flight crew checks that the criteria are met to begin executing the IM Clearance.

27.1.3.3 Execution Phase

After the flight crew accepts the IM Clearance, the IM Aircraft executes the IM Operation. An IM Speed from FIM equipment is essentially equivalent to a speed instruction from the controller. The flight crew is expected to implement the IM Speed changes, and the IM Turn (when applicable), in a timely manner consistent with other cockpit duties. There are three stages in the Execution Phase: Achieve, Maintain, and Suspend.

- In the Achieve Stage which is part of normal execution, the flight crew implements the IM Speeds in order to achieve the Assigned Spacing Goal at the Achieve-by Point.
- In the Maintain Stage which is part of normal execution, the flight crew implements the IM Speeds to continually maintain the Assigned Spacing Goal.
- In the Suspend / Resume Stage which is expected to be used infrequently, the controller wishes to suspend the current IM Operation and transition to non-IM Operations with the intention of resuming the IM Operation at a later time. This may be used, for example, to handle a short duration event such as needing to maneuver the IM Aircraft for separation assurance or due to a temporary loss of the Target Aircraft surveillance information at a sufficient quality that supports being a valid IM Target aircraft for the current IM Operation.

During the execution of the IM Operation, the controller continues to monitor the IM Aircraft to ensure separation from all aircraft, including the Target Aircraft, and to ensure that the IM Clearance is still consistent with the orderly and efficient flow of traffic. The flight crew monitors the IM Operation to detect whether the operation has become infeasible and that the IM Speeds are operationally acceptable.

27.1.3.4 Termination Phase

Termination is accomplished when the FIM Equipment no longer provides IM Speeds and removes any IM Speeds displayed on the FIM Equipment's interface. The termination phase may occur automatically when the aircraft reaches the Planned Termination Point; when an internal situation occurs that prevents valid IM Speeds from being presented; or by direct action of the flight crew. The controller may also terminate the IM Clearance if it is no longer meeting goals or expectations.

27.1.4 IM Use Case Activity Diagrams with Communication Phases Highlighted

The four phases of IM operation were overviewed in Section 27.1.3 above. This section provides use case activity diagrams that identify the activities that occur during each phase of IM Operations. Figure 335 illustrates the pre-initiation phase, Figure 336 the initiation phase, Figure 337 and Figure 338 the execution phase, and Figure 339 the termination phase.

The specific actions or decisions being made in each step are identified as being done by either the aircraft (AC) or ground (GND) domain "actors." Where applicable, further specificity is provided to the specific actions taken by the aircraft flight crew (AC-FC), the aircraft avionics (AC-AV), and ground air traffic controllers (GND-ATC). The steps in the use case diagrams where communications occur are highlighted with yellow shading on the figures, and an indication of whether the information is communicated from aircraft-to-ground (A-G), ground-to-aircraft (G-A), or aircraft-to-aircraft (A-A) is provided.

The specific information needed to perform each of the use case steps is identified in Appendix A of RTCA/DO-328.

Pre-Initiation

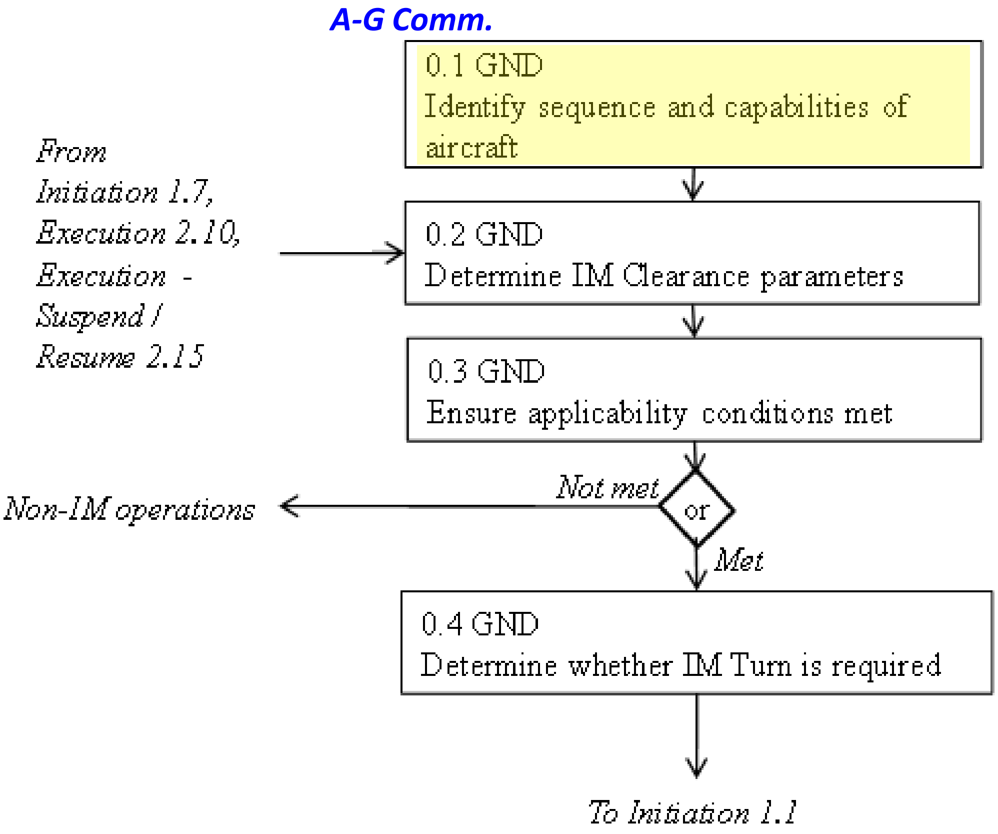


Figure 335 – IM Pre-Initiation Phase Activity Diagram

[Reference: Modified from Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

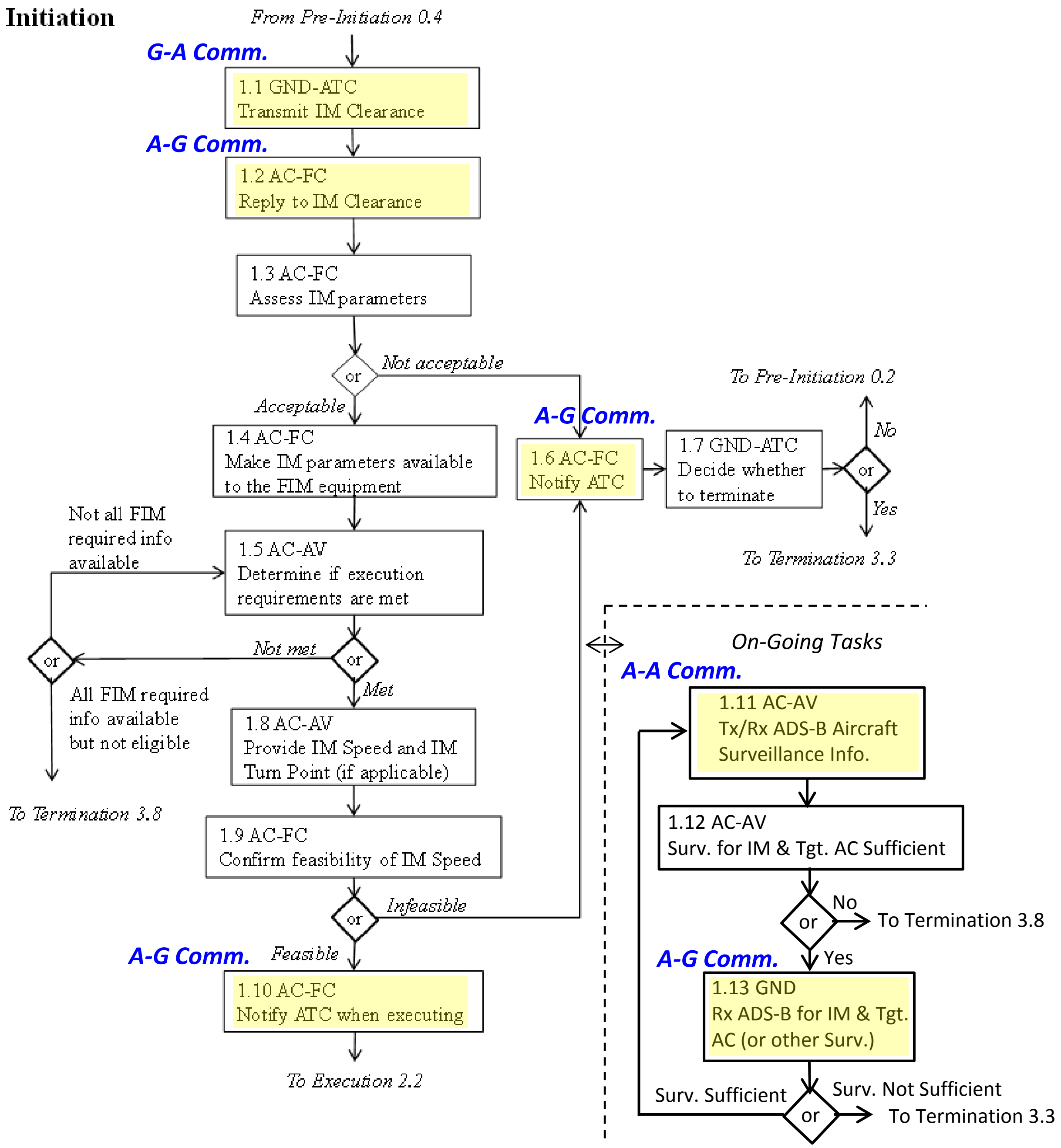


Figure 336 – IM Initiation Phase Use Case Activity Diagram

[Reference: Modified from Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

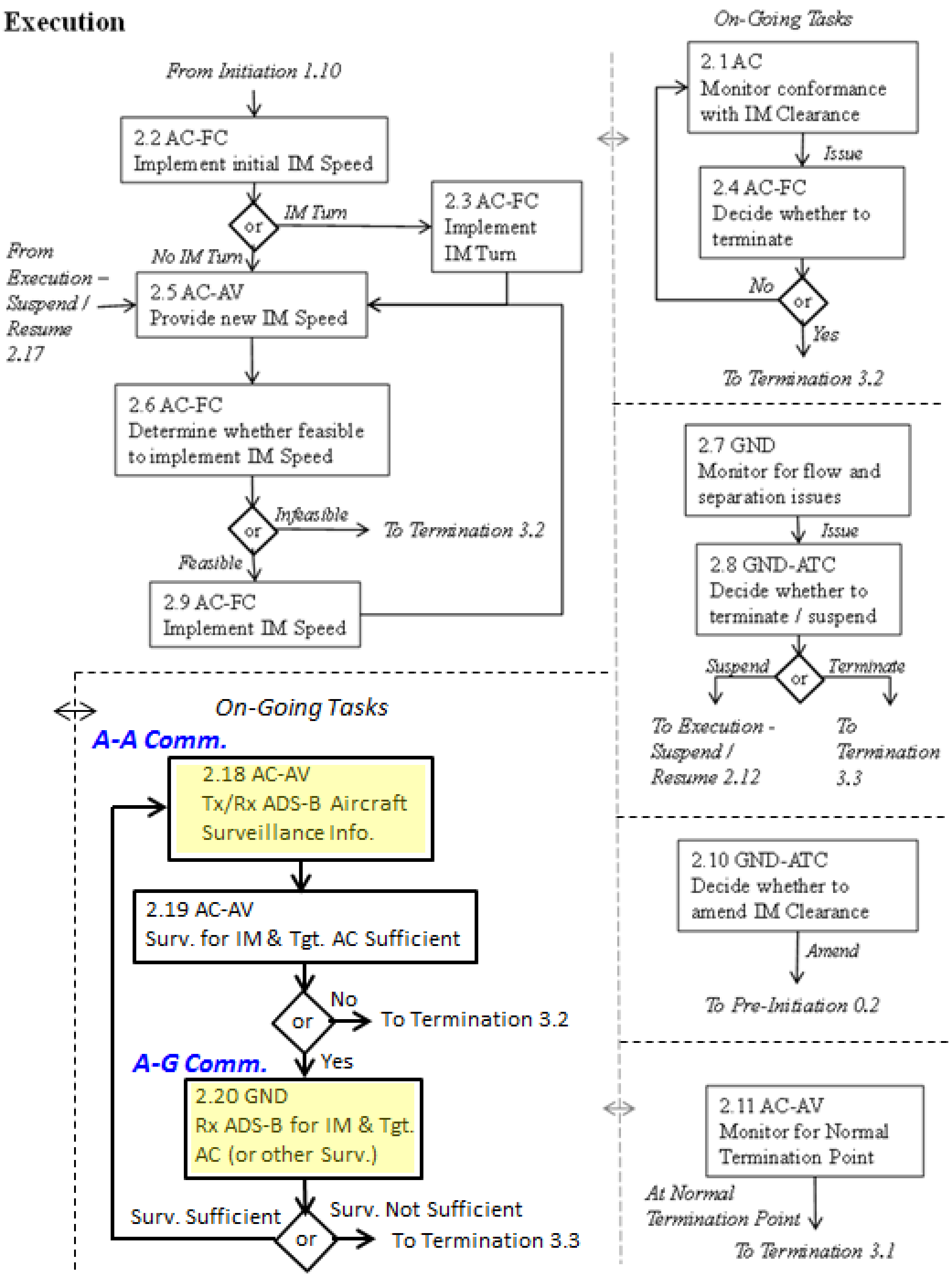


Figure 337 – IM Execution Phase Use Case Activity Diagram – Part 1 of 2 (Normal Execution)

[Reference: Modified from Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

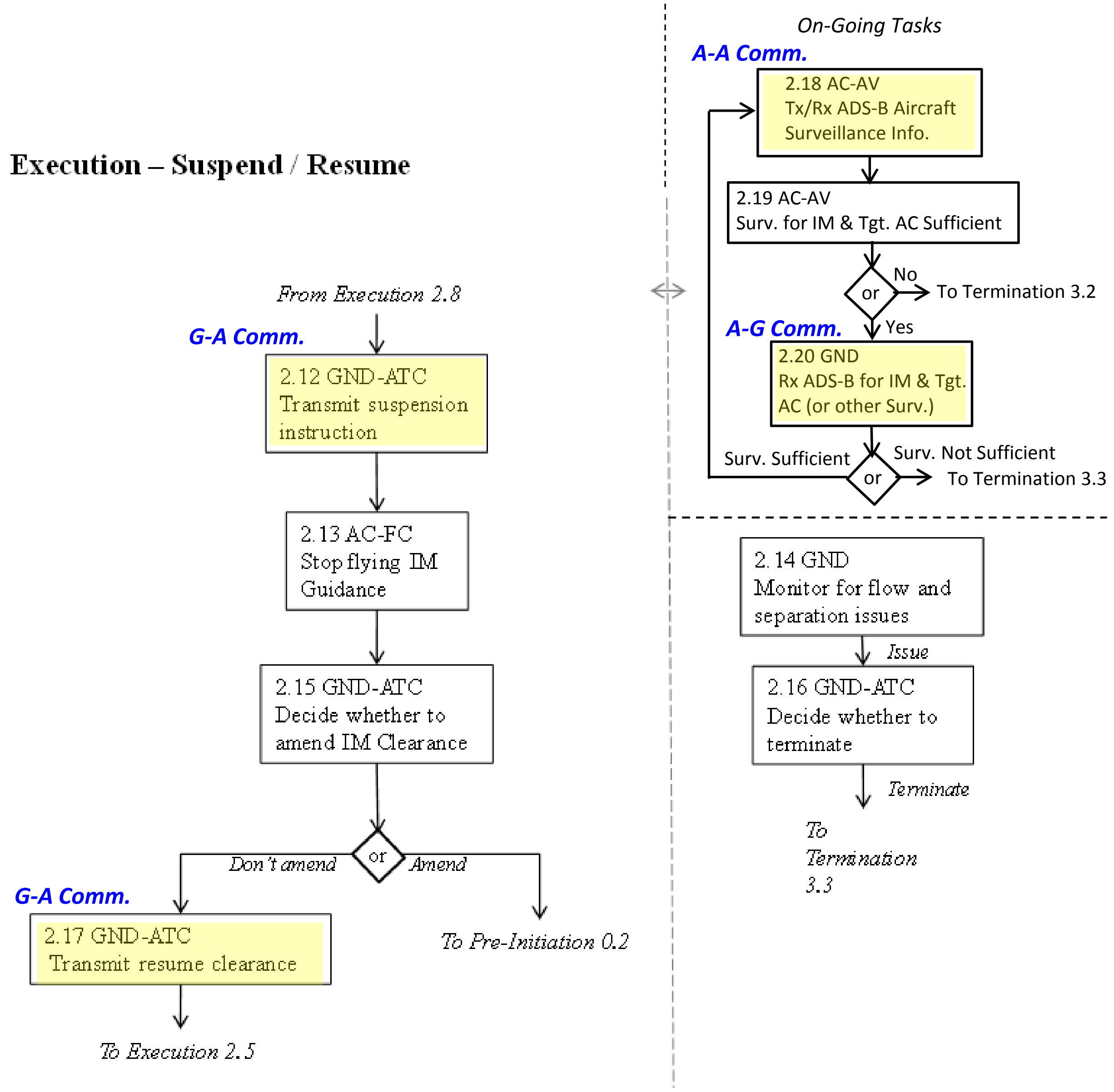


Figure 338 – IM Execution Phase Use Case Activity Diagram – Part 2 of 2 (Suspend / Resume)

[Reference: Modified from Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

Termination

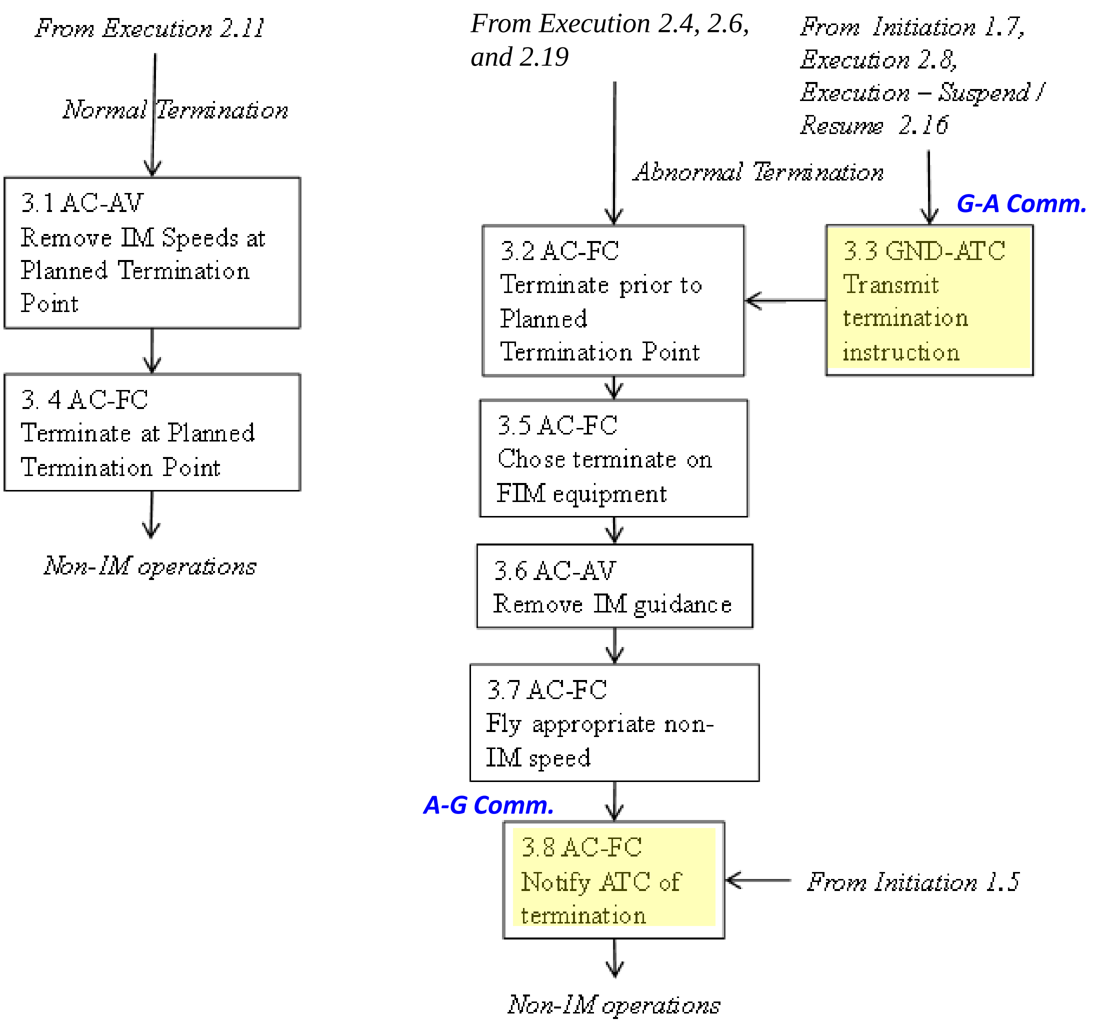


Figure 339 – IM Termination Phase Use Case Activity Diagram

[Reference: Modified from Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, draft V1.01 RTCA DO-328A, April 2014.]

27.1.5 IM Communications Information and Infrastructure

The communications information and infrastructure required to enable the IM application is described in the subsections below for the aircraft-to-aircraft, ground-to-aircraft, and aircraft-to-ground communication domains.

27.1.5.1 IM Aircraft-to-Aircraft Communications

The A-A communications infrastructure to support flight deck IM includes the transmission and reception of aircraft-to-aircraft surveillance information between the IM Target Aircraft (one or more lead aircraft) and the IM Aircraft (trailing/spacing aircraft). The communicated surveillance information needs to be of sufficient quality to support the operation. The RTCA flight deck IM safety and performance requirements document specifies the minimum ADS-B A-A surveillance information and data quality requirements (i.e., see RTCA/DO-328 or later revision and as of this writing an RTCA FIM MOPS is in the process of being developed). The FAA's 2020 ADS-B Out mandated minimum performance has been developed to be of sufficient quality to support the flight deck IM operation. Future IM applications that specify very tight IM Tolerances may need performance above and beyond the minimum performance specified in the FAA's 2020 ADS-B Out rule. The communication requirements for FIM include having the availability of surveillance information as sufficient quality, which includes for example, having position information with at least 0.1 NM accuracy (95%) and 0.2 NM integrity bound (with an integrity risk not to exceed 1 x 10^{-5} per flight hour) that has a received update interval not to exceed 12.1 seconds (95%) with a latency less than or equal to 2 seconds [reference: DO-328]. These levels of required FIM A-A communications performance for the surveillance information can be met with the A-A communication candidates identified in Section 26.1.

In addition, A-A communications will be needed to support the aircraft-based collision avoidance function of TCAS or the future TCAS enhancement (i.e., ACAS-X). Over the years, the aircraft-based collision avoidance function is expected to become less dependent upon today's TCAS 1030/1090 MHz interrogations/replies and more reliant on ADS-B Out broadcasts for surveillance information, or some combination thereof (i.e., hybrid surveillance).

27.1.5.2 IM Ground-to-Aircraft Communications

The IM application requires specific information to be communicated between ATC and the IM Aircraft. In general, this communication can be supported via both voice and data communications. However, it is envisioned that over time, IM communications will become mostly supported by data comm.

For the G-A (and A-G) communications to support IM, the communications infrastructure will need to meet the performance necessary for the delivery (G-A) and reply (A-G) of ATC safety services within the airspace where the IM operation is being conducted. This minimum performance varies as it does today in different ATC controlled airspaces. It is anticipated that in the future as traffic densities increase, aircraft separations are reduced, and security requirements are added, the communications performance requirements associated with the delivery and reply to ATC clearances may be increased. The candidates that meet the IM A-G and G-A communication requirements in the various airspaces are identified in Section 26.1.

To support IM Operations, the following information is communicated from the Ground Domain (ATC) to the IM Aircraft as part of the IM Clearance communications [reference: RTCA/DO-328]:

- Target Aircraft Identification;

- Assigned Spacing Goal [i.e., if may be in terms of distance or time, and may be a “precise value” (e.g., 90 seconds), “at or greater interval” (e.g., 90 seconds or more”), or a “closed interval” (e.g., 90 to 120 seconds)];
- IM Clearance Type; [e.g., Achieve-by then Maintain, Maintain Current Spacing, and IM Turn]
- Starting Event (as applicable); [e.g., a specific event such as reaching a specified altitude or waypoint, a specific time, or a time after the IM Clearance is received, (e.g., as soon as possible/immediate, when able, when able after a specific event X, expected, etc.]
- Achieve-by Point (as applicable);
- Intercept Point (as applicable);
- Planned Termination Point (as applicable);
- IM Tolerance (used to define the operationally acceptable spacing objective region, see Figure 340 and Figure 341);
- Performance Level;
- Target Aircraft Intended Flight Path Information, and
- Other (optionally) constraints [e.g., speed, altitude, safety zone parameters (for paired approach), etc.].

The Target Aircraft intended flight path information may be the same route or procedure as the IM Aircraft, direct to a common point, one or more sequence of named procedures, sequence of waypoints, sequence of latitude/longitude pairs, on a heading or intercept to a final approach course, or any combination of the above.

Note that the IM Clearance information may be explicitly communicated on an approved ATC safety services communication link, or may be communicated indirectly. For example, indirect communications may include: a) context specific implication that the IM Target Aircraft and IM Aircraft will fly the same routes unless otherwise indicated, b) reference to standard routes or procedures or IM-specific standardized clearance procedures stored onboard the aircraft supplemented by procedure specific dynamic information (e.g., to designate the IM Target Aircraft), and c) communication for much of the clearance using a non-ATC safety services link with a short data communication on an ATC safety services link that provides integrity/security verification, or d) combinations of the above.

Note also that as of this writing, a draft revision of DO-328A and draft FIM MOPS have removed IM Tolerance and Performance Level as minimum required communication parameters that were included in the original DO-328 (FIM SPR) for the IM Clearance information. It is anticipated that these parameters will be reincorporated into IM Clearance over the longer term to address a wider range of future airspace and operational needs [e.g., when using IM in different operating environments/airspaces (oceanic vs. terminal area) and when using alternative/backup PNT sources for navigation and surveillance], and thus have been retained for the purposes of this study.

The IM Tolerance is used to define the operationally acceptable objective region for conducting the IM operation. It is defined as the bounds on the difference between the Spacing Interval and the Assigned Spacing Goal at the Achieve-by-Point or during the Maintain Stage within which the goals of the IM Operation are intended to be met. Figure 340 depicts the IM Tolerance relevant to a “precise” Assigned Spacing Goal, and Figure 341 depicts the IM Tolerance with an “at or greater than” Assigned Spacing Goal. Operational needs will drive the specification of different IM Tolerances. For instance, an IM Tolerance of +/- 6 seconds may be operationally needed for IM approach operations at high density airports, while larger (less restrictive) IM Tolerances of on the order of +/- 30 seconds may be operationally acceptable for IM enroute operations, and even larger IM Tolerances greater than +/- 45 seconds may be operationally acceptable in oceanic/remote/polar airspaces.

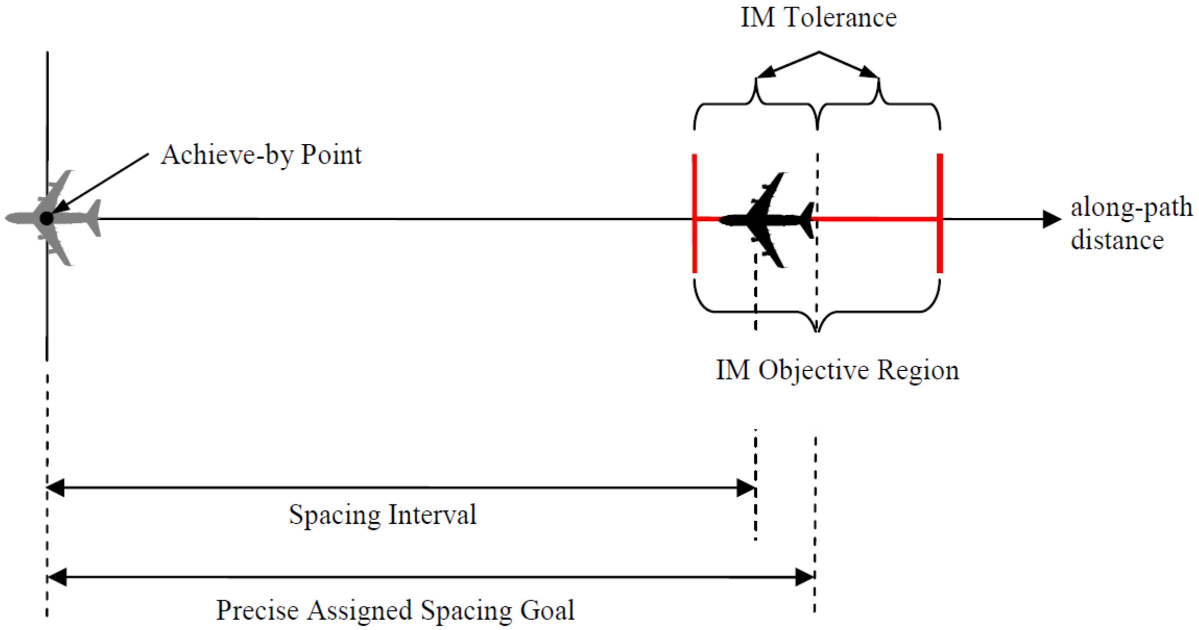


Figure 340 – IM Tolerance with Precise Assigned Spacing Goal

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, RTCA DO-328, May 19, 2011.]

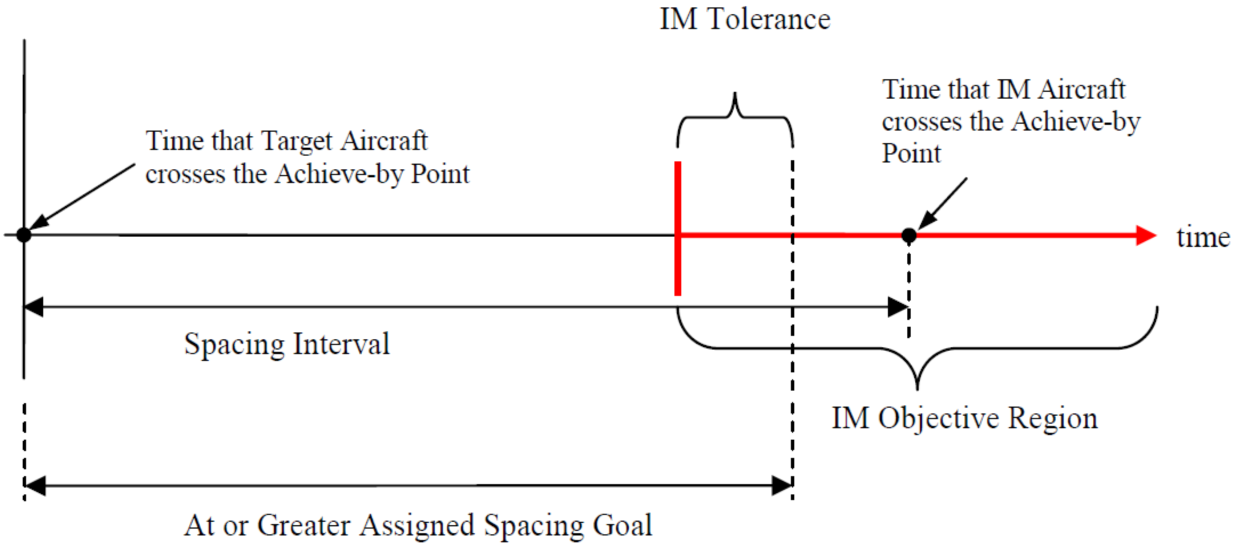


Figure 341 – IM Tolerance with At or Greater Than Assigned Spacing Goal

[Reference: Safety, Performance, and Interoperability Requirements Document for Airborne Spacing – Flight Deck Interval Management, RTCA DO-328, May 19, 2011.]

In addition to the aforementioned IM clearance information, ATC may at any time during the execution of the IM operation command the flight crew to terminate, suspend, or change the IM clearance.

27.1.5.3 IM Aircraft-to-Ground Communications

The IM Aircraft responds to ATC clearances received from the ground indicating that it will comply, or will not be able to comply with the clearance and will seek other instruction. The IM Aircraft needs to inform ATC when it is executing, suspending, terminating, or cannot execute the IM operation. Some IM intended uses will necessitate that the IM Aircraft communicate other operationally relevant information to ATC, like the planned final approach speed (see IM Scenario #3 in Section 27.1.2.3). Some IM concepts of operation have the IM Aircraft communicate the applications that it is capable of performing such that ATC is aware of whether or not FIM is installed and operational on the aircraft. Such information could also be known by ATC in other ways (e.g., part of the filed flight plan), and not require specific A-G communications.

In addition to supporting the delivery of IM specific communications, typically (but not required if there is other suitable surveillance information) A-G communications of ADS-B surveillance information from the IM and Target Aircraft will likely be required as the primary means of ATC aircraft surveillance. It is anticipated that backup/supplemental ATC surveillance information will come from Secondary Surveillance Radars (SSR) (which require G-A interrogations and A-G reply communications) as well as primary radar. It is anticipated that in the future the SSR interrogation rate and the resulting aircraft replies will be reduced with ground hybrid surveillance techniques that integrate ADS-B, SSR, and primary radar information.

27.1.5.4 Data Communication Information Requirements for IM

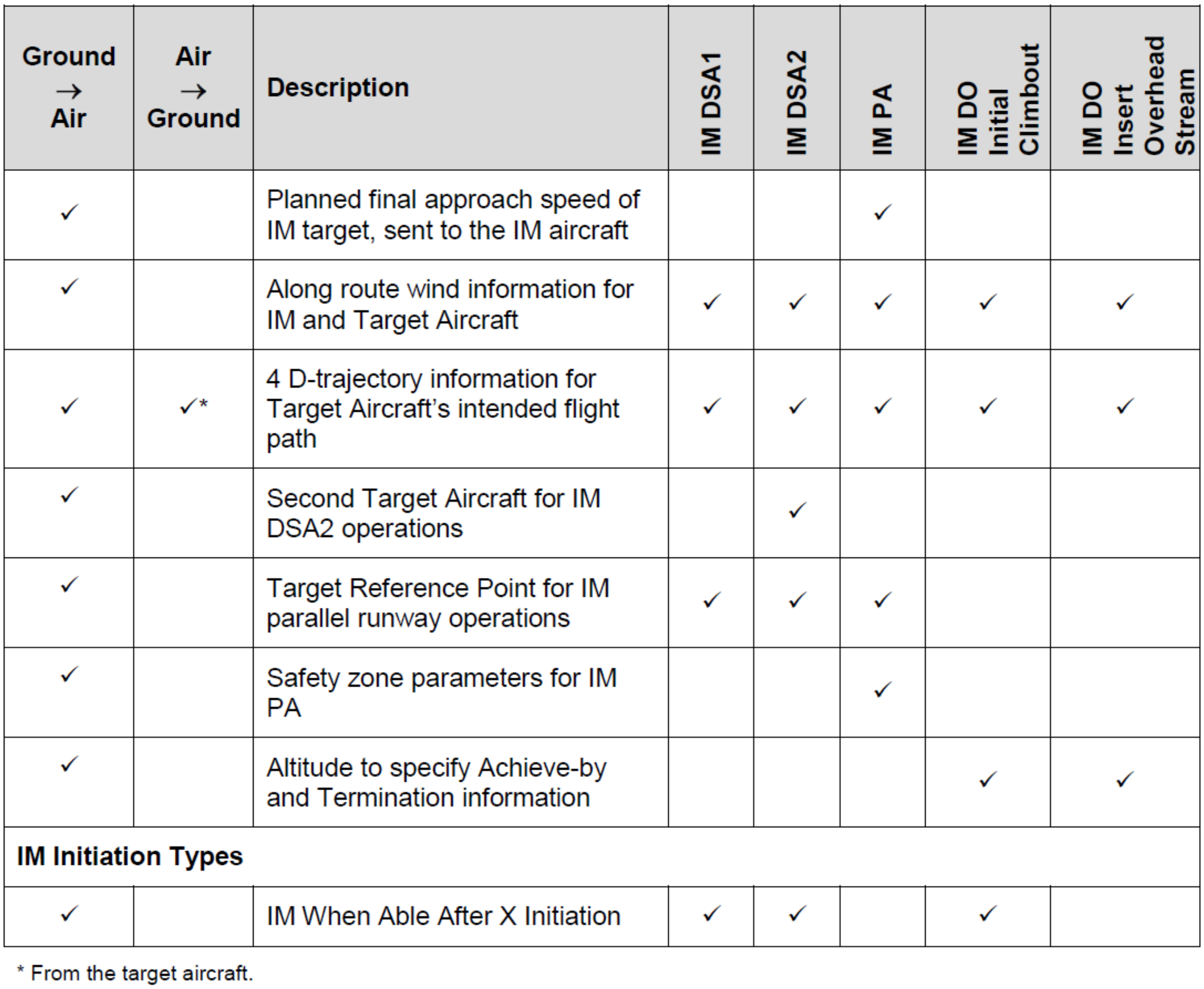
This section summarizes the information that needs to be communicated to support Baseline and Advanced IM operations as of this writing. The information requirements are derived from the operational scenarios described previously.

Figure 342 lists the Data Communication for the Baseline IM application as defined in the FAA’s Advanced Interval Management, Preliminary Concept of Operations document (Version 1.0 dated March 27, 2014) that is aligned with the currently defined Data Comm as defined by RTCA in the Safety and Performance Standard for Baseline 2 ATS Data Communications (PU-10 SPR, Version N, 20 December, 2013). Figure 343 lists elements for more advanced IM operations beyond the baseline IM data communications messages. Note the following terminology is used in the figures: 1) “IM DSA1” and “IM DSA2” stand for IM Dependent Staggered Approaches with one and two targets, respectively, 2) the term “IM DO” stands for IM Departure Operations, 3) “DM” stands for Downlink Message, and 4) “UM” stands for Uplink Message.

Ground → Air	Air → Ground	Description	IM DSA1	IM DSA2	IM PA	IM DO Initial Climb	IM DO Insert Overhead Stream	Baseline Data Comm Msg
	✓	Planned final approach speed	✓	✓	✓			DM149
✓		Suspend FIM	✓	✓	✓	✓	✓	UM337
✓		Resume FIM	✓	✓	✓	✓	✓	UM338
	✓	FIM changes to active	✓	✓	✓	✓	✓	DM150
✓		Cancel FIM	✓	✓	✓	✓	✓	UM339
	✓	Unable to continue FIM	✓	✓	✓	✓	✓	DM153
IM Initiation Types								
✓		IM Immediate	✓	✓			✓	UM330
✓		IM When Able	✓	✓			✓	UM330 & UM332
✓		Expect IM Initiation			✓			UM331

Figure 342 – IM Baseline Data Comm for G-to-A and A-to-G

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]



Ground → Air	Air → Ground	Description	IM DSA1	IM DSA2	IM PA	IM DO Initial Climbout	IM DO Insert Overhead Stream
✓		Planned final approach speed of IM target, sent to the IM aircraft			✓		
✓		Along route wind information for IM and Target Aircraft	✓	✓	✓	✓	✓
✓	✓*	4 D-trajectory information for Target Aircraft's intended flight path	✓	✓	✓	✓	✓
✓		Second Target Aircraft for IM DSA2 operations		✓			
✓		Target Reference Point for IM parallel runway operations	✓	✓	✓		
✓		Safety zone parameters for IM PA			✓		
✓		Altitude to specify Achieve-by and Termination information				✓	✓
IM Initiation Types							
✓		IM When Able After X Initiation	✓	✓		✓	

* From the target aircraft.

Figure 343 – IM Beyond Baseline Data Comm for G-to-A and A-to-G

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]

27.1.5.5 ATN2 Baseline Messages for FIM

Figure 344 and Figure 345 identify the current uplink messages and Figure 346 the downlink messages for IM from the current ATN2 baseline as defined by RTCA SC-214 in DO-350 entitled "Safety and Performance Standard for Baseline 2 ATS Data Communications (Baseline 2 SPR Standard), as documented in the FAA's Advanced Interval Management Preliminary Concept of Operations, dated March 27, 2014.

With reference to the tables provided in these figures, the first column identifies the Message Identifier (Msg. ID) as an Uplink Message (UM) or Downlink Message (DM) with a message number, the second column contains a brief description of the message intent/use, the third column identifies the message element, the fourth column indicates the alert attributes, the fifth column indicates the response attributes, and the last column indicates who is sending the message (ground "G" or aircraft "A") as well as if the message is mandatory ("M"), optional ("O"), or is mandatory when the specified condition ("C") is met. Thus, "G-M" is a ground ("G") message that is mandatory ("M"). Similarly, "G-O" is a ground ("G") message that is optional

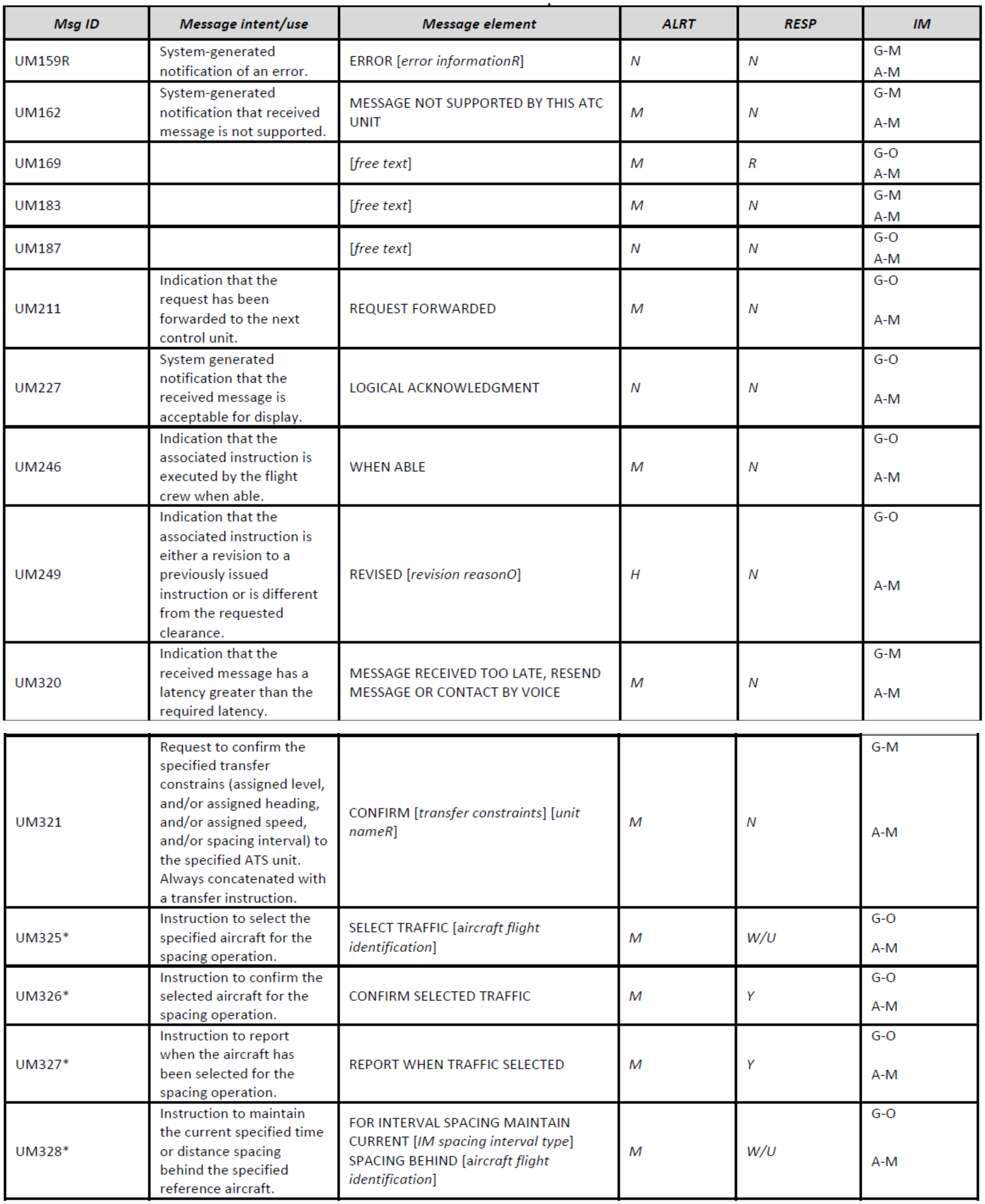
(“O”), and “G-C” is a ground (“G”) message that is mandatory, when the specified condition (“C”) is met. The same applies for aircraft messages, where “A-M” is an aircraft downlink message that is mandatory, “A-O” is an aircraft message that is optional, and “A-C” is an aircraft message that is mandatory, when the specified condition is met.

The alert (ALRT) attribute indicates the type of alerting and queuing required upon message receipt. Distinct indications are used for high (“H”) alert, medium (“M”), and no (“N”) alert downlink messages, to allow prioritized handling of messages when multiple messages are available.

A response (RESP) attribute indicates: a) when a response is required or prohibited, and b) when a response is required, the permitted response messages. A response message contains a message reference number identical to the message identification number of the message to which it refers. The response options are:

- W (WILCO): After the flight crew has determined that they can comply with a received message requiring a W/U response, the flight crew responds with a DM0 WILCO;
- Y (Yes): When the message requires a Y response, the flight crew responds with a CPDLC message;
- U (Unable): After the flight crew has determined that they cannot comply with a received message or do not understand the received message requiring a W/U or R response, the flight crew responds with a DM1 UNABLE;
- R (Roger): After the flight crew has determined that they understand a message requiring a R response, the flight crew responds with a DM3 ROGER; and
- N (None): No response required.

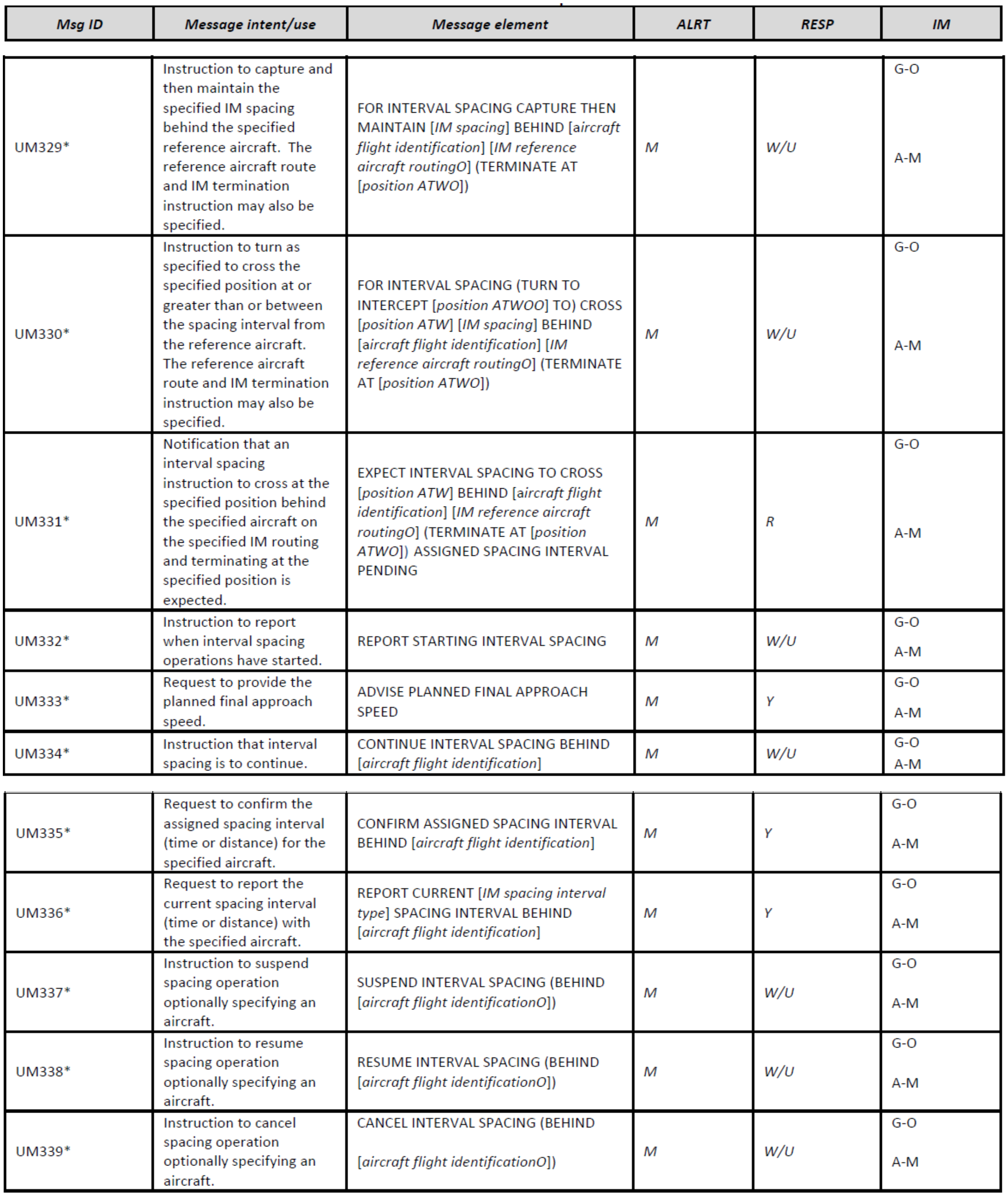
Note that the “*” designation in the Message Identifier (Msg ID) column of Figure 344, Figure 345, and Figure 346 indicates that the message is unique to supporting IM operations.



Msg ID	*Message intent/use*	*Message element*	*ALRT*	*RESP*	*IM*
UM159R	System-generated notification of an error.	ERROR [*error informationR*]	*N*	*N*	G-M A-M
UM162	System-generated notification that received message is not supported.	MESSAGE NOT SUPPORTED BY THIS ATC UNIT	*M*	*N*	G-M A-M
UM169		[*free text*]	*M*	*R*	G-O A-M
UM183		[*free text*]	*M*	*N*	G-M A-M
UM187		[*free text*]	*N*	*N*	G-O A-M
UM211	Indication that the request has been forwarded to the next control unit.	REQUEST FORWARDED	*M*	*N*	G-O A-M
UM227	System generated notification that the received message is acceptable for display.	LOGICAL ACKNOWLEDGMENT	*N*	*N*	G-O A-M
UM246	Indication that the associated instruction is executed by the flight crew when able.	WHEN ABLE	*M*	*N*	G-O A-M
UM249	Indication that the associated instruction is either a revision to a previously issued instruction or is different from the requested clearance.	REVISED [*revision reasonO*]	*H*	*N*	G-O A-M
UM320	Indication that the received message has a latency greater than the required latency.	MESSAGE RECEIVED TOO LATE, RESEND MESSAGE OR CONTACT BY VOICE	*M*	*N*	G-M A-M
UM321	Request to confirm the specified transfer constrains (assigned level, and/or assigned heading, and/or assigned speed, and/or spacing interval) to the specified ATS unit. Always concatenated with a transfer instruction.	CONFIRM [*transfer constraints*] [*unit nameR*]	*M*	*N*	G-M A-M
UM325*	Instruction to select the specified aircraft for the spacing operation.	SELECT TRAFFIC [*aircraft flight identification*]	*M*	*W/U*	G-O A-M
UM326*	Instruction to confirm the selected aircraft for the spacing operation.	CONFIRM SELECTED TRAFFIC	*M*	*Y*	G-O A-M
UM327*	Instruction to report when the aircraft has been selected for the spacing operation.	REPORT WHEN TRAFFIC SELECTED	*M*	*Y*	G-O A-M
UM328*	Instruction to maintain the current specified time or distance spacing behind the specified reference aircraft.	FOR INTERVAL SPACING MAINTAIN CURRENT [*IM spacing interval type*] SPACING BEHIND [*aircraft flight identification*]	*M*	*W/U*	G-O A-M

Figure 344 – Current Baseline ATN2 Data Comm. “Uplink” Info. for IM (Part 1 of 2)

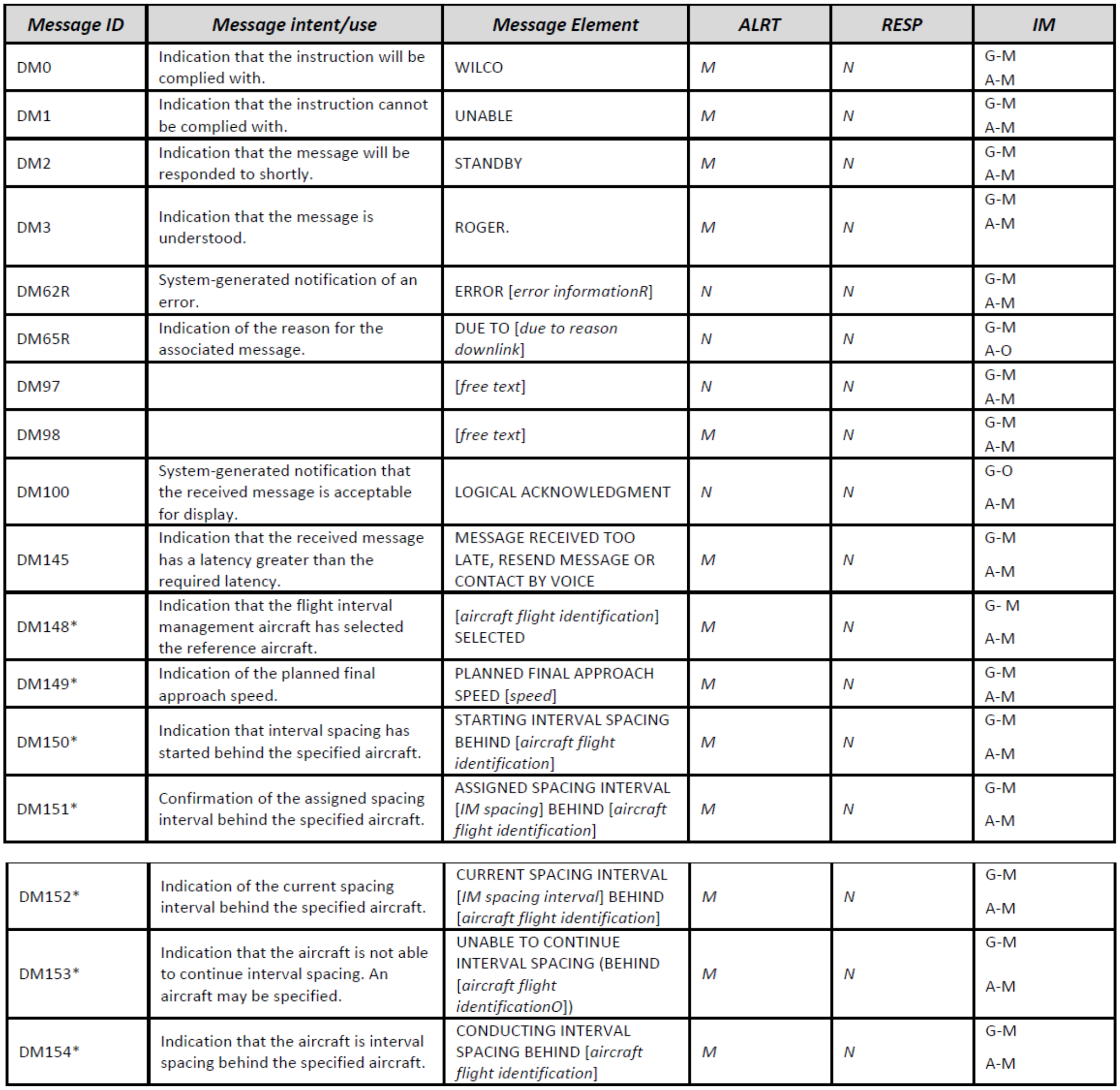
[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]



Msg ID	Message intent/use	Message element	ALRT	RESP	IM
UM329*	Instruction to capture and then maintain the specified IM spacing behind the specified reference aircraft. The reference aircraft route and IM termination instruction may also be specified.	FOR INTERVAL SPACING CAPTURE THEN MAINTAIN [*IM spacing*] BEHIND [*aircraft flight identification*] [*IM reference aircraft routingO*] (TERMINATE AT [*position ATWO*])	*M*	*W/U*	G-O A-M
UM330*	Instruction to turn as specified to cross the specified position at or greater than or between the spacing interval from the reference aircraft. The reference aircraft route and IM termination instruction may also be specified.	FOR INTERVAL SPACING (TURN TO INTERCEPT [*position ATWOO*] TO) CROSS [*position ATW*] [*IM spacing*] BEHIND [*aircraft flight identification*] [*IM reference aircraft routingO*] (TERMINATE AT [*position ATWO*])	*M*	*W/U*	G-O A-M
UM331*	Notification that an interval spacing instruction to cross at the specified position behind the specified aircraft on the specified IM routing and terminating at the specified position is expected.	EXPECT INTERVAL SPACING TO CROSS [*position ATW*] BEHIND [*aircraft flight identification*] [*IM reference aircraft routingO*] (TERMINATE AT [*position ATWO*]) ASSIGNED SPACING INTERVAL PENDING	*M*	*R*	G-O A-M
UM332*	Instruction to report when interval spacing operations have started.	REPORT STARTING INTERVAL SPACING	*M*	*W/U*	G-O A-M
UM333*	Request to provide the planned final approach speed.	ADVISE PLANNED FINAL APPROACH SPEED	*M*	*Y*	G-O A-M
UM334*	Instruction that interval spacing is to continue.	CONTINUE INTERVAL SPACING BEHIND [*aircraft flight identification*]	*M*	*W/U*	G-O A-M
UM335*	Request to confirm the assigned spacing interval (time or distance) for the specified aircraft.	CONFIRM ASSIGNED SPACING INTERVAL BEHIND [*aircraft flight identification*]	*M*	*Y*	G-O A-M
UM336*	Request to report the current spacing interval (time or distance) with the specified aircraft.	REPORT CURRENT [*IM spacing interval type*] SPACING INTERVAL BEHIND [*aircraft flight identification*]	*M*	*Y*	G-O A-M
UM337*	Instruction to suspend spacing operation optionally specifying an aircraft.	SUSPEND INTERVAL SPACING (BEHIND [*aircraft flight identificationO*])	*M*	*W/U*	G-O A-M
UM338*	Instruction to resume spacing operation optionally specifying an aircraft.	RESUME INTERVAL SPACING (BEHIND [*aircraft flight identificationO*])	*M*	*W/U*	G-O A-M
UM339*	Instruction to cancel spacing operation optionally specifying an aircraft.	CANCEL INTERVAL SPACING (BEHIND [*aircraft flight identificationO*])	*M*	*W/U*	G-O A-M

Figure 345 – Current Baseline ATN2 Data Comm. “Uplink” Info. for IM (Part 2 of 2)

[Reference: Advanced Interval Management, Preliminary Concept of Operations, Version 1.0, FAA, March 27, 2014.]



Message ID	Message intent/use	Message Element	ALRT	RESP	IM
DM0	Indication that the instruction will be complied with.	WILCO	*M*	*N*	G-M A-M
DM1	Indication that the instruction cannot be complied with.	UNABLE	*M*	*N*	G-M A-M
DM2	Indication that the message will be responded to shortly.	STANDBY	*M*	*N*	G-M A-M
DM3	Indication that the message is understood.	ROGER.	*M*	*N*	G-M A-M
DM62R	System-generated notification of an error.	ERROR [*error informationR*]	*N*	*N*	G-M A-M
DM65R	Indication of the reason for the associated message.	DUE TO [*due to reason downlink*]	*N*	*N*	G-M A-O
DM97		[*free text*]	*N*	*N*	G-M A-M
DM98		[*free text*]	*M*	*N*	G-M A-M
DM100	System-generated notification that the received message is acceptable for display.	LOGICAL ACKNOWLEDGMENT	*N*	*N*	G-O A-M
DM145	Indication that the received message has a latency greater than the required latency.	MESSAGE RECEIVED TOO LATE, RESEND MESSAGE OR CONTACT BY VOICE	*M*	*N*	G-M A-M
DM148*	Indication that the flight interval management aircraft has selected the reference aircraft.	[*aircraft flight identification*] SELECTED	*M*	*N*	G- M A-M
DM149*	Indication of the planned final approach speed.	PLANNED FINAL APPROACH SPEED [*speed*]	*M*	*N*	G-M A-M
DM150*	Indication that interval spacing has started behind the specified aircraft.	STARTING INTERVAL SPACING BEHIND [*aircraft flight identification*]	*M*	*N*	G-M A-M
DM151*	Confirmation of the assigned spacing interval behind the specified aircraft.	ASSIGNED SPACING INTERVAL [*IM spacing*] BEHIND [*aircraft flight identification*]	*M*	*N*	G-M A-M
DM152*	Indication of the current spacing interval behind the specified aircraft.	CURRENT SPACING INTERVAL [*IM spacing interval*] BEHIND [*aircraft flight identification*]	*M*	*N*	G-M A-M
DM153*	Indication that the aircraft is not able to continue interval spacing. An aircraft may be specified.	UNABLE TO CONTINUE INTERVAL SPACING (BEHIND [*aircraft flight identificationO*])	*M*	*N*	G-M A-M
DM154*	Indication that the aircraft is interval spacing behind the specified aircraft.	CONDUCTING INTERVAL SPACING BEHIND [*aircraft flight identification*]	*M*	*N*	G-M A-M

Figure 346 – Current Baseline ATN2 Data Comm. "Downlink" Info. for IM

[Reference: Advanced Interval Management, Preliminary ConOps, Version 1, FAA, March 27, 2014.]

27.1.6 IM Application Use with One-to-One and One-to-Many Aircraft

As described above, the IM application is intended to be capable of supporting a one-to-one Interval Management spacing, as well as a one-to-several inter aircraft spacings. As of this writing, "advanced" IM application documents (e.g., Advanced Interval Management Preliminary Concept of Operations, FAA, March 27, 2014) identify IM spacing with no more than two target aircraft. The intent of the two target aircraft per the current concept definition is to support approach operations on parallel runways. However, this may be expanded beyond two target aircraft in the future. Thus, the application is not intended to be used in a one-to-many role, but certainly one-to-several is appropriate.

27.2 Delegated Separation (DS) Use Case Analysis

Delegated Separation (DS) is a future concept of ATM operations whereby aircraft separation tasks for a limited number of aircraft are delegated from ATC to the aircraft flight crew in a manner conceptually similar to today's visual separation on approach. Such a delegation can potentially reduce controller workload and enable improved traffic flow management by improving the efficiency of merging and spacing aircraft, approach and landing aircraft, aircraft flow in domestic and oceanic/remote enroute airspace, as well as aircraft flow in departures.

There are a number of preliminary documents and concepts that address various sub applications within the broader scope of DS. As of this writing, such concepts include:

- FIM-DS: Flight Deck Interval Management – Delegated Separation
- CAVS: CDTI-Assisted Visual Separation
- CEDS: CDTI-Enabled Delegated Separation
- CSPR: Closely Spaced Parallel Runway (operations include both approach and departure)

In each of these concepts of operation, the controllers assign and the flight crew accepts separation responsibility from one or more "specifically designated" aircraft. Note that "specifically designated" aircraft may be identified by a unique aircraft identifier provided by ATC as part of the DS clearance (e.g., aircraft call sign, aircraft 24-bit address, etc.) or automatically designed by the operating rules associated with the DS clearance (e.g., automatically designate aircraft in a parallel approach path).

27.2.1 DS Concept of Operations Overview

Delegated separation is an air traffic management capability in which responsibility for separation from one or more designated aircraft is assigned by ATC to the flight crew in specific tactical situations to improve operational efficiency.

The operational concept is based upon the widely used visual separation on approach that is used in today's operations. However, rather than being limited to just the approach phase of flight and visual conditions, the DS concept of operations expands this to not only the approach phase of flight, but also virtually all other phases of flight and visibility conditions.

The operational concept for delegated separation is very similar to the concept of Delegated Interval (DI) [also known as Interval Management (IM)] that was described in Section 27.1. In DI, as previously described a spacing task is assigned (delegated) by ATC to the flight crew to maintain a specified interval from a particular aircraft, and where the required interval is greater than the minimum authorized ATC surveillance-enabled separation for the airspace and phase of flight. Such a spacing assignment would be treated much like any other clearance element such as speed, heading, or altitude. In DI, ATC retains ultimate responsibility for ensuring aircraft separation.

In DS, the responsibility for separation (collision avoidance) is transferred to the flight crew who are then responsible for maintaining a safe distance between the one or more specifically ATC designed aircraft. For all other aircraft other than those specifically designated by ATC, the separation responsibility remains with ATC.

Just like with DI, in DS, the delegation of responsibilities can vary in duration. The duration can be very long (e.g., for enroute oceanic operations) or relatively short (e.g., for the final approach segment of closely spaced parallel runway approach operations).

27.2.2 DS Operational Scenarios

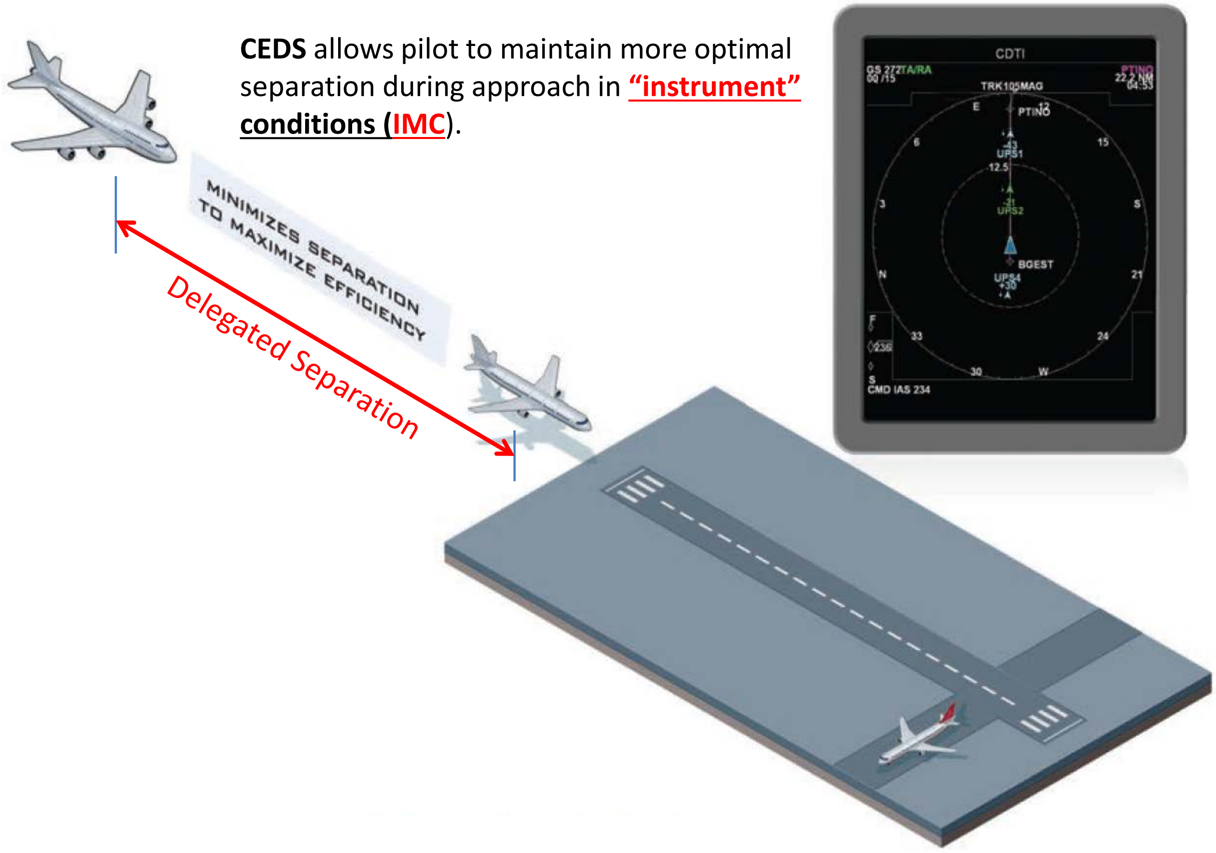
The operational scenarios for use of the DS application are vast and are potentially applicable to all phases of flight. In the future, separation standards may be reduced from normal ATC aircraft separation standards in specific tactical aircraft encounter scenarios whereby the controller delegates (via the DS application) the separation responsibility to the flight crew for specifically designed aircraft in specific situations in order to improve operational efficiency. The normal ATC standards may be reduced using DS in specific tactical scenarios, because for example, the additional buffers that are put into the system to accommodate controller recognition of the conflict and delays in communicating and flight crew implementing the controller's commands to resolve the conflict can be reduced or eliminated. In DS, the responsibility for separation (collision avoidance) is transferred to the flight crew who are then responsible for maintaining a safe distance between the one or more specifically ATC designed aircraft. All other aircraft, other than those specifically designated by ATC remain the separation responsibility of ATC. Just like with DI, in DS, the delegation of responsibilities can vary in duration.

Example DS applications addressing various operational scenarios are in various stages of research & development including CDTI Enabled Delegated Separation (CEDS), CDTI Assisted Visual Separation (CAVS), Flight Deck Interval Management – Delegated Separation (FIM-DS), and a variety of closely spaced runway operations (including both approach and departure). These operational scenarios are described below.

27.2.2.1 DS Scenario #1: CDTI Enabled Delegated Separation (CEDS)

The operational concept for CEDS is to try to achieve equivalent visual operational approach rates in less than visual conditions as depicted in Figure 347. The basic operational concept is to adapt the procedures, roles, and responsibilities currently used by pilots and air traffic controllers in visual approach operations to IFR operations, using CDTI information in lieu of visual contact. The CDTI information is typically better than the estimates of range, closure rate, and relative altitude that pilots are able to make when observing traffic visually.

Operationally, the controller determines that DS will be useful, designates the traffic to be referenced, verifies that the flight crew has identified the designated traffic on the CDTI, and at the appropriate time, issues a CDTI enabled delegated separation clearance. Thereafter, the flight crew is responsible for safe separation from the designated aircraft, just as they are today when using visual separation. When performing a delegated separation task while operating in IMC, the crew adheres to its IFR clearance (e.g., flies a standard instrument approach) while monitoring separation from the designated aircraft. Trajectory adjustments in this case are primarily speed adjustments to maintain separation along track.



CEDS allows pilot to maintain more optimal separation during approach in **“instrument” conditions (IMC)**.

Figure 347 – DS Scenario #1: CEDS

[Reference: Modified figure from “ADS-B IN Avionics for NextGen Flight”, Aviation Communications & Surveillance Systems Brochure, 2013.]

27.2.2.2 DS Scenario #2: CDTI Assisted Visual Separation (CAVS)

The operational concept for CAVS is depicted in Figure 348 and is nearly identical to CEDS. The basic differences are a few additional limitations for CAVS including:

- CAVS must be conducted entirely in visual meteorological conditions (VMC), whereas CEDS can be initiated in instrument meteorological conditions (IMC); and
- CAVS traffic must be initially acquired visually out-the-window and then cross-correlated on the CDTI. CEDS traffic can be initially acquired on the CDTI.

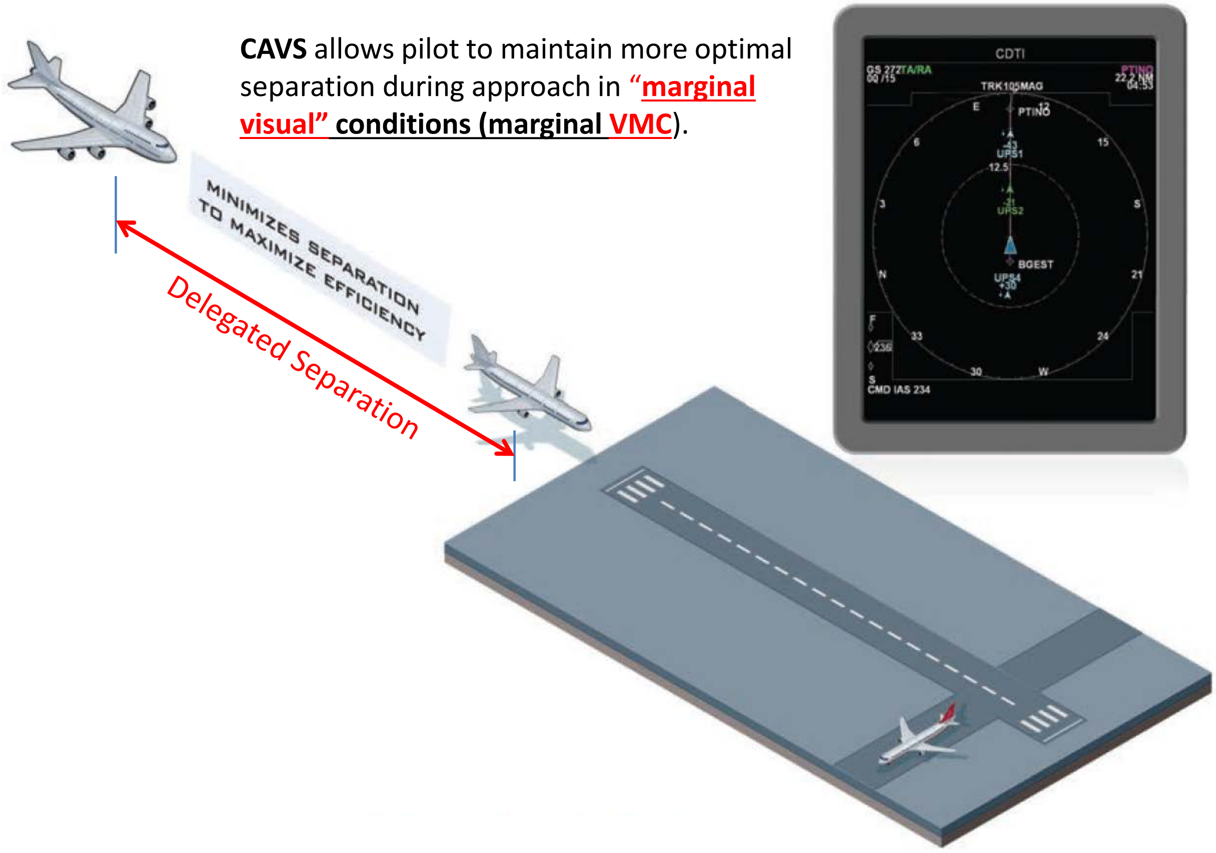


Figure 348 – DS Scenario #2: CAVS

[Reference: Modified figure from "ADS-B IN Avionics for NextGen Flight", Aviation Communications & Surveillance Systems Brochure, 2013.]

Figure 349 illustrates an example CDTI intended to support the flight crew in performing the delegated separation task per the CEDS and CAVS concepts of operation.

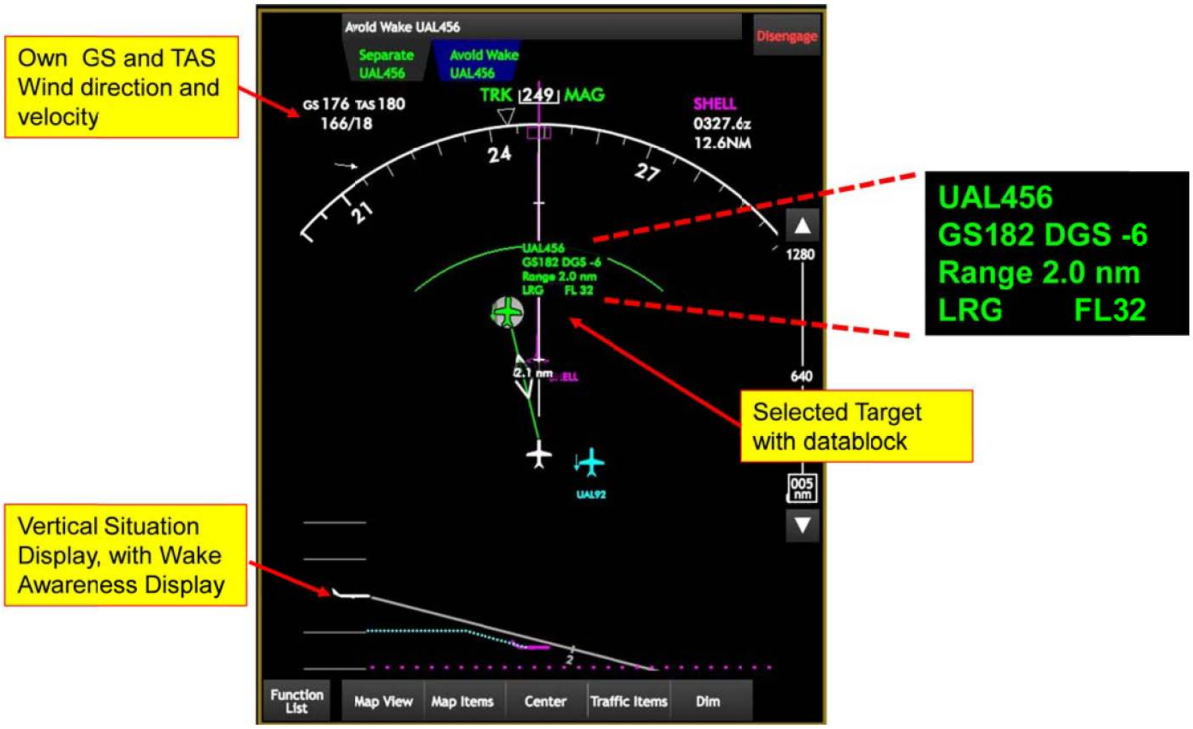


Figure 349 – Example CDTI to Support CEDS and CAVS

[Reference: ADS-B IN Aviation Rulemaking Committee Report to the FAA, September 30, 2011.]

27.2.2.3 DS Scenario #3: Flight Deck Interval Management – Delegated Separation

The operational concept for FIM with delegated separation (FIM-DS) is exactly aligned with the operational concept for Delegated Interval/Interval Management (DI/IM) (as described in Section 27.1) except rather than the controller only delegating an interval spacing task to the flight crew, the controller is delegating the separation responsibility for maintaining a safe separation from the designated aircraft (one or more).

All the operational scenarios described for Interval Management (see Sections 27.1.1 and 27.1.2) are also applicable to FIM-DS. The difference is that for DS, the controller (via the clearance) is delegating separation responsibility against specific aircraft; whereas, for IM the controller is only delegating a spacing task and separation responsibility remains with ATC.

27.2.2.4 DS Scenarios #4 and #5: Closely Spaced Parallel Runway (CSPR)

The operational objective the closely-spaced parallel runway delegated separation operations is to improve the efficiency (and safety) of approach (Scenario #4) and/or departure (Scenario #5) operations. For example, approach applications are intended to enable simultaneous independent or dependent approaches to closely-spaced parallel runways in degraded visual conditions including IMC and thereby maintain an arrival rate equivalent or better than under visual approach operations. Such concepts of operations are expected to be applicable to close runway spacings, at least down to 2500 feet for independent approach operations and down to much smaller spacings for dependent runway operations (e.g., 750 feet at San Francisco). Departure applications with DS are intended to enable independent parallel runway departures for closely spaced parallel runways and allow the operation to be conducted with the currently required 15 degree departure track divergence that is currently required immediately after take-off.

Closely spacing parallel runway application operational concepts have been described by the ADS-B IN ARC as the Closely-Spaced Parallel Runway (CSPR) application and RTCA as the Independent Closely Spaced Parallel Approach (ICSPA) application. A precision departure application has been defined as part of the European Space Agency “FILGAPP” program, so named for “’Filling the Gaps’ in GNSS Advanced Procedures and Operations.” Each of these concepts is briefly described in the subsections below.

27.2.2.4.1 DS Scenario #4: Closely Spaced Parallel Runway Approach

There are several concepts for closely spaced parallel runway approach operations, including the ADS-B IN ARC’s Closely Spaced Parallel Runway Approach (CSPA) concept and RTCA’s Independent Closely Spaced Parallel Approach (ICSPA).

The ADS-B IN ARC operational concept for CSPR approach with DS is based upon the CEDS approach concept described in Section 27.2.2.1 above. The procedure uses defined arrival paths and/or instrument approach procedures. The CDTI, or primary flight display, would include a vertical situation display enabling flight crews to assess and respond to wake concerns as the lateral separation between the traffic to follow aircraft reduces closer to the runways. Flight crews would monitor display information and respond as necessary to maintain appropriate wake avoidance behind the traffic to follow aircraft on the adjacent approach.

RTCA SC-186 has also defined a concept of operations for what is known as Independent Closely Spaced Parallel Approaches (ICSPA), which is described in Appendix J of RTCA DO-289 entitled “MASPS for Aircraft Surveillance Applications.” Per the RTCA ICSPA operational concept, separation responsibility for aircraft on the parallel approach is transferred to each aircraft conducting the approach. ATC maintains separation responsibility for aircraft approaching the same runway (i.e., the lead and in-trail aircraft). Separation responsibility for aircraft on the parallel approach is transferred when the aircraft accepts the approach clearance. ICSPA aircraft are tracked automatically by the ICSPA system, and thus do not need to be specifically identified by ATC, as is usual with delegated separation applications. All separation responsibility returns to ATC when the aircraft lands, or when ATC accepts the aircraft back into normal separation coverage after a Missed Approach or Breakout maneuver (the latter of which is described below).

In the event that one aircraft deviates from its assigned approach path, trajectory and conflict prediction algorithms onboard each of the aircraft in the parallel stream provide visual and auditory alerts to notify the deviating aircraft and threatened parallel traffic of the off-course situation. If the deviating aircraft fails to return to course, and “blunders” towards the parallel traffic, it will be required to execute a Breakout maneuver, turning away from the parallel approach course. If the blundering aircraft still fails to respond, and threatens an aircraft in the parallel stream, the threatened aircraft is provided with a break out command and will execute a climbing turn away from the threatening aircraft. After the flight crew has the aircraft established on the Breakout procedure and are avoiding the blundering aircraft, they will contact ATC who will then issue vectors to begin another approach in exactly the same manner as missed approaches are currently handled. Note that since aircraft in the two independent parallel approach streams are likely to have different approach speeds, any aircraft may be overtaken by another aircraft in the parallel stream. As such, the application needs to be active for more than one aircraft.

Figure 350 and Figure 351 illustrate delegated separation scenarios #4a and #4b for independent and dependent approach operations, respectively.

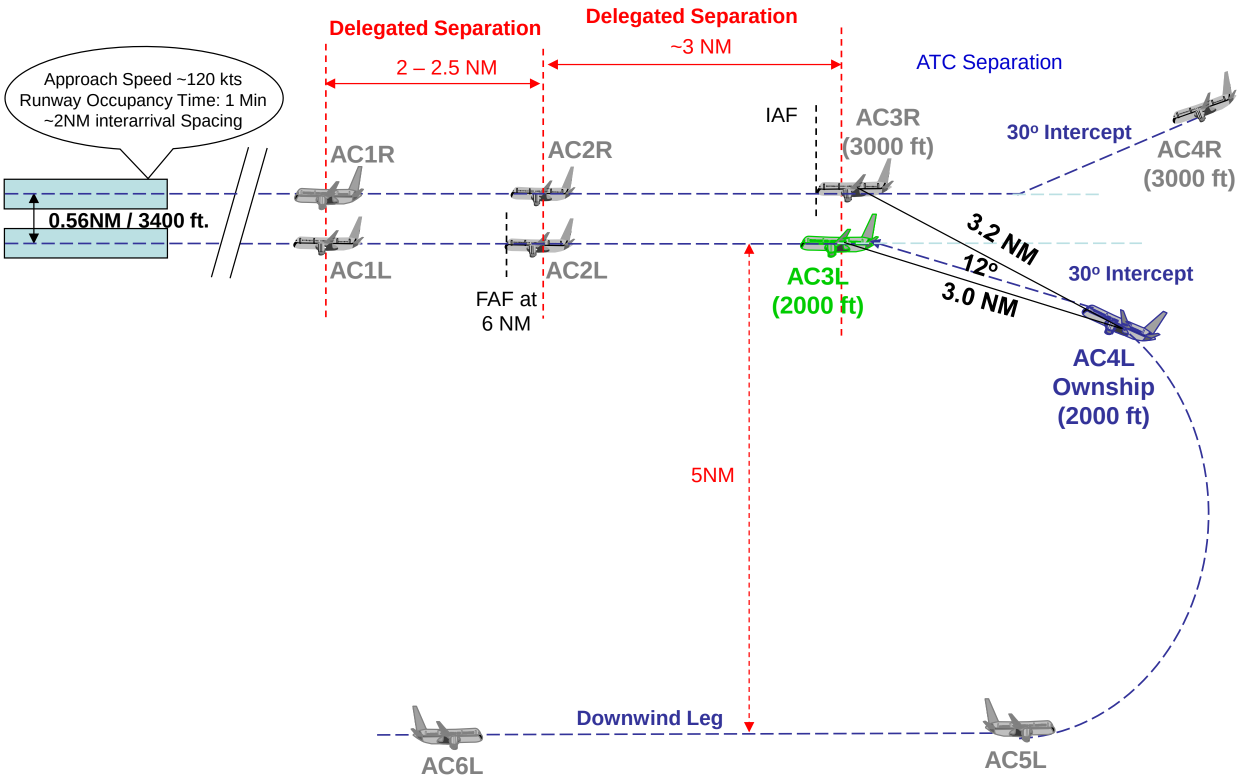


Figure 350 – DS Scenario #4a: Independent Closely Spaced Parallel Approach (ICSPA)

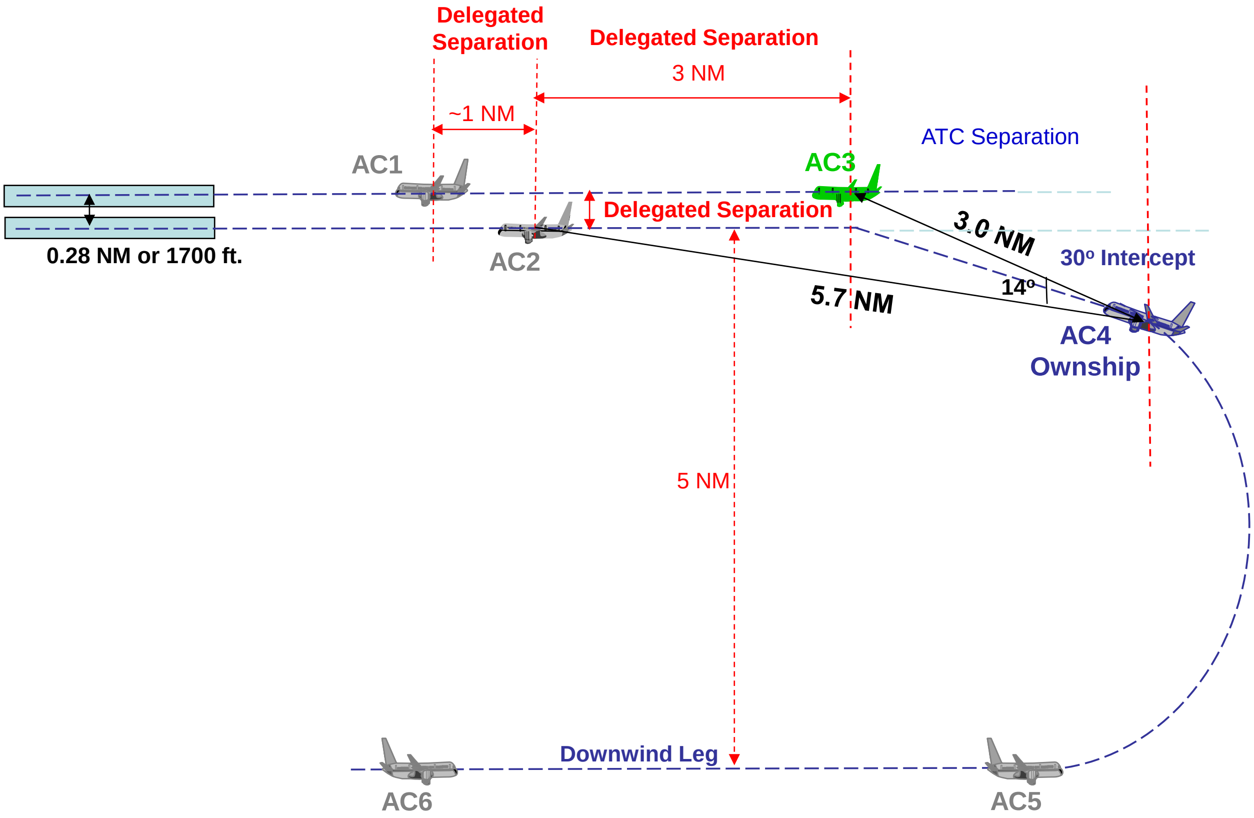


Figure 351 – DS Scenario #4b: Dependent Closely Spaced Parallel Approach (DCSPA)

27.2.2.4.2 DS Scenario #5: Closely Spaced Parallel Runway Precision Departure

A precision departure operation is a vertically and laterally guided procedure. In order to enable a variety of outbound tracks where there are closely spaced parallel runways and without widely diverging departure tracks to be initiated immediately after take-off, a closely spaced parallel departure application has been defined analogous to the closely spaced parallel runway approach application described above. In this application, separation responsibility for aircraft departing (including departure and initial climb) from the parallel runway is delegated by ATC to each of the aircraft flight crews, supported by airborne equipment. In the event that one aircraft deviates from its assigned departure path, trajectory and conflict prediction algorithms onboard each of the aircraft in the parallel stream provide visual and auditory alerts to notify the deviating aircraft and threatened parallel traffic of the off-course situation. If the deviating aircraft fails to return to course, and “blunders” towards the parallel traffic, it will be required to execute a Breakout maneuver, turning away from the parallel departure course. If the blundering aircraft fails to respond and threatens an aircraft in the parallel stream, the threatened aircraft will be provided with a breakout command to turn away from the threatening / blundering aircraft.

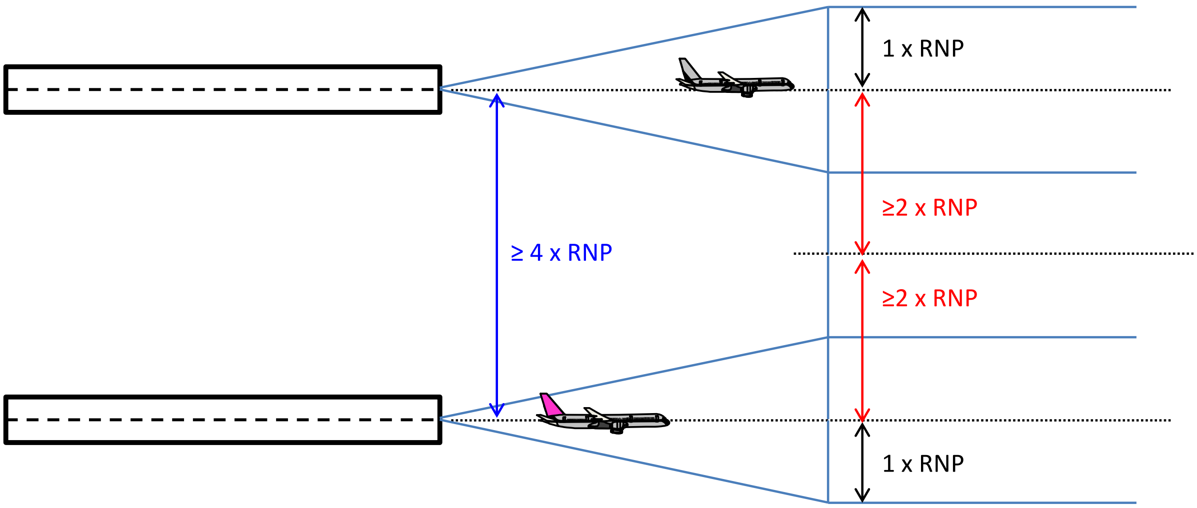


Figure 352 – DS Scenario #5: Closely Spaced Parallel Runway Departure

[Reference: Precision Departures, contractor report prepared by Thomas Dautermann from DLR with changes from Joel Wichgers and Steve Koczo for the European Space Agency as part of FILGAPP program, draft March 4, 2014.]

27.2.3 DS Phases of Operation

For the purposes of this use case analysis, the DS application has been broken down into four phases of operation including:

1. Pre-initiation
2. Initiation
3. Execution
4. Termination

These four phases of DS operation are briefly described in the subsections below.

27.2.3.1 Pre-Initiation Phase

In the pre-initiation phase, the controller evaluates the traffic pattern and evaluates if a DS Operation is appropriate for ATM. The pre-initiation activities include the determination by the controller (or associated ground tools) of the DS Clearance, including the appropriate DS operational points/constraints, given the desired operations and current operational environment.

27.2.3.2 Initiation Phase

The controller determines that the use of DS would be beneficial. After determining that the DS Operation can be successfully performed, including that the relevant aircraft are able to participate, the controller instructs the flight crew(s) of the aircraft (by issuing a DS Clearance) to conduct the DS Operation. Before accepting the DS Clearance, the flight crew(s) checks that the criteria are met to begin executing the DS Clearance.

27.2.3.3 Execution Phase

After the flight crew(s) accepts the DS Clearance, the DS Operation is executed. The flight crew is expected to maneuver within the limits of the clearance to maintain safe separation from the designated aircraft.

During the execution of the DS Operation, the controller continues to monitor the DS Aircraft to ensure separation from all other non-designated aircraft.

27.2.3.4 Termination Phase

Termination of DS normally would occur when the aircraft reaches the Planned Termination Point of the DS Clearance. However, it may also occur abnormally when an internal situation occurs that prevents valid aircraft separation information to be provided to the flight crew, or by direct action of the flight crew. The controller may also terminate the DS Clearance if it is no longer meeting ATM goals or expectations, or other safety consideration.

27.2.3.5 Phase Diagram

As an example, the specific roles of the flight crew and ATC during these phases of an Independent Closely Spaced Parallel Approach operation (per DS Scenario #4a) are summarized in the phase diagram given in Figure 353, as specified in the “MASPS for Aircraft Surveillance Applications” [RTCA DO-289].

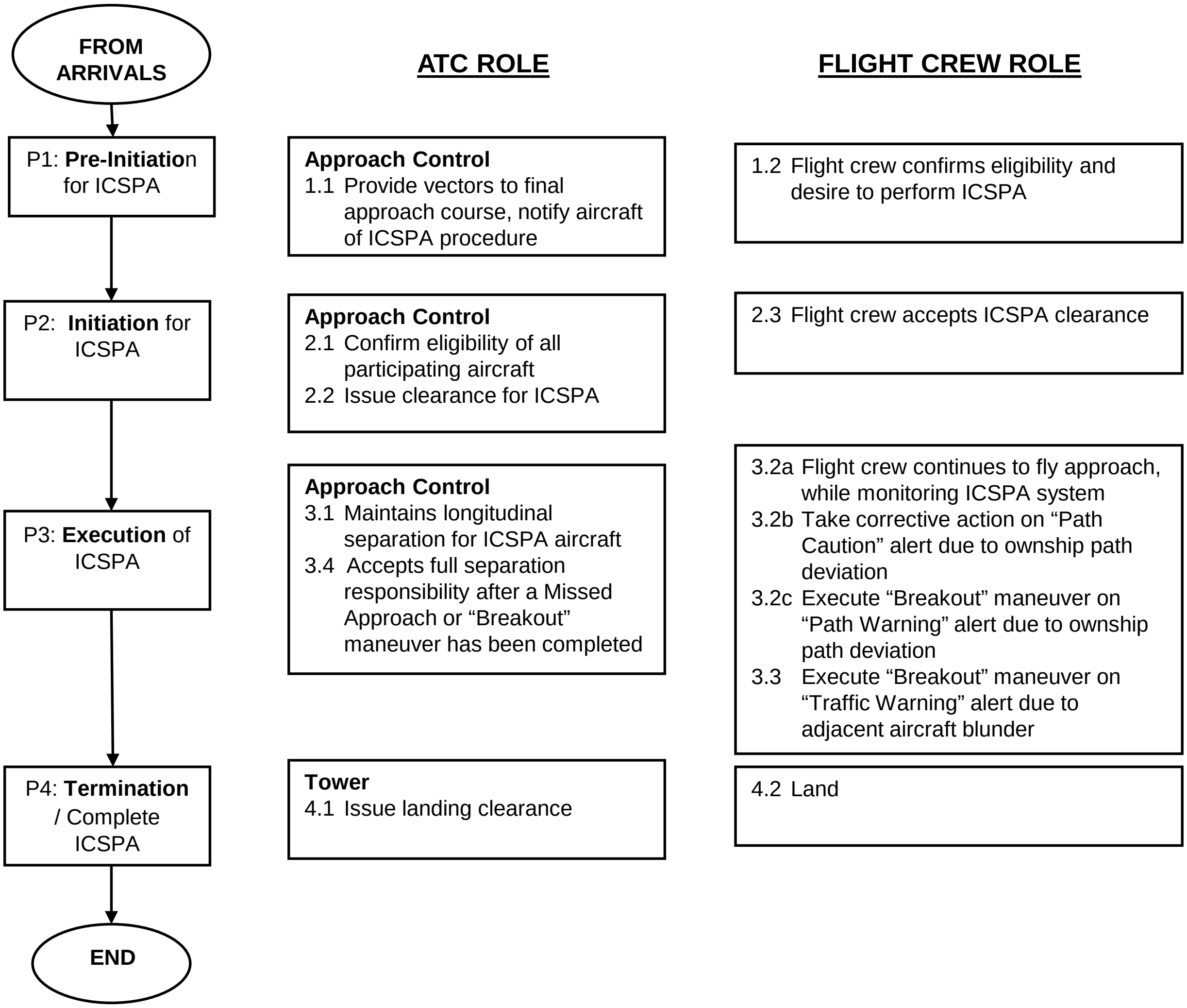


Figure 353 – DS Phase Diagram for ICSPA

[Reference: Modified diagram based upon DO-289, “MASPS for Aircraft Surveillance Applications,” RTCA, December 9, 2003.]

27.2.4 DS Use Case Activity Diagram with Communication Phases Highlighted

The four phases of the DS operation were overviewed in Section 27.2.3 above. This section provides an example use case activity diagram (see Figure 354) that identifies the activities that occur during each phase of operation in which the DS system is supporting the flight crew with the ICSPA delegated separation operation. This activity diagram has been extracted with modest modification from RTCA DO-289.

The specific actions being made by the application’s “actors” in each step are identified as being done by the flight crew or ATC. The actions not taken by the flight crew or ATC are done by the DS System. The steps in the use case diagram where communications occur are highlighted with yellow shading in the figure, and an indication of whether the information is communicated from aircraft-to-ground (A-G), ground-to-aircraft (G-A), or aircraft-to-aircraft (A-A) is provided.

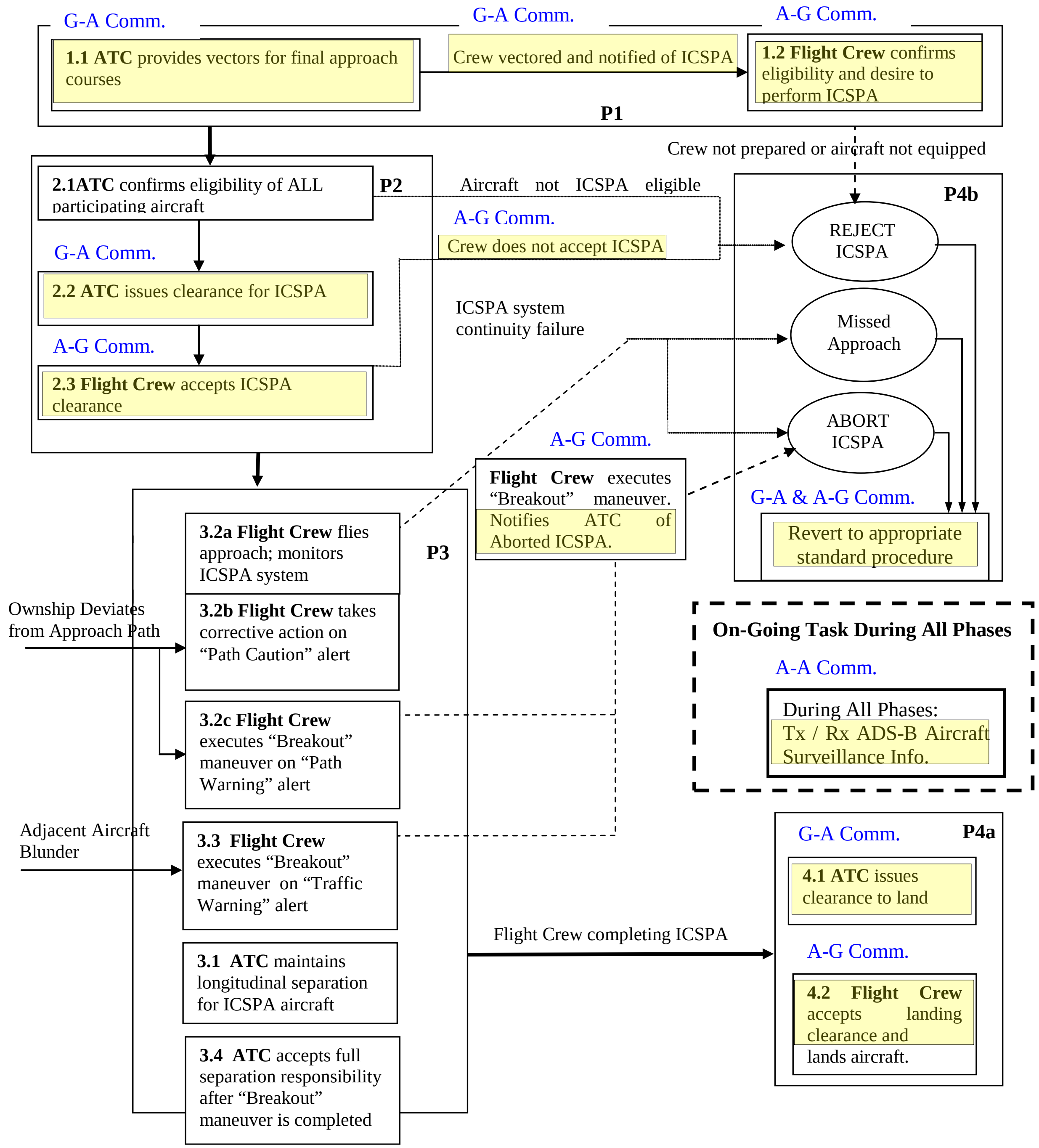


Figure 354 – DS Use Case Activity Diagram for ICSPA

[Reference: Modified diagram based upon DO-289, "MASPS for Aircraft Surveillance Applications," RTCA, December 9, 2003.]

27.2.5 DS Communications Information and Infrastructure

As indicated previously, the DI and DS applications are very similar. The primary difference is whether just a spacing task is delegated by ATC and separation responsibility remains with

ATC as per DI application, or whether ATC is delegating the spacing task and separation responsibility for specifically designated aircraft as in the DS application.

The A-A, A-G, and G-A communications information and infrastructure associated with DS are essentially identical to those indicated in Section 27.1.5 for DI. The only difference is that the DS clearance information will clearly indicate that the flight crew has been delegated the separation responsibility for the designated Target Aircraft, not just a spacing task.

27.2.6 DS Application Use with One-to-One and One-to-Many Aircraft

As described above, the DS application is intended to be capable of supporting a one-to-one delegated separation, as well as a one-to-several aircraft delegated separations in specific tactical situations. Thus, the application is not intended to be used in a one-to-"many" role, as the separation delegations need to be specifically identified but certainly one-to-several is appropriate. This specific DS limited delegation of separation differs from the Airborne Self-Separation application that is described in Section 27.3. Airborne Self-Separation is defined to be a one-to-many aircraft-to-aircraft interaction application (where "many" is "all" other aircraft).

27.3 Airborne Self-Separation (ASS) Use Case Analysis

Airborne self-separation is a future concept of ATM operations whereby the capability, authority, and responsibility for separation from other aircraft resides with the flight crew as supported by avionics systems. Self-separation applications require flight crews to separate their flight from all surrounding traffic, in accordance with the applicable airborne separation minima and rules of flight.

Operational concepts of operation for self-separation applications have been defined in several documents including:

- NASA/TP-2011-217174, entitled Autonomous Flight Rules (AFR), A Concept for Self-Separation in U.S. Domestic Airspace, by David J. Wing (NASA Langley Research Center) and William B. Cotton (Cotton Aviation Enterprises),
- DO-289, entitled "MASPS for Aircraft Surveillance Applications," RTCA, December 9, 2003 [specifically, the application entitled "Airborne Conflict Management" (ACM)],
- DO-338, entitled "MASPS for ADS-B Traffic Surveillance Systems and Applications (ATSSA)," RTCA, June 13, 2012.

The above documents are used as the basis for this use case analysis.

27.3.1 Airborne Self-Separation Concept of Operations Overview

In airborne self-separation operations, the flight crew is given capability, authority, and responsibility for separation from all other aircraft.

In the context of an airborne self-separation "application," it is envisioned that the flight crew is given aircraft separation responsibility for all or a specifically defined segment of the flight. As part of the responsibility, the flight crew is granted authority to modify their trajectory (possibly within defined degrees of freedom – e.g., per the clearance or defined airspace operating rules) without renegotiating with ATC. Where the self-separation is less than the entire flight, the self-separating aircraft is given a clearance as to when and where the separation portion of the flight begins and terminates. The beginning and termination of airborne self-separation is envisioned to be at an agreed location, altitude, airspace boundary, and/or time where separation responsibility is transferred from ATC to the flight crew for beginning the application and from the flight crew back to ATC for the termination of the application.

This airborne self-separation application can be implemented in either a homogeneous environment, in which all aircraft are self-separating, or in a mixed-operations environment (as depicted in Figure 355), in which some aircraft are receiving separation services from ATC and some aircraft are self-separating.

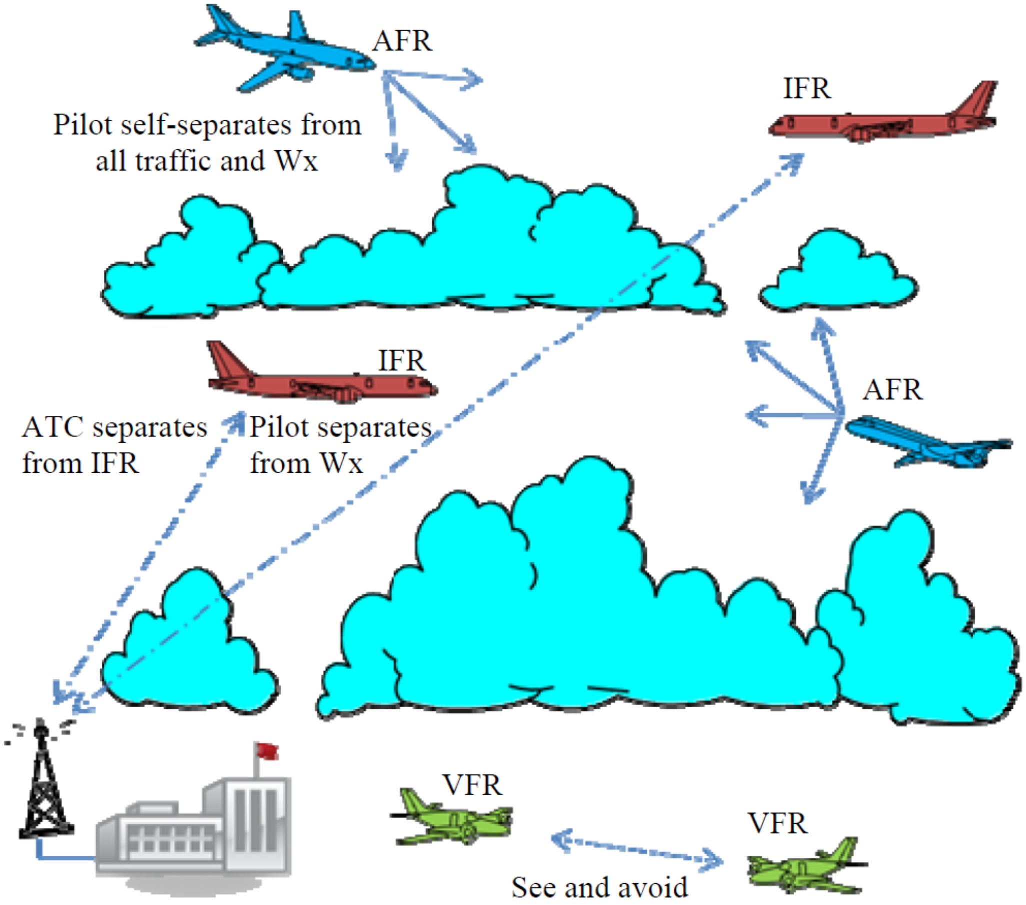


Figure 355 – Integrated Mix of AFR, IFR, and VFR Operations

[Reference: David Wing and Bill Cotton, For Spacious Skies: Self-Separation with "Autonomous Flight Rules" in US Domestic Airspace, American Institute of Aeronautics and Astronautics, 2011.]

27.3.1.1 Autonomous Flight Rules Airborne Self-Separation Concept Overview

NASA has been investigating advanced air traffic concepts that incorporate greater control in the cockpit for more than a decade. A self-separation concept has emerged called Autonomous Flight Rules (AFR) in which the capability, authority, and responsibility for separation from other aircraft resides with cockpit avionics and the flight crew. The concept is described in detail in NASA Technical Paper NASA/TP-2011-217174, which can be accessed at: http://ntrs.nasa.gov.

AFR is an aircraft self-separation concept of operation that places the responsibility for maintaining safe and legal distances from one's own aircraft to all other aircraft with the flight crew, using aircraft systems and procedures designed to support this function.

While executing the self-separation function, such aircraft would be operating under a flight status referred to as “Autonomous Flight Rules” (AFR). Through new policies and a significant update to the Federal Aviation Regulations (FAR), the equipment, training, and procedural requirements to enable AFR operations can be established that meet the stringent safety requirements of a primary separation system. Aircraft and flight crews operating under AFR need to maintain separation from all other aircraft in the airspace, including Visual Flight Rules (VFR) aircraft, IFR aircraft, and other AFR aircraft. AFR aircraft also would self-separate from terrain and obstacles, hazardous weather, and operationally restricted Special Use Airspace (SUA). Aircraft that are self-separating are removed from the ground-based ATM system’s responsibility for the separation function whenever operating under the autonomous flight rules of this application. Normally, this application spans from the time the AFR aircraft are released by the Air Navigation Service Provider (ANSP) during departure until they are reinserted into the landing flow to a runway. The AFR aircraft cooperatively share their current trajectories and any changes with other aircraft and the ANSP, and they adjust their trajectories as needed to achieve the ANSP arrival plan for that aircraft.

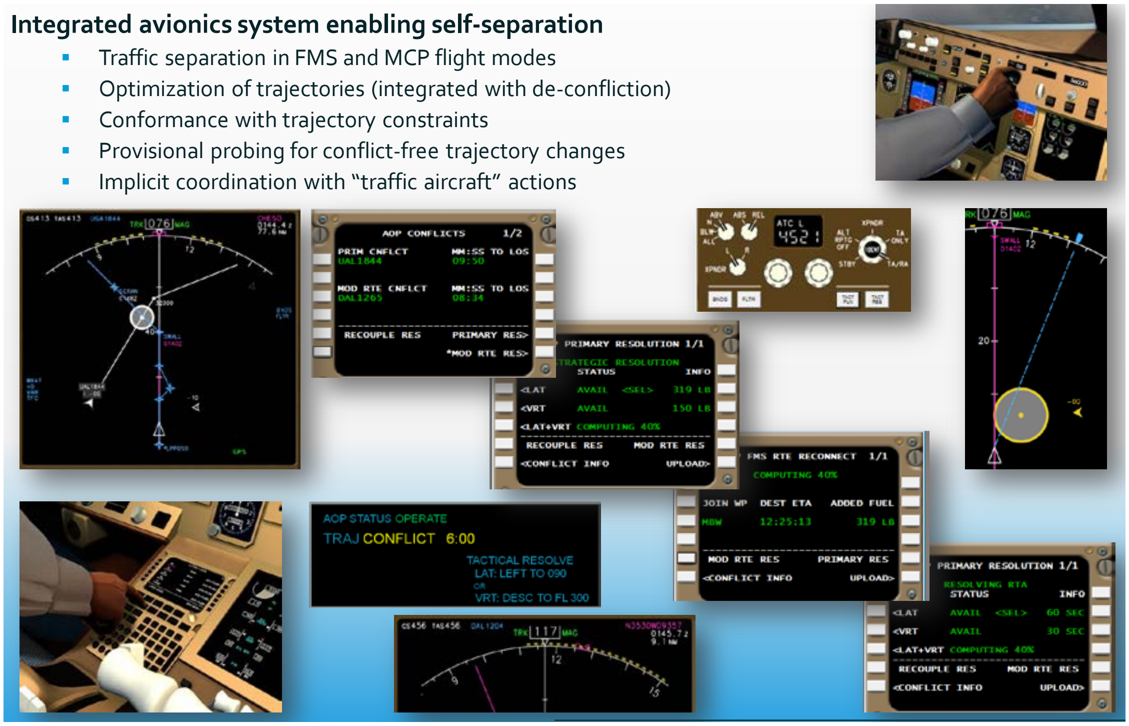
Self-separation is technically enabled by the widespread use of the emerging cooperative airborne surveillance technology, Automatic Dependent Surveillance Broadcast (ADS-B). ADS-B will provide AFR aircraft with the position, altitude, and velocity vector (state vector) of other aircraft in the vicinity as well as potentially their intended state if turning or changing altitude. Additional trajectory intent data could be provided by ADS-B and/or ground systems such as System Wide Information Management (SWIM). Backup airborne surveillance capability is provided by a ground-based Traffic Information Service Broadcast (TIS-B) system and by the aircraft-to-aircraft Traffic Alert and Collision Avoidance System (TCAS) or next generation TCAS system (i.e., ACAS-X). Both of these systems make use of the transponders in other aircraft for surveillance independent of the ADS-B positioning information. Weather information will be available from both on-board sensors and access to ground-based weather products provided through appropriate communication links. SUA status and other NAS information will also be available digitally to the automation onboard the AFR aircraft. In addition to cooperative airborne surveillance, self-separation is technically enabled by an “Airborne Separation Assistance System” (ASAS), a software automation system onboard the AFR aircraft. Integrated with the aircraft’s navigation, surveillance, and display systems, the ASAS will model the traffic situation and perform conflict detection, resolution, and prevention functions. It will provide guidance to AFR flight crews to plan for and maintain separation from other aircraft, restricted airspace, and weather hazards. The ASAS will also assist flight crews in conforming to arrival and other operational constraints, such as a Required Time of Arrival (RTA), without compromising separation.

Benefits of AFR operations should accrue to both the aircraft operators and the ANSP. Under AFR, flight trajectories are under direct control of the aircraft operator, rather than the ANSP. Having assumed responsibility for separation for the aircraft, the operator may select flight trajectories that more closely match the business case optimum, producing both cost reductions and environmental benefits. In addition, because an AFR aircraft imposes minimal burden on the enroute ground system for separation, the aircraft should be exempted from Traffic Flow Management (TFM) initiatives associated with enroute congestion and can depart and arrive much closer to the operator’s preferred schedule. Once airborne, the AFR flight crew has the authority and flexibility to alter the trajectory according to changing conditions within the limits of the AFR clearance. ANSP benefits should also accrue. AFR aircraft will not be managed by controllers, opening up additional ground system capacity for IFR aircraft and increasing the ANSP ability to more strategically manage NAS resources. AFR flights will be able to operate in the same airspace with IFR and VFR operations, thereby reducing the need for complex airspace structures or segregated operations far from the optimum business trajectories of AFR and IFR aircraft.

As IFR flights convert to AFR, controller workload will be reduced, and the absence of complex airspace structures for segregation will greatly simplify coordination and handoff procedures. In mixed operating environments with a mix of AFR and ATC controlled aircraft where the right-of-way is given to the IFR aircraft by operating procedure, controllers will be able to focus their attention and services on the IFR population, while the AFR traffic will be required to give way to all IFR traffic.

The AFR operational concept encompasses primarily the climb, enroute, and initial descent phases of flight. It may terminate at the boundary of terminal airspace or, with ground automation, at an arrival merge point or metering fix. It may also smoothly integrate with and transition to arrival operations including Delegated Interval and Delegated Separation applications.

For a more comprehensive description of the AFR concept, see the NASA Technical Paper referenced earlier in this section. Figure 356 depicts a set of Aircraft Automation Technologies currently under research and development by NASA that are intended to enable AFR self-separation operations.



Integrated avionics system enabling self-separation

- Traffic separation in FMS and MCP flight modes
- Optimization of trajectories (integrated with de-confliction)
- Conformance with trajectory constraints
- Provisional probing for conflict-free trajectory changes
- Implicit coordination with "traffic aircraft" actions

AOP STATUS OPERATE
TRAJ CONFLICT 6:00
TACTICAL RESOLVE
LAT: LEFT TO 090
OR
VRT: DESC TO FL 300

Figure 356 – Aircraft Automation Technologies for AFR

[Reference: Presentation by Bill Cotton, "Air Traffic Unit for AFR," dated March 4, 2013.]

The term "autonomous" was chosen as part of the AFR nomenclature to imply "independence." There are two fundamental principles of AFR operations: 1) the degree of authority the aircraft operator has over the trajectory of the aircraft, and 2) the degree of responsibility the operator has to ensure safe operations. The autonomous authority provides the operator the independence to define and change the trajectory without outside (i.e., ATC) approval, as in VFR, but with additional independence from VFR meteorological and airspace restrictions. The autonomous responsibility compels the operator to independently ensure (without relying on ATC as a ready fallback) that their trajectory does not breach established separation criteria from other traffic, a stronger safety requirement than VFR's "see and avoid." Thus, AFR represents not a "free for all" but rather a structured operating mode with rules and procedures that, while highly flexible, methodically ensures separation safety with the utmost integrity.

27.3.1.2 RTCA Airborne Conflict Management (ACM) Self-Separation Concept Overview

Appendix H in RTCA/DO-289 provides a description of the self-separation application known as Airborne Conflict Management (ACM). The ACM concept is conceptually very similar to the AFR concept. It includes detecting conflicts, monitoring for potential conflicts, and suggesting resolutions to prevent a violation of airspace separation criteria against all other properly equipped aircraft/vehicles. It is expected that ACM will also take into account known, non-aircraft "threats" (e.g., terrain, weather, and restricted airspace).

ACM is a core enabling function for the global implementation of the Free Flight concept, as it will aid flight crews to fly user-preferred trajectories while avoiding conflicts with other aircraft. ACM is intended to enhance safety by providing a distributed, cooperative, separation assurance system. ACM is an application that performs the functions of Conflict Detection (CD), Conflict Prevention (CP), and Conflict Resolution (CR).

A CD alert informs the flight crew of a predicted loss of separation and enable them to more quickly and accurately identify the aircraft and geometry involved in the conflict, thereby enhancing traffic conflict awareness. Without this alert, the flight crew may identify a conflict later in the process, or not at all. With it, both traffic awareness, and traffic conflict awareness are enhanced. In this way, CD is intended to mitigate failures that can lead to a loss of separation, which in turn leads to increased chances for a collision.

The CR part of this application provides recommended conflict resolutions or guidance cues to resolve conflicts detected by the CD function. The CR function is designed to be completely interoperable with and functionally independent of existing Airborne Collision Avoidance Systems (ACAS). Under normal circumstances, conflicts are expected to be resolved at long range by minor changes to the flight path. However, ACM is also envisioned to have two shorter-range alert thresholds in which increasingly urgent alerts and updated resolutions are provided as necessary for required avoidance maneuvers.

The CP part of this application predicts conflicts that may occur if current flight state or own aircraft intent is changed. As such, it offers guidance cues to prevent changes that will lead to other conflicts.

The self-separation application will notify the flight crew of an actionable conflict by both visual and aural indications. Multi-level alerting systems with visual and aural indications will reflect the urgency for flight crew response. Each of these CD, CR, and CP functions and their multi-level altering functions as envisioned by RTCA Special Committee-186 are described a bit more in the subsections below.

27.3.1.2.1 Conflict Detection (CD) Function

As indicated above, the ACM application provides conflict detection, conflict prevention, and conflict resolution functions against all other properly equipped vehicles (or targets). Position and trajectory information is obtained from traffic surveillance information received (normally received via ADS-B messages), and compared to the position and trajectory of own aircraft. (“Own aircraft” is a terminology for the aircraft on which the ACM system being described is operating.) By comparing the “own” and “target” information, the CD function monitors and can predict violations of separation standards (see Figure 357). The long surveillance range and accuracy provided by ADS-B allows these predictions to be made well in advance of any such conflict.

The CD function provides three alerting levels:

- CD Advisory: An optional Low Level CD Alert (advisory) designed to enhance awareness about a developing traffic situation and issued as early as possible with due consideration given to nuisance alerts. These alerts may be disabled to further reduce nuisance alerts. This advisory alerts is provided well before the required CD caution and warning alerts described below.
- CD Caution: A required CD Alert (caution) triggered off the Conflict Detection Zone (CDZ) and issued soon enough to allow the flight crew sufficient time to maneuver to avoid loss of separation.
- CD Warning: A required CD Alert (warning) triggered off the Conflict Avoidance Zone (CAZ) and issued soon enough that a dangerous situation and ACAS alert is avoided.

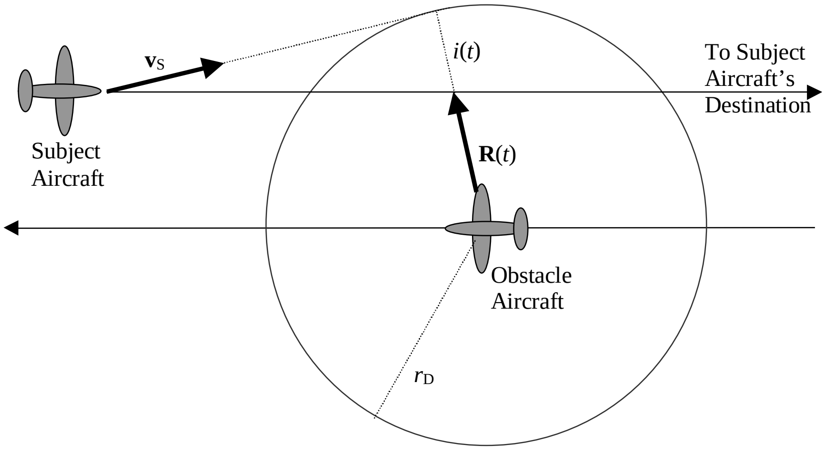


Figure 357 – Conflict Detection

[Reference: Modified diagram based upon DO-289, “MASPS for Aircraft Surveillance Applications,” RTCA, December 9, 2003.]

Note that the three functions (CD, CR, and CP) are built around two zones (CAZ and CDZ, as depicted in Figure 358 and Figure 359, respectively) that define the legal and safety separation standards for any aircraft pairing. These zones are defined by a number of parameters. Some of these parameters, such as the position uncertainty, are dynamically calculated; while others such as the Assured Collision Avoidance Distance (ACAD) and Assured

Normal Separation Distance (ANSD) are fixed or could be a function of the aircraft types and airspace, and may be communicated to the aircraft or stored in an on-board database.

The Assured Collision Avoidance Distance (ACAD) is the minimum assured vertical or horizontal distance allowed between aircraft geometric centers. If this separation is not maintained, a collision or dangerously close spacing will occur. These distances are fixed numbers calculated by risk modeling, based upon factors such as: a) the type of aircraft being separated, b) the airspace environment, c) the intended aircraft operations, and d) for aircraft operating in a mixed environment, the separation standards currently being used by ATC in the airspace.

Assured Normal Separation Distance (ANSD) is used in conflict avoidance and is the normal minimum assured vertical or horizontal distance allowed between aircraft geometric centers. These distances are entered by the flight crew or set by the system. In a mixed airspace environment for separation from ATC separated aircraft, the ANSD will be based on current separation standards (and will be larger than the ACAD) to prevent ATC alerts. In the long term, collision risk modeling will set the ANSD. Ultimately the ANSD may be reduced toward the value of the ACAD.

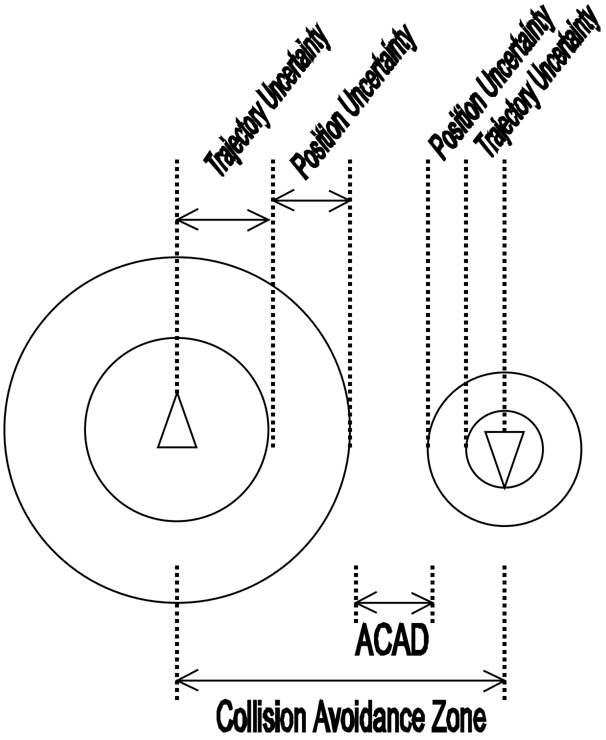


Figure 358 – Collision Avoidance Zone (CAZ)

[Reference: Modified diagram based upon DO-289, "MASPS for Aircraft Surveillance Applications," RTCA, December 9, 2003.]

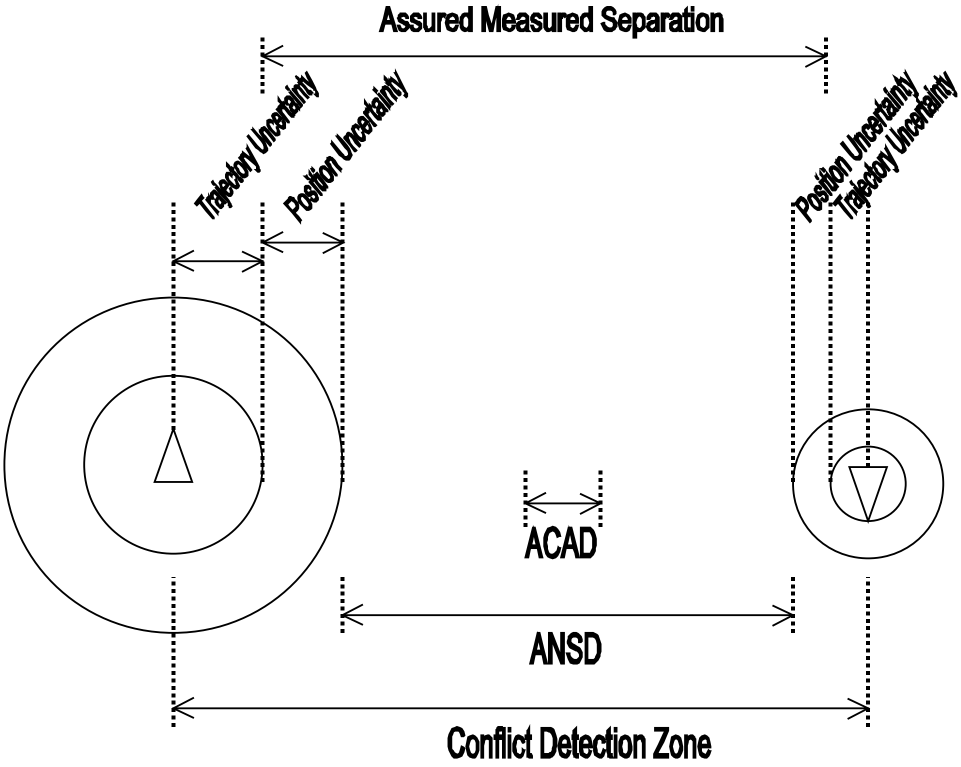


Figure 359 – Conflict Detection Zone (CDZ)

[Reference: Modified diagram based upon DO-289, "MASPS for Aircraft Surveillance Applications," RTCA, December 9, 2003.]

27.3.1.2.2 Conflict Resolution (CR) Function

The CR function provides three corresponding levels of maneuver advisories (MA), which are displayed concurrently with the corresponding CD alerts. At the first level, MAs need not be coordinated. At the two higher levels, implicit or explicit coordination of MAs is required. Aircraft are required to follow predetermined rules for resolving a conflict. The rules dictate which aircraft must maneuver and/or the maneuver degrees of freedom. These MAs provide one or more suggested maneuvers to the flight crew to resolve the conflict.

- <u>CR Advisory</u>: An optional Low Level CR Maneuver Alert (MA) (advisory) that does not require pilot compliance. These MAs are not coordinated, and provide the pilot with the most flexibility in resolving the conflict. These MAs are disabled if the Low Level Alert is disabled.
- <u>CR Caution</u>: A required CDZ CR Maneuver Alert (caution) that should offer the pilot a selection of maneuvers. These MAs are coordinated with other ACM systems, and pilot compliance is required in a timely manner.
- <u>CR Warning</u>: A required CAZ CR Maneuver Alert (warning) that will offer the pilot a specific maneuver. This MA is coordinated with other ACM systems, and pilot compliance is required immediately.

27.3.1.2.3 Conflict Prevention (CP) Function

The CP function provides corresponding prevention advisories (PA). These are determined by analyzing possible own aircraft maneuvers, and results in recommended maneuvering limitations. The PAs are intended to prevent the flight crew from selecting conflict resolution maneuvers from one aircraft that will cause conflicts with one or more other aircraft. There are correspondingly three levels of PA alerts:

- CP Advisory: An optional CP (advisory) alert that indicates maneuvers which, if completed, would immediately trigger a CD advisory alert.
- CP Caution: A required CP (caution) alert that indicates maneuvers which, if completed, would immediately trigger a CD caution alert.
- CP Warning: A required CP (warning) alert that indicates maneuvers which, if completed, would immediately trigger a CD warning alert.

27.3.2 Airborne Self-Separation Operational Scenarios

The ASS application is expected to operate in all phases of flight and under all air traffic environments. The activities involved in using ACM will vary with the air traffic environment and thus the operational scenarios have been identified in the four different operational environments including: 1) autonomous self-separation airspace, 2) mixed controlled and autonomous self-separation airspace, 3) uncontrolled airspace, and 4) controlled airspace.

It is anticipated that the ASS application will result in procedures that will allow changes and transitions in separation responsibility between ATC and flight crews. The separation responsibility may be fully on the flight crews with the use of on-aircraft ASS systems, fully with ATC with situational awareness information provided by ASS, or perhaps as part of a future concept of operations some shared responsibility of separation.

27.3.2.1 Scenario #1: Autonomous Self-Separation Airspace

Operational scenario #1 is depicted in Figure 360. This scenario involves the use of the Airborne Self-Separation application in segregated airspace, for which only aircraft capable of self-separation are allowed to operate in. This airspace may, for example, be defined by location/altitude and perhaps additionally also by time.

In autonomous segregated airborne self-separation airspace, which is likely to evolve first in places such as oceanic, remote, and polar area airspaces, as well as in domestic upper airspace environments over the US and Europe), all aircraft will be required to be equipped with a full ASS system and the flight crew would assume separation responsibility using the ASS system.

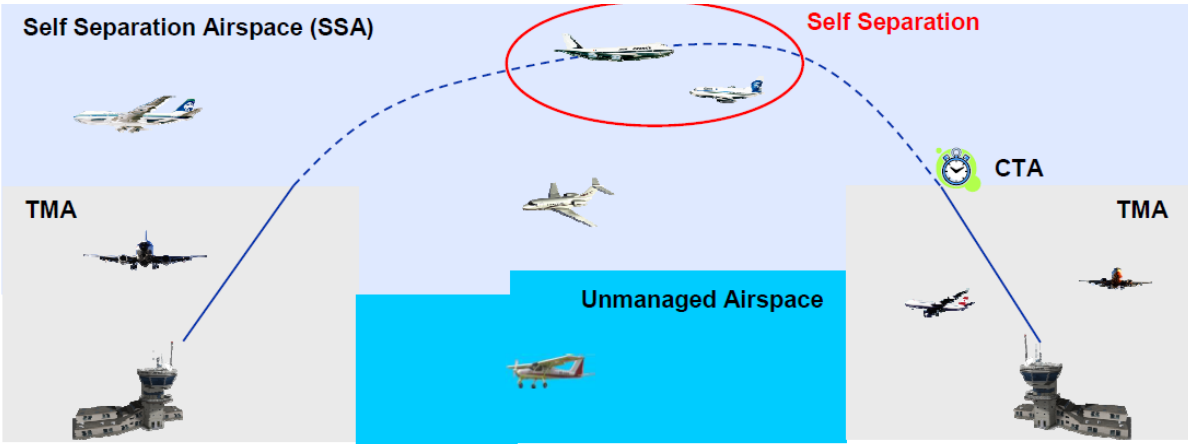


Figure 360 – ASS Scenario #1: Autonomous Self-Separation Airspace

[Reference: iFly. Presentation entitled “WP1: A^3 Concept of Operations,” by Petr Casek, September 29, 2009.]

27.3.2.2 Scenario #2: Mixed Controlled and Autonomous Operations Airspace

Operational scenario #2 is depicted in Figure 361. This scenario is one of a mixture of ATC separated aircraft and autonomous separated aircraft operations. Such a situation may occur in enroute airspace. It is a scenario where there is cooperative and distributed ATM, whereby ATC is responsible to separate some aircraft and self-separating aircraft have the responsibility for safely separating their aircraft from all other aircraft. There will be a clear transfer of separation responsibility from ATC to the flight crew for self-separating aircraft, and a clear transfer of separation responsibility back to ATC when terminating the Aircraft Self-separation operation.

Normal control of enroute IFR flights by ATC could continue with minimum regard given to the presence of self-separating flights operating under “Autonomous Flight Rules (AFR).” The ANSP has no separation or trajectory management responsibility for AFR flights from the time they are cleared/released to AFR until re-established on an IFR clearance, normally in the vicinity of the destination terminal airspace. AFR flights will be displayed on the controller's display but, at the controller's discretion, may have reduced or suppressed data tags, similar to VFR flights in certain airspace. Separation logic is designed to detect and resolve conflicts between AFR aircraft and ANSP-managed IFR aircraft in a timely fashion to preclude controller concern about whether the AFR flight is going to resolve the conflict or how it will be resolved. A concerned controller may always take action by maneuvering the IFR aircraft, but that should rarely happen. Normal ANSP procedures of not creating a known hazard apply. In addition, ATC communicating with AFR aircraft via voice/data is available, if needed, to aid situation awareness and operational efficiency. In normal operations, voice communication between enroute controllers and AFR flight crews should not be frequently required.

For use of Airborne Self-Separation in this Mixed environment, the flight crew is given the responsibility for safe separation from all other aircraft, and the authority to maneuver their aircraft without any need to obtain additional ATC authorization. That responsibility and authorization has already been provided as part of the AFR clearance, and any associated limitations imposed by that clearance.

Figure 361 – ASS Scenario #2: Mixed Controlled & Autonomous Operations Airspace

[Reference: NLR 2012 Annual Report, per http://annualreport.nlr.nl/2012/Projects/Accessibility/Aircraft%20self-separation/.]

27.3.2.3 Scenario #3: Unmanaged Airspace

Operational Scenario #3 is depicted in Figure 362. This scenario is one of use of that self-separation application in unmanaged airspace. In current unmanaged airspace operations, the flight crew has separation responsibility. The ASS application is expected to increase safety between not only ASS equipped aircraft, but also between ASS-equipped aircraft and aircraft whose surveillance information is available to the ASS-equipped aircraft. Surveillance information is expected to be primarily available through ADS-B aircraft-to-aircraft surveillance, but other sources of surveillance may include ADS-R, TIS-B, TCAS, and radar / optical sensors. The flight crews of the ASS-equipped aircraft must be aware that the surveillance information for all other aircraft may not be available.

Figure 362 – ASS Scenario #3: Unmanaged Airspace

[Reference: SAE International, http://articles.sae.org/6784/, with modifications.]

27.3.2.4 Scenario #4: Controlled Airspace

Operational Scenario #4 is depicted in Figure 363. This scenario is one where ATC has the separation responsibility for "all" aircraft (perhaps with limited DS), but aircraft equipped with the Autonomous Self-Separation application may use the application to enhance situational awareness. In controlled airspace, separation responsibility remains with ATC, and any Autonomous Self-Separation capability utilized on the aircraft acts as an advisory tool to the flight crew. In such a scenario, the ASS capability may improve flight crew situational awareness and help detect and mitigate very rare failures in ATC-separated airspace before they lead to a loss of separation or mid-air collision. The flight crew must obtain ATC approval prior to executing any ASS recommended conflict resolutions.

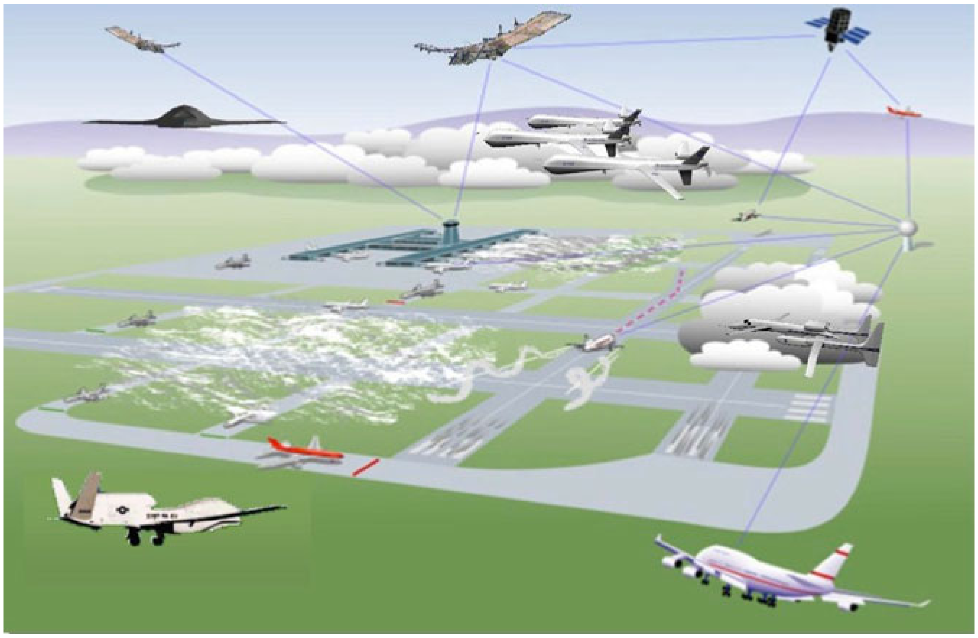


Figure 363 – ASS Scenario #4: ATC Controlled Airspace

[Reference: NASA, http://www.nasa.gov/centers/armstrong/news/FactSheets/FS-075-DFRC.html#.U3ytbPldVkg.]

27.3.3 Airborne Self-Separation Phases of Operation

For the purposes of this use case analysis, the airborne self-separation application has been broken down into four phases of operation including:

1. Pre-initiation
2. Initiation
3. Execution
4. Termination

These four phases of ASS operation are briefly described below.

During the Pre-initiation Phase, the flight crew role is to switch on the ASS equipment and the equipment runs comprehensive self-tests to ensure that it is capable of properly functioning to support the airborne separation assurance function.

During the Initiation Phase, the flight crew prepares to enter the ASS assisted phase of flight. For use in autonomous and mixed controlled/autonomous airspaces (per Scenarios #1 and #2), the flight crew would be provided an AFR clearance (via communication with ATC). For use in unmanaged and controlled airspaces (per Scenarios #3 and #4), there is no role for ATC and no clearance is provided.

During the Execution Phase where the flight crew has separation responsibility (Scenarios #1, #2, and #3), the flight crew uses the ASS equipment to maintain safe separation from all other aircraft. During the Execution Phase of use in airspace where the controller has separation responsibility for all aircraft (Scenario #4), the ASS equipment functions only as an advisory tool to the flight crew.

During the Termination Phase, the handover of separation responsibility is transferred back to ATC for use in the Autonomous and Mixed Controlled and Autonomous Operations airspaces (per Scenarios #1 and #2). During the Termination Phase for use in Unmanaged or Controlled airspaces, the portion of flight where the ASS equipment is useful to support self-separation or provide advisory information has concluded.

The specific roles of the flight crew, ATC, and the ASS equipment are summarized in Figure 364 for use in the Autonomous and Mixed Controlled and Autonomous Operations airspaces (Scenarios #1 and #2).

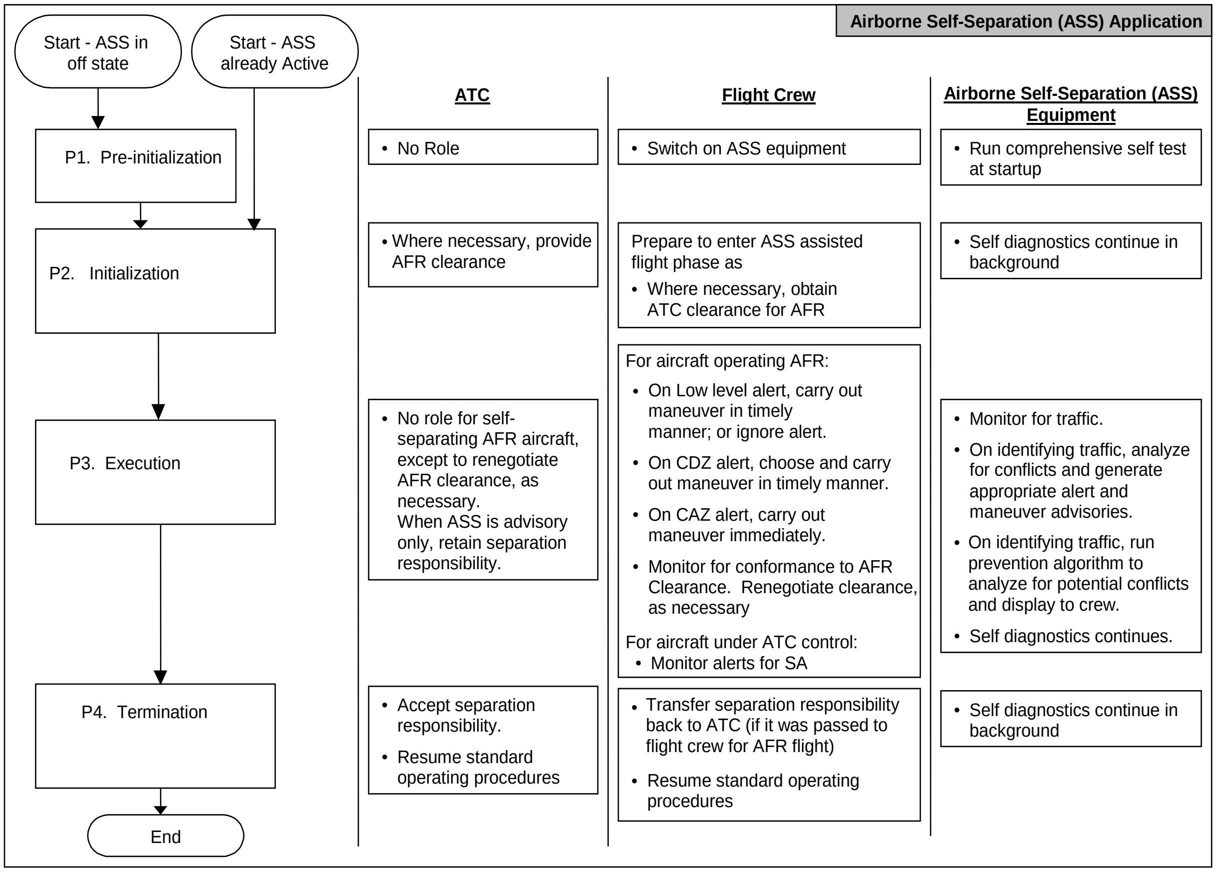


Figure 364 – ASS Phase Diagram for Autonomous and Mixed Controlled / Autonomous Airspaces

[Reference: Modified diagram based upon DO-289, "MASPS for Aircraft Surveillance Applications," RTCA, December 9, 2003.]

27.3.4 Airborne Self-Separation Use Case Activity Diagram with Comm. Phases Highlighted

The four phases of the Airborne Self-Separation operation were overviewed in Section 27.3.3 above. This section provides a use case activity diagram (see Figure 365) that identifies the activities that occur during each phase of operation for which the ASS system is supporting the flight crew with airborne self-separation in autonomous and mixed operations airspaces.

The specific actions being made by the application's "actors" in each step are identified as being done by the flight crew (labeled "Crew" in the figure), ATC, or the Airborne Self-Separation System (labeled "ASS" in the figure). The steps in the use case diagram where communications occur are highlighted with yellow shading on the figures, and an indication of whether the information is communicated from aircraft-to-ground (A-G), ground-to-aircraft (G-A), or aircraft-to-aircraft (A-A) is provided.

The use case activity diagram shown in Figure 365 is appropriate for ASS Scenarios #1 and #2. For ASS Scenario #3 (use in unmanaged airspace), the activity diagram is very similar to that provided in Figure 365. The big change is that no AFC clearance is needed, so the actions/communications associated with the flight crew and ATC requesting, providing, acknowledging, monitoring, and renegotiating the AFR clearance would not be done. Similarly, for ASS Scenario #4 (use in ATC fully-controlled airspace), the activity diagram is also very similar to that depicted in Figure 365. However, no AFR clearance is needed and the flight crew must not maneuver with the traffic alerts provided by ASS. In Scenario #4, the alerts are intended to be used only for advisory situational awareness and the flight crew needs to obtain ATC approval prior to executing any ASS recommended conflict resolution maneuvers.

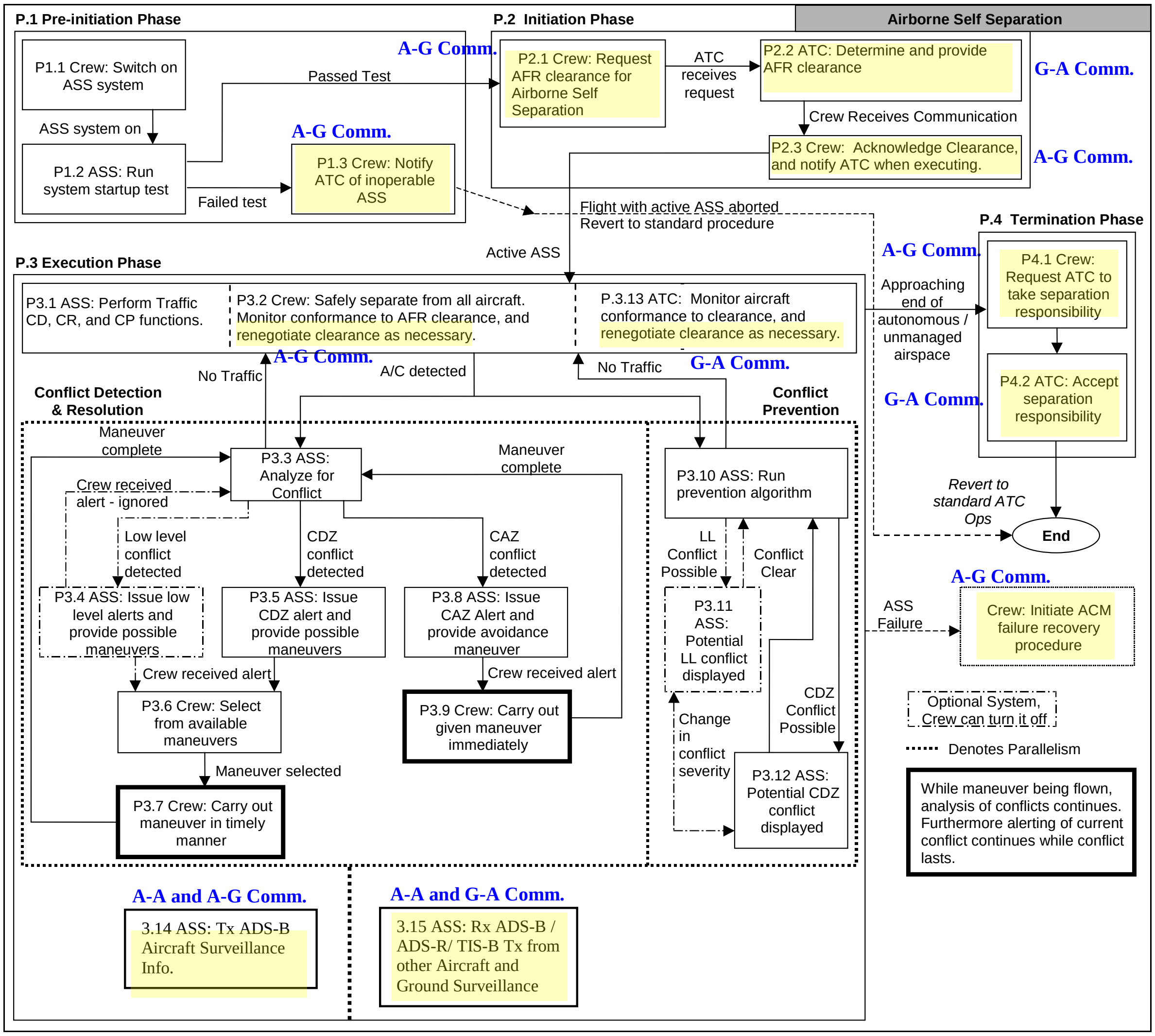


Figure 365 – ASS Use Case Activity Diagram for Autonomous and Mixed Controlled / Autonomous Airspace

[Reference: Modified diagram based upon DO-289, MASPS for Aircraft Surveillance Applications," RTCA, December 9, 2003.]

27.3.5 Airborne Self-Separation Communications Information and Infrastructure

The communications information and infrastructure required to enable the ASS application is described in the subsections below for the aircraft-to-aircraft, ground-to-aircraft, and aircraft-to-ground communication domains.

27.3.5.1 ASS Aircraft-to-Aircraft Communications

To enable airborne self-separation, ADS-B IN is required on the ASS aircraft. To enable ASS in autonomous in mixed environment airspaces (per scenarios #1 and #2), ADS-B Out will be required on all aircraft in the airspace.

The functional requirements associated with the ADS-B Out are anticipated to be higher in terms of continuity and availability than the FAA's ADS-B Out 2020 rule requirements. If the continuity and availability of surveillance information for the Traffic Aircraft are not high enough for a given airspace, then supplemental surveillance information (e.g., from TIS-B and ADS-R ground-to-aircraft communications) will be required. The information requirements at a minimum include those defined in the current ADS-B standard, but preferably in the future would also include aircraft intent information.

For use in unmanaged and ATC controlled airspaces, ADS-B Out will not be required at a minimum to enable use of ASS. While ADS-B Out is highly desired from all traffic aircraft, in the unmanaged and ATC controlled airspaces, the ASS function is providing advisory/ supplemental situational awareness information and is not providing the primary means of separation (per scenarios #3 and #4). In unmanaged airspace, ADS-B Out will not be required by Traffic Aircraft and the flight crew needs to use other means (e.g., see and avoid) to separate from traffic threats unknown to the ASS system. In controlled airspace where ATC is providing separation services for all aircraft, it is expected that ATC will have ADS-B Out requirements for all traffic to support ground surveillance (provided by the aircraft via A-G communications); however, ATC may allow aircraft without ADS-B Out in the airspace when other means of surveillance is available.

In addition, A-A communications will be needed to support the aircraft-based collision avoidance function of TCAS or the future TCAS enhancement (i.e., ACAS-X) and to provide supplemental and backup surveillance information for the ASS system. Over the years, the aircraft-based collision avoidance function is expected to become less dependent upon today’s TCAS 1030/1090 MHz interrogations/replies and more reliant on ADS-B Out broadcasts for surveillance information, or some combination thereof (i.e., hybrid surveillance).

27.3.5.2 ASS Ground-to-Aircraft Communications

For AFR use as the primary means of separation in autonomous and mixed airspaces, it is envisioned that ATC will provide the ASS-relevant G-A communications to the aircraft via a digital data or voice communications link that meets the ATC safety services Required Communications Performance (RCP) associated with providing ATC clearances in the airspace. Similarly, the flight crew will acknowledge the ATC AFR-relevant communications (using A-G comm.) on an approved ATC safety services communications link that meets the RCP in the airspace where the operation is being conducted. This minimum performance varies as it does today in different ATC controlled airspaces.

The ASS application requires specific information to be communicated between ATC and the ASS Aircraft (e.g., the AFR clearance, renegotiation of clearance, acknowledgement of AFR communications from the aircraft) when using this application as the primary means of separation (i.e., in autonomous and mixed airspaces per scenarios #1 and #2). In general, this communication can be supported via both voice and data communications. However, it is envisioned that over time, the AFR communications will be mostly supported by data comm. For use in unmanaged and ATC controlled airspaces, it is not envisioned that any G-A ATC communications are needed to support the flight crew use of the ASS system as a supplemental/advisory function.

In addition to AFR clearance, the ASS aircraft needs to be capable of receiving the traffic surveillance services broadcasts from TIS-B and ADS-R, as a backup source of traffic surveillance information.

27.3.5.3 ASS Aircraft-to-Ground Communications

For AFR use as the primary means of separation in autonomous and mixed airspaces, it is expected that aircraft will request AFR clearances and respond to ATC AFR-relevant communications via a digital data or voice communications link that meets the ATC safety services RCP.

All aircraft operating the ASS function are expected to broadcast ADS-B Out surveillance information for use by ATC (A-G communications) and other aircraft (A-A).

27.3.6 Airborne Self-Separation Application Use with One-to-One and One-to-Many Aircraft

By definition, this Airborne Self-Separation application is intended to be a one-to-many aircraft application. The application is intended to safely separate from all traffic targets for which surveillance information is known and available to the ASS equipment. Thus, Airborne Self-Separation is not a one-to-one application and is by definition a one-to-many application, whereby in today's concept as described herein, "many" is defined to be "all" other aircraft. In the future, the ASS concept of operations may be expanded whereby it could also include some limited delegation of separation responsibility back to the controller (e.g., the ASS has separation responsibility for most aircraft, except a small number of specifically identified aircraft that will remain an ATC responsibility). Such an expanded concept of operations may be required for accommodating vehicles whose surveillance information may not be available to the ASS aircraft conducting the AFR operation.

28 PHASE 4 – INTERIM STUDY FINDINGS

The section of the report summarizes the interim study findings and provides a conclusion to the fourth phase of the study.

28.1 Summary of Phase 4 Interim Study Findings

Phase 4 of the study includes the results from prioritizing and describing a set of representative ATM applications that are enabled by A-A and/or A-G communications that are expected to be utilized in the long-term NextGen and beyond NAS. A defensible prioritization process has been developed that leverages the prioritization process developed by the RTCA NextGen Advisory Committee (NAC). The NAC prioritization process was modified as described herein to de-weight the relative importance of today's "implementation readiness" evaluation metric given the longer term nature of this study than the applications the NAC committee was evaluating and to incorporate a specific individual cost assessment evaluation metric. The application prioritization assessment evaluated each of the identified long-term ATM applications according to five evaluation criteria that included:

1) Benefits (Monetizable) [45%] *[i.e., benefits that can readily be estimated to have a monetary (or cash) value, including, for example, capacity and efficiency]*;
2) Benefits (Non-Monetizable) [15%] *[i.e., benefits difficult to estimate the monetary (or cash) value, including, for example, safety and security]*;
3) Cost [25%] *[i.e., cost of elements needed to enable the application]*;
4) Implementation Readiness [5%] *[i.e., assessment of whether the needed elements are in place to achieve a given operational capability, including, for example standards, policy, and systems]*; and
5) Other Considerations [10%] *[i.e., factors including global harmonization, confidence that the benefits will be realized, and whether the capability is a critical element for a broad set of NextGen improvements]*.

The individual scores from the five evaluations were multiplied by the weighting factors for each evaluation criterion as identified above (percentages) and summed to obtain a total relative score for each application. The total scores for all applications were ranked to establish a relative prioritization of the applications such that Delegated Interval (DI), Delegated Separation (DS), and Airborne Self-Separation (ASS) applications were in the top tier of applications. Other applications, including In-Trail Procedures (ITP), Optimized Profile Descent (OPD), and Airborne Access to SWIM (AAtS) were ranked in the middle tier, and applications including GNSS/GBAS Category I/II/III Precision Approach, Surface Situational Awareness with Indications and Alerts (SURF IA), and Ground-based Interval Management (GIM) (without Flight Deck IM) were ranked in the lowest tier.

For each of the 52 long-term ATM applications, an assessment of the A-A and A-G communication candidates that would be capable of meeting the application's communication requirements was made. This assessment was made by comparing the Required Communications Performance (RCP) needed to enable each of the long-term ATM applications with the Actual Communications Performance (ACP) provided by each of the communications candidates.

Use case analyses were completed for three of the highest priority applications including: 1) Delegated Interval (DI) / Interval Management (IM), 2) Delegated Separation (DS), and Airborne Self-Separation (ASS).

Each of the use case analysis included the following: a) a description of the concept of operations, b) an identification of a representative set of example operational scenarios used as the basis for the analyses, c) a partitioning of the application into its constituent phases of operation (e.g., pre-initiation, initiation, execution, and termination), d) the development of use case activity diagrams that identify the specific activities in the context of the application where A-A, A-G, and Ground-to-Aircraft (G-A) communications take place, and e) a description of the specific communications needed during each phase of the application.

The interim study findings from the Phase 4 analyses are summarized as follows:

1. A broad set of 52 NextGen and beyond long-term NAS ATM applications were identified, described, and subjectively assessed relative to each other using the evaluation process described in Section 21 of this report. A results summary table that ranks all of these applications is provided in Figure 11 (page 27). This evaluation has led to prioritizing the applications into 3 prioritized tiers as given in Figure 12 (page 28) with “Tier 1” being the highest priority application grouping, “Tier 2” being the middle priority grouping, and “Tier 3” being the lowest priority grouping.
2. No one single communications data link technology can meet the needs of all the future NAS operations in all airspaces. A combination of various communication technologies are needed to address the diverse aeronautical communications requirements across all the operational flight domains.
3. At least one of the communication candidates identified is able to meet the communication requirements needed enable each of the long-term ATM applications. In other words, no application has been identified for which there is no communication data link technology capable of satisfying the application’s RCP.

28.2 Interim Study Report Conclusion

This concludes Phase 4 of the study (presented in Sections 25 to 28 of this report) which was originally documented in the fourth in a series of five interim reports that were completed during the execution of this study to identify and evaluate air-to-air and air-to-ground candidates for meeting the long-term evolving needs of the National Airspace System during the modernization time horizon of 50 years. Subsequent sections of this document describe the results from Phase 5 of the study.

Phase 5 of the study is documented in Sections 29 to 32. These sections identify criteria for prioritizing the communication candidates and describe the use of the criteria to prioritize the candidates from most promising to least promising.

29 CRITERIA FOR EVALUATING AND PRIORITIZING CANDIDATES

The section of the report identifies and describes the criteria for evaluating and prioritizing the future NAS ATM communications systems candidates.

29.1 Criteria Used for Evaluating and Prioritizing Candidates

The 25 criteria that have been selected for the purposes of evaluating and prioritizing the communication candidates are identified in Figure 366. The evaluation criteria encompass a broad range of factors that have been grouped into categories of technical performance, cost, and risk. They are traceable to the necessary elements for future aeronautical communications systems as articulated in the Eurocontrol/FAA Communications Operating Concepts & Requirements (COCR) for the Future Radio Systems document, the Eurocontrol/FAA/NASA Future Communication Study Report, and various ICAO consensus documents including ICAO ANC Conference Recommendations and ICAO Doc 9750 (Global Air Navigation Plan for CNS/ATM Systems).

Category	Evaluation Category Description	#	Criteria
Technical Performance	Technical performance of candidate capabilities needed to support future NextGen and beyond ATM communication services.	1	Coverage Volume / Communications Range
		2	Data Rate
		3	Spectral Efficiency
		4	Capacity
		5	Number of Users
		6	Availability & Continuity
		7	Integrity
		8	Latency
		9	Scaleability / Flexibility / Ability to Incorporate New Technologies
		10	Security / Vulnerabilities
		11	Robustness to Interference / Environment
		12	Installable on Range of Air Vehicles
		13	Ability to Support Broadcast Communications
		14	Satisfy Requirements for Aviation Safety Services
		15	Satisfy Requirements for Aviation Advisory Services
Cost	Costs associated with candidate including airborne/ ground/ satellite infrastructure, and maturation & standards.	16	Airborne Infrastructure Cost
		17	Ground / Satellite Infrastructure Cost
		18	Technology Maturation & Standards Cost
Risk	Risks associated with candidate in the areas of spectrum availability, technology readiness, global acceptance, standards, certification, and transition.	19	Spectrum Availability & Compatibility
		20	Technical Maturity / Readiness Level (TRL)
		21	Standardization Status
		22	Global Harmonization Risk
		23	Certification Complexity
		24	Susceptible to Wide Outage / Long MTTR
		25	Ease of Transition

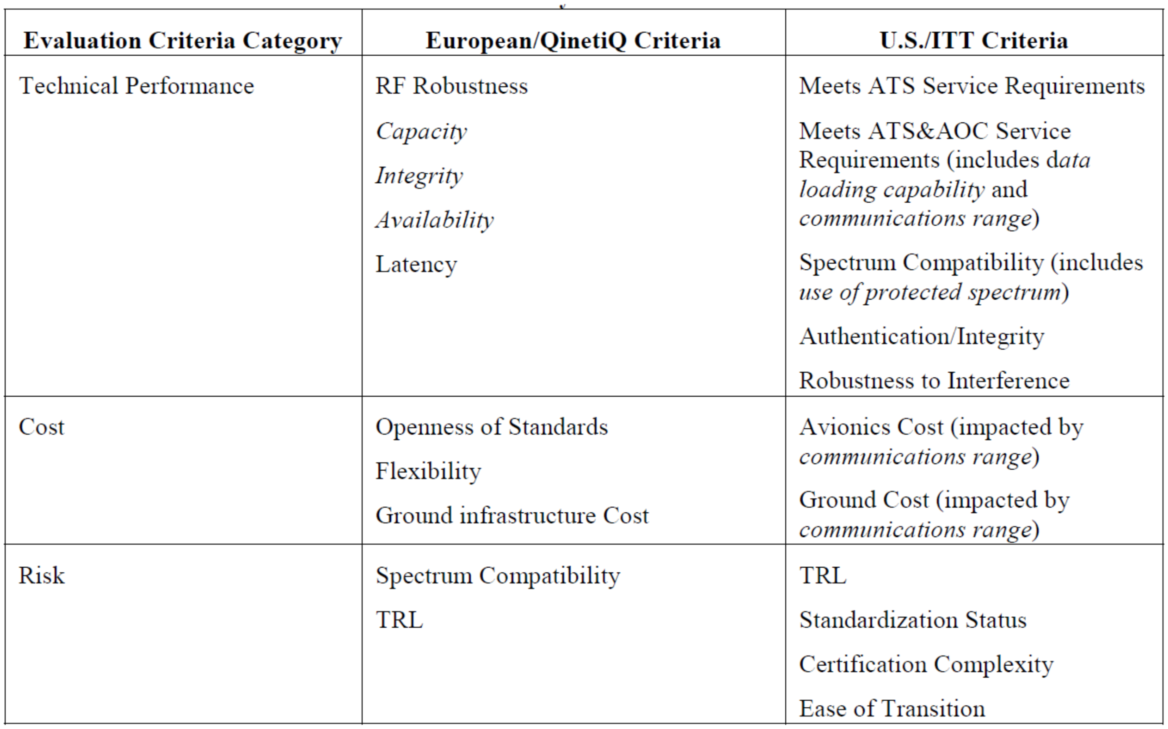
Figure 366 – Criteria Used to Evaluate / Prioritize Communications Candidates

This set of criteria was developed by leveraging the evaluation criteria that have been identified and documented in previous NAS future communication systems study reports, with some expansion and tailoring of the criteria commensurate with the longer term nature of this study.

Previous NAS Future Communication Systems studies have been documented in a number of reports and presentations including a report entitled, "*Eurocontrol/FAA/NASA, Action Plan 17, Future Communication Study Report, Final Conclusions and Recommendations" (version 1.1, dated November 2007).* Figure 293 summarizes and categorizes the set of evaluation criteria utilized by European /QinetiQ (a set of 10 criteria) and U.S. / ITT (a set of 11 criteria) study teams (respectively), as reported in the aforementioned report. Note that in this figure, the criteria scripted in italics font were also used for the initial candidate screening /down-selection process done in the studies described in the reference report.

Figure 368 identifies how the European/QinetiQ study team prioritized their set of 10 evaluation criteria. Figure 369 and Figure 370 illustrate the process by which the U.S. / ITT team derived their evaluation criteria from COCR and ICAO ANC documents.

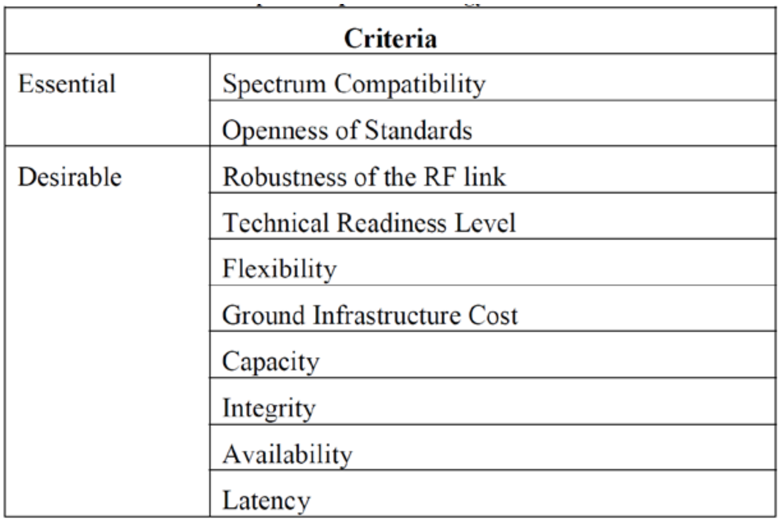
While the U.S. and European Future Comm evaluation teams developed different evaluation criteria and metrics, both sets of criteria can be grouped into three general areas of applicability: 1) technical performance, 2) cost, and 3) risk. These groupings were used as the basis for developing the more comprehensive list of evaluation and prioritization criteria that is presented in Figure 366 and is used to evaluate and prioritize the communications candidates in this report. The criteria identified herein built on the criteria identified in the previous Future Communications Studies and incorporated additional relevant elements analyzed as part of the Com50 study.



Evaluation Criteria Category	European/QinetiQ Criteria	U.S./ITT Criteria
Technical Performance	RF Robustness *Capacity* *Integrity* *Availability* Latency	Meets ATS Service Requirements Meets ATS&AOC Service Requirements (includes *data loading capability* and *communications range*) Spectrum Compatibility (includes *use of protected spectrum*) Authentication/Integrity Robustness to Interference
Cost	Openness of Standards Flexibility Ground infrastructure Cost	Avionics Cost (impacted by *communications range*) Ground Cost (impacted by *communications range*)
Risk	Spectrum Compatibility TRL	TRL Standardization Status Certification Complexity Ease of Transition

Figure 367 – Summary of Evaluation Criteria Used in Previous Future Comm. Studies

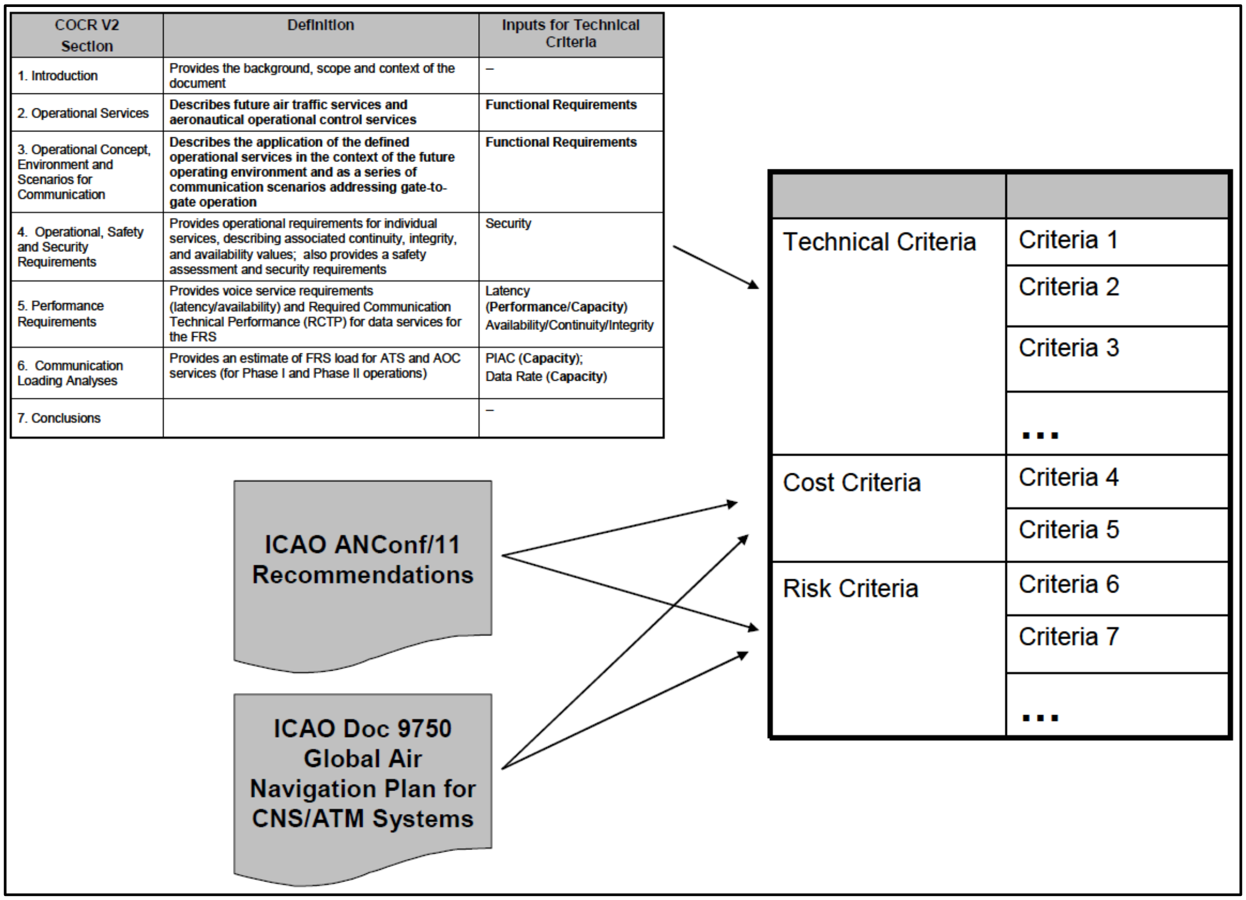
[Reference: Eurocontrol/FAA/NASA, Action Plan 17, Future Communication Study, Final Conclusions and Recommendations Report, version 1.1, November 2007.]



Criteria	
Essential	Spectrum Compatibility
	Openness of Standards
Desirable	Robustness of the RF link
	Technical Readiness Level
	Flexibility
	Ground Infrastructure Cost
	Capacity
	Integrity
	Availability
	Latency

Figure 368 – European / QinetiQ Prioritized Criteria Used in Future Comm. Study

[Reference: Eurocontrol/FAA/NASA, Action Plan 17, Future Communication Study, Final Conclusions and Recommendations Report, version 1.1, November 2007.]



COCR V2 Section	Definition	Inputs for Technical Criteria
1. Introduction	Provides the background, scope and context of the document	–
2. Operational Services	**Describes future air traffic services and aeronautical operational control services**	**Functional Requirements**
3. Operational Concept, Environment and Scenarios for Communication	**Describes the application of the defined operational services in the context of the future operating environment and as a series of communication scenarios addressing gate-to-gate operation**	**Functional Requirements**
4. Operational, Safety and Security Requirements	Provides operational requirements for individual services, describing associated continuity, integrity, and availability values; also provides a safety assessment and security requirements	Security
5. Performance Requirements	Provides voice service requirements (latency/availability) and Required Communication Technical Performance (RCTP) for data services for the FRS	Latency **(Performance/Capacity)** Availability/Continuity/Integrity
6. Communication Loading Analyses	Provides an estimate of FRS load for ATS and AOC services (for Phase I and Phase II operations)	PIAC (**Capacity**); Data Rate (**Capacity**)
7. Conclusions		–

Figure 369 – Derivation of Evaluation Criteria for U.S. / ITT Future Comm. Study

[Reference: Eurocontrol/FAA/NASA, Action Plan 17, Future Communication Study, Final Conclusions and Recommendations Report, version 1.1, November 2007.]

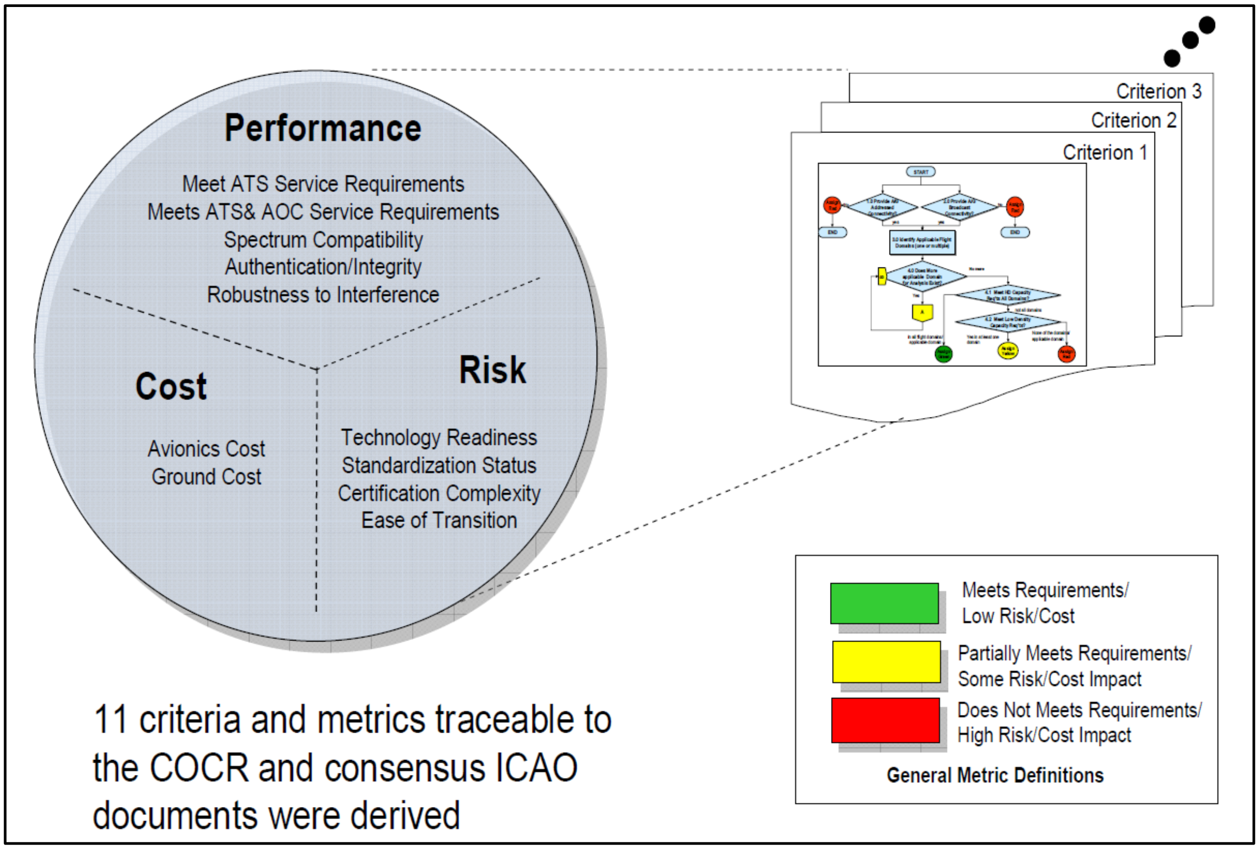


Figure 370 – Evaluation Criteria and Metrics for U.S./ITT Future Comm. Study

[Reference: Eurocontrol/FAA/NASA, Action Plan 17, Future Communication Study, Final Conclusions and Recommendations Report, version 1.1, November 2007.]

29.2 Criteria Descriptions and Rating Scales

29.2.1 Overview of Rating Scales

As an introductory overview of the rating scales, Figure 371 identifies the generalized rating system used to evaluate the candidates across the criteria that have been identified in Figure 366. Note that the specific rating system used is identified in Section 29.2.2. The generalized rating system across all of the technical performance, cost, or risk criteria is such that a rating of “1” is “poor” (i.e., very low technical performance, very high cost, or very high risk) and a rating of “5” is “very good” (i.e., very high technical performance, very low cost, or very low risk). Similarly, the intermediate ratings of 2, 3, and 4 incrementally improve from “fair,” to “medium,” to “good” (respectively) assessments of the evaluation criteria.

For a few of the criteria in addition to numerical ratings from 1 to 5, there is an additional rating of “showstopper” (SS). Such a rating indicates that a candidate’s performance against the criterion relevant to meeting the ATM communication services needs is completely unacceptable (i.e., a “showstopper”) in the flight domain(s) being assessed. For example, a “showstopper” rating may be given when a communication technology candidate provides no useable service anywhere in the coverage volume or is infeasible to implement the candidate in the flight domain from a cost standpoint. When such a rating is given for a particular communication candidate, further assessment of that candidate is stopped for the flight domain(s) under investigation since the candidate’s rating for the criterion is determined to be completely unacceptable (i.e., a “showstopper” to selection as a viable candidate).

Category	Evaluation Category Description	Rating Scale	Generalized Rating Description
Technical Performance	Technical performance of candidate capabilities needed to support future NextGen and beyond ATM communication services.	5	**Very High** Performance
		4	**High** Performance
		3	**Medium** Performance
		2	**Low** Performance
		1	**Very Low** Performance
		SS	**Showstopper** – Lack of Technical Performance
Cost	Costs associated with candidate including airborne/ ground/ satellite infrastructure, and maturation & standards.	5	**Very Low** Cost
		4	**Low** Cost
		3	**Moderate** Cost
		2	**High** Cost
		1	**Very High** Cost
		SS	**Showstopper** – Infeasible from Cost Standpoint
Risk	Risks associated with candidate in the areas of spectrum availability, technology readiness, global acceptance, standards, certification, and transition.	5	**Very Low** Risk
		4	**Low** Risk
		3	**Moderate** Risk
		2	**High** Risk
		1	**Very High** Risk
		SS	**Showstopper** – Infeasible from Risk Standpoint

Figure 371 – Generalized Category Ratings Used to Evaluate / Prioritize Candidate

29.2.2 Specific Criteria Descriptions and Specific Rating Scales

Figure 299, Figure 373, and Figure 374 define the technical performance, cost, and risk evaluation criteria (respectively) and the specific rating scale used for each criterion in the evaluation of the A-A and A-G communication technology candidates that is presented in Section 30. Note that Figure 375 summarizes the specific rating scales for all the evaluation criteria.

Figure 372 – Technical Performance Evaluation Criteria and Rating Scales

#	Performance Criteria	Definition and Rating Scale
1	Coverage Volume / Communication Range	Candidate technology can readily be fielded without gaps in the coverage volume with suitable communication range to cover the flight domain(s) under investigation. **Rating Scale:** **5**: Very high coverage (100% coverage) can be readily achieved across the entire flight domain(s) under investigation **4**: High coverage (nearly 100% coverage in all areas) **3**: Medium coverage (good coverage in most areas, but a few gaps) **2**: Poor coverage (good coverage in many areas, but number of gaps are expected to occur) **1**: Very poor coverage (not good coverage in a number of areas) **SS**: (Showstopper) The candidate provides no usable service in the flight domain(s) under investigation.
2	Data Rate	This metric compares the data rate that is expected to be achieved by a candidate communication technology during the modernization time horizon of the study. **Rating Scale:** **5**: Very high data rate (> 1000 MBPS) **4**: High data rate (< 1000 MBPS) **3**: Medium data rate (< 200 MBPS) **2**: Low data rate (< 1 MBPS) **1**: Very low data rate (> 0.1 MBPS)
3	Spectral Efficiency	This metric is an evaluation of the spectral efficiency that is expected to be achieved by a candidate communication technology during the modernization time horizon of this study. **Rating Scale:** **5**: Very high spectral efficiency (> 15 bits/Hz) **4**: High spectral efficiency (< 15 bits/Hz) **3**: Medium/average spectral efficiency (< 5 bits/Hz) **2**: Low spectral efficiency (< 2.5 bits/Hz) **1**: Very low spectral efficiency (< 0.5 bits/Hz)

#	Performance Criteria	Definition and Rating Scale
4	Capacity	This metric is a relative comparison of the capacity that is expected to be achieved by a candidate communication technology relative to the other candidates. **Rating Scale:** **5**: Very high relative capacity **4**: High relative capacity **3**: Medium/average relative capacity **2**: Low relative capacity **1**: Very low relative capacity
5	Number of Users	This metric assesses the relative capability of the technology candidate to support a high number of users within the flight domain(s) under investigation. **Rating Scale:** **5**: Very high number of users **4**: High **3**: Medium **2**: Low **1**: Very Low
6	Availability & Continuity	This metric is a relative comparison of the availability and continuity that is expected to be achieved by a communication technology candidate relative to the other candidates. **Rating Scale:** **5**: Very high for both “availability and continuity” (e.g., > 0.999995) **4**: At least high for both (e.g., > 0.99995) **3**. At least medium for both (e.g., > 0.9999) **2**. Cases other than 1, 3, 4, and 5 (e.g., > 0.999) **1**. Very poor for both (e.g., < 0.999)
7	Integrity	Assessment of the relative ability of the technology candidate to meet the aviation communications safety services integrity requirements. **Rating Scale:** **5**: Very high integrity **4**: High integrity **3**: Medium integrity **2**: Low integrity **1**: Very low integrity
8	Latency	This metric assesses the latency that is expected to be achieved by a candidate communication technology. **Rating Scale:** **5**: Very low latency (< 0.2 seconds) **4**: Low latency (< 1.0 seconds) **3**: Medium latency (Latency threshold adequate for voice com.) **2**: High latency (< 5.0 seconds) **1**: Very high latency (> 5.0 seconds)

#	Performance Criteria	Definition and Rating Scale
9	Scaleability / Flexibility / Ability to Incorporate New Technologies	This metric is a relative comparison of the ability of the technology candidate relative to the other candidates to be: a) scaled to accommodate greater or lesser communication demands in various environments (e.g., provide greater communication bandwidth in regions where operationally needed), b) flexible / adaptable to accommodate changing communication needs over time, and c) able to incorporate new technologies over time. **Rating Scale:** **5**: Very High Scaleability / Flexibility / Ability to Incorporate New Technologies **4**: High **3**: Average **2**: Low **1**: Very Low
10	Security / Vulnerabilities	Assessment of the technology candidate's security / vulnerabilities robustness against the security measures of: 1) Data integrity from deliberate and accidental modification, 2) Authentication, 3) Non-repudiation for denial of communications services, 4) Availability/Continuity of the communication service to remain reliable and accessible to all authorized parties, 5) Data Separation of the communication service to assure that the data belonging to one function is not subverted by another function, and 6) Confidentiality from unauthorized data access. **Rating Scale:** **5**: Very high security/ vulnerability robustness as assessed against all 6 security measures **4**: High security/ vulnerability robustness **3**: Medium security/ vulnerability robustness **2**: Low security/ vulnerability robustness **1**: Very low security/ vulnerability robustness
11	Robustness to Interference / Environment	Assessment of the technology candidate's robustness against interference in the environment that may cause outages. Examples include rain, fog, snow, haze, bright sunlight, signal blockages (e.g., buildings or structures), adjacent channel interference, noise floor, solar weather, other emitters, etc. **Rating Scale:** **5**: Very high robustness to all known environmental interference sources **4**: High robustness (e.g., low sensitivity to environmental events) **3**: Medium robustness (e.g., a few rare environmental events may cause outages) **2**: Low robustness (e.g., a few common environmental events may cause outages) **1**: Very low robustness (e.g., many common environmental occurrences may cause outage).

#	Performance Criteria	Definition and Rating Scale
12	Installable on Range of Air Vehicles	Candidate technology is readily installable considering size (e.g., antenna), weight, and power on range of aircraft vehicle types including: small / medium / large UAVs, general aviation, helicopters, business aircraft, regional aircraft, air transport aircraft, military aircraft, and space planes. **Rating Scale:** **5**: Easy to install on all air vehicle types **4**: Easy to install on most air vehicle types **3**: Medium difficulty to install on range air vehicles types **2**: Hard or impractical to install on at least a few air vehicle types **1**: Hard or impractical to install on at least several air vehicle types
14	Satisfy Requirements for Aviation Safety Services Applications	Candidate technology provides or is envisioned to provide capabilities to satisfy the requirements for ATS aviation safety services for all the NextGen and beyond airspace ATM applications identified across the flight domain(s) under investigation as follows: **Rating Scale:** **5**: Expected to easily meet / exceed the quality of service requirements in all flight domains **4**: Low risk in meeting the requirements in all flight domains **3**: Medium risk in meeting the requirements in at least one flight domain for at least one application **2**: High risk in meeting the requirements in at least one flight domain for at least one application **1**: Does not provide sufficient capability to support safety services in any flight domain
15	Satisfy Requirements for Aviation Advisory Services Applications	Candidate technology provides or is envisioned to provide capabilities to satisfy the requirements for ATS aviation advisory services for all the NextGen and beyond airspace ATM applications identified across the flight domain(s) under investigation as follows: **Rating Scale:** **5**: Expected to easily meet / exceed the quality of service requirements in all flight domains **4**: Low risk in meeting the requirements in all flight domains **3**: Medium risk in meeting the requirements in at least one flight domain for at least one application **2**: High risk in meeting the requirements in at least one flight domain for at least one application **1**: Very high risk in meeting the requirements in at least one flight domain for at least one application **SS**: (Showstopper) The candidate does not provide sufficient capability to support advisory services in any flight domain under investigation.

Figure 373 – Cost Evaluation Criteria and Rating Scales

#	Cost Criteria	Definition and Rating Scale
C1 (16)	Airborne Infrastructure Cost	This metric is a relative comparison of the cost to develop, deploy, and operate & maintain the avionics infrastructure across the aircraft fleet. The relative cost metric is assessed against set of candidate technologies identified as potentially suitable (i.e., candidates that are not identified as a showstopper) for the flight domain(s) under investigation as follows: **Rating Scale:** **5**: Very low relative cost **4**: Low relative cost **3**: Medium relative cost **2**: High relative cost **1**: Very high relative cost **SS**: (Showstopper) The candidate airborne infrastructure cost is infeasible to implement.
C2 (17)	Ground and Satellite Infrastructure Cost	This metric is a relative comparison of the cost to develop, deploy, and operate & maintain the ground and satellite infrastructure in the coverage volume. The relative cost metric is assessed against set of candidate technologies identified as potentially suitable (i.e., candidates that are not identified as a showstopper) for the flight domain(s) under investigation as follows: **Rating Scale:** **5**: Very low relative cost **4**: Low relative cost **3**: Medium relative cost **2**: High relative cost **1**: Very high relative cost **SS**: (Showstopper) The candidate ground/satellite infrastructure cost is infeasible to implement to cover the flight domain(s) under investigation.
C3 (18)	Technology Maturation & Standardization Costs	This metric is a relative comparison of the cost to mature (as needed) and develop aviation standards for the aviation use of the technology candidate. The relative cost metric is assessed against the set of candidate technologies identified as potentially suitable (i.e., candidates that are not identified as a showstopper) for the flight domain(s) under investigation as follows. **Rating Scale:** **5**: Very low relative cost **4**: Low relative cost **3**: Medium relative cost **2**: High relative cost **1**: Very high relative cost

Figure 374 – Risk Evaluation Criteria and Rating Scales

#	Risk Criteria	Definition and Rating Scale
R1 (19)	Spectrum Availability and Compatibility	This metric evaluates the risk that the spectrum is or could become available within the study modernization time horizon to support the intended NAS A-A and A-G communications. The assessment considers the extent to which the potential technology candidate frequency bands are available and consistent with the aeronautical safety critical / advisory communications. **Rating Scale:** **5**: Very High Spectrum Availability & Compatibility. The spectrum is available for the candidate technology frequency band and there are existing global allocations in the band for Aeronautical Mobile Communication Services. **4**: High. The spectrum is currently allocated to civil aviation and is expected to become available to support Aeronautical Mobile Communication Services. **3**: Medium. It can be reasonably expected that an additional global allocation for terrestrial or satellite-based Aeronautical Mobile Communication Services could be added to the candidate band or if the band is shared with other aviation systems, it is feasible that appropriate frequency assignment criteria could be developed within ICAO that would prevent interference with the other aviation systems. **2**: Low. Spectrum is available, but is not allocated. **1**: Very Low. Spectrum is currently allocated to non-civil aviation users. **SS**: (Showstopper) The spectrum for the candidate is not expected to become available nor is compatible to support Aeronautical Mobile Communication Services.
R2 (20)	Technical Maturity / Readiness Level (TRL)	The candidate technology currently has or is expected to have a Technology Readiness Level sufficient for implementation in 15 years. Higher TRL corresponds with lower risk. **Rating Scale:** **5**: TRL of 7 or above. **4**: TRL of 6. **3**: TRL of 4 or 5. **2**: TRL of 3. **1**: TRL of 1 or 2.

#	Risk Criteria	Definition and Rating Scale
R3 (21)	Standardization Status	Existence of some standardized technical descriptions is indicative of technology maturity and tends to reduce risk if they have been adopted for aeronautical use or even other commercial / military use. Existence of aeronautical specifications (e.g., ICAO, RTCA, and EUROCAE) for a technology candidate is indicative of high level of maturity for the application of interest. The existence of aeronautical standards is a significant risk mitigation factor for implementation; while standardization of the technology in other forums (e.g., commercial, military) provides some implementation risk mitigation. **Rating Scale:** **5**: Publically available aeronautical standards are available that would require minor modifications to incorporate new technology candidate. **4**: Publically available aeronautical standards are available that would require major modifications to incorporate new technology candidate. **3**: Publically available commercial or military standards are available that would require minor modifications to incorporate new technology candidate. **2**: Publically available commercial or military standards are available that would require major modifications to incorporate new technology candidate. **1**: Technology for which standards do not exist or are not publically available.
R4 (22)	Global Harmonization Risk	The likelihood of global harmonization is an assessment of perceived risk in the technology candidate being acceptable for worldwide ATS communications within the study time horizon. **Rating Scale:** **5**: Very low risk in global acceptance **4**: Low risk **3**: Medium risk **2**: High risk **1**: Very high risk
R5 (23)	Certification Complexity	Certification complexity is an indication of risk. Technologies that are currently certified or are in the certification process pose significantly less risk. Technologies used for other services (safety or non-safety) provide risk mitigation for meeting certification requirements. **Rating Scale:** **5**: Technology candidate has products or similar products in the aviation industry that are currently certified. **4**: Technology candidate has products or similar products planned to be certified in the aviation industry within 15 years. **3**: Technology candidate utilized for safety related services (e.g., public safety) but not currently in the avionic certification process. **2**: Technology candidate used for non-safety of life services. **1**: Technology candidate is not currently used. **SS**: (Showstopper) Candidate is impractically complex relative to other alternatives.

#	Risk Criteria	Definition and Rating Scale
R6 (24)	Susceptibility to Wide Outage / Long MTTR	Assessment of the technology candidate’s susceptibility to large coverage volume outages and potentially long mean time to repair (MTTR) the service. **Rating Scale:** **5**: Very Low Risk: Very Highly Robust to wide service volume outages and has a very short MTTR. **4**: Low Risk: Achieves at least high robustness to wide service volume outages and short MTTR. **3**: Medium Risk: Achieves at least medium robustness to wide service volume outages and moderate MTTR. **2**: High Risk: Cases other than 1, 3, 4, and 5. **1**: Very High Risk: Candidate has both very low robustness to wide service volume outages and has potentially a very long MTTR.
R7 (25)	Ease of Transition	Assessment of the ease of transitioning from today’s communication means to incorporate the new communications technology candidate into widespread use in the air transportation system. **Rating Scale:** **5**: Very Easy: Candidate very highly satisfies all of the following: a) Can be deployed to achieve ROI (i.e., service provision/benefit) without requiring full investment/deployment, b) Can be operated simultaneously (in adjacent airspace) with legacy CNS systems (i.e., can bring the new system up incrementally while bringing down the legacy system incrementally), and c) Initial transition can be nearly operationally transparent (i.e., initially users do not have to significantly alter procedures) or features that drive changes in operational procedures, and d) can be deployed incrementally. **4**: Easy: Candidate highly satisfies all items “a” to “d” as identified above. **3**: Moderately Easy: Candidate satisfies at least 3 of the items “a” to “d”. **2**: Hard: Candidate satisfies at least 2 of the items “a” to “d”. **1**: Very Hard: Candidate satisfies less than 2 of the items “a” to “d”.

					Ratings Scale Summary					
	#	Criteria Weight (%)	Evaluation Criteria	Brief Description	5	4	3	2	1	SS
					Very Good	Good	Medium	Fair	Poor	Showstoper for Candidate
Technical Performance	1	6	Coverage Volume/ Comm. Range	Coverage in flight domain(s)	100% Coverage	Nearly 100%	A few gaps	Some gaps	Many gaps	No service in at least one Flight Domain
	2	5	Data Rate	Data rate expected to be achieved by the candidate	> 1000 MBPS	< 1000 MBPS	< 200 MBPS	< 1 MBPS	< 0.01 MBPS	---
	3	3	Spectral Efficiency	bit rate/BW	> 15	< 15	< 5	< 2.5	< 0.5	---
	4	5	Capacity	Relative comparison of the total communication BW of candidate	Very High	High	Medium	Low	Very Low	---
	5	3	Number of Users	Relative comparison of the total number of simultaneous users	Very High	High	Medium	Low	Very Low	---
	6	3	Availability & Continuity	Availability & continuity assessment	Very High (>0.999995)	High (> 0.99995)	Medium (> 0.9999)	Low (> 0.999)	Very Low (< 0.999)	---
	7	3	Integrity	Relative comparison to meet aviation services integrity requirements	Very High	High	Medium	Low	Very Low	---
	8	3	Latency	Communication system latency (sec)	< 0.2	< 1.0	Threshold for adequate voice com.	< 5	> 5	---
	9	2	Scaleability /Flexibility /Incorp. New Tech.	Candidate Scaleability, Flexibility, & Ability to incorporate new technology	Very High	High	Average	Low	Very Low	---
	10	3	Security /Vulnerabilities	Robustness against 6 data security measures	Very Highly Robust to Security Measures	Highly Robust to Security Measures	Moderately Robust to Security Measures	Low Robustness to Security Measures	Very Low Robustness to Security Measures	---
	11	3	Robustness to Interference /Environment	Robustness against environmental interference	Very Highly Robust to Interference	Highly Robust to Interference	Moderately Robust to Interference	Low Robustness to Interference	Very Low Robustness to Interference	---
	12	3	Installable on Range of Air Vehicles	East of incorporating on range of aircraft types	Easy for all air vehicles	Easy for most air vehicles	Medium	Hard or impractical for some air vehicles	Hard or impractical for many air vehicles	---
	13	5	Ability to Support Broadcast Comms.	Candidates ability to support broadcast communications	Very Good	Good	Medium	Very limited broadcast capability	No practical broadcast capability	---
	14	8	Satisfy RCP for Safety Services (QoS)	Ability to satisfy safety services RCP for identified ATM applications	Easilty Meets	Meets	Meets most	Meets many	No safety service	---
	15	8	Satisfy RCP for Advisory Services (QoS)	Ability to satisfy advisory services RCP for identified ATM applications	Easilty Meets	Meets	Meets most	Meets many	Meets some	Does not meet QoS for Advisory Services
Cost	16	9	Airborne Infrastructure Cost	Relative airbonre cost	Very Low	Low	Average	High	Very High	Cost Showstoper
	17	4	Ground / Satellite Infrastructure Cost	Relative cost of ground/satellite infrastructure to civil aviation	Very Low	Low	Average	High	Very High	Cost Showstoper
	18	1	Technology Maturation & Stds. Cost	Relative civil aviation cost to mature and standardize candidate	Very Low	Low	Average	High	Very High	---
Risk	19	9	Spectrum Availability & Compatibility	Risk of spectrum availability & compatibility with AMCS	AMCS Band Unused	Aeronautical Band Under Use	Aero. Allocation of Spectrum Expected	Spectrum Available, but not Allocated	Spectrum in use non-civil aviation users	Spectrum not Avail. nor AMCS compatible
	20	1	Technical Maturity /Readiness Level	Predicted TRL in 15 years	TRL >= 7	TRL = 6	TRL 4 or 5	TRL = 3	TRL 1 or 2	---
	21	1	Standization Status	Existance of standards (Stds.)	Aeronautical Stds. - Minor Mod.	Aeronautical Stds. - Major Mod.	Commercial/Military Stds. - Minor Mod.	Commercial/Military Stds. - Major Mod.	No Current Stds.	---
	22	3	Global Harmonization Risk	Risk in global acceptance of candidate for ATM applications	Very Low	Low	Medium	High	Very High	---
	23	3	Certification Complexity	Risk in certification of candidate for Aviation Services Applications	Similar Aviation Products Certified	Plan to Certify within 15 years	Used in Non-Aviation Safety Service	Used for Non-Safety Services	Technology is Not Currently Used	Impractical Relative to Other Alternatives
	24	3	Susceptible to Wide Outage / Long MTTR	Candidate susceptability to large coverage area outages / long MTTR	Very Low	Low	Medium	High	Very High	---
	25	3	Ease of Transition	Ease of transitioning NAS to the new candidate	Very Easy	Easy	Moderately Easy	Hard	Very Hard	---

Figure 375 – Specific Rating Scale Summary for All Evaluation Criteria

29.3 Weighting Factors for Candidate Evaluation Criteria

While all evaluation criteria are important, it was deemed necessary to more heavily weight the relative importance of the ratings associated with some criteria over other criteria. For the results presented in this document, each criterion has been assigned a weighting factor as given in Figure 376 that is intended to characterize its relative importance in the prioritization of communication candidates. The weighting factors were assigned values that attempted to balance the collective interests of all the aviation stakeholders. Weighting factors were assigned as percentages, such that the sum of the weighting factors for all criteria totaled 100%. These weighting factors are used in the communication candidate prioritization process to determine a total relative score that is used to rank the candidates as described in Section 29.4.

Category	#	Criteria	Weighting Factors (Percentages)
Technical Performance	1	Coverage Volume / Communications Range	6
	2	Data Rate	5
	3	Spectral Efficiency	3
	4	Capacity	5
	5	Number of Users	3
	6	Availability & Continuity	3
	7	Integrity	3
	8	Latency	3
	9	Scaleability / Flexibility / Ability to Incorporate New Technologies	2
	10	Security / Vulnerabilities	3
	11	Robustness to Interference / Environment	3
	12	Installable on Range of Air Vehicles	3
	13	Ability to Support Broadcast Communications	5
	14	Satisfy Requirements for Aviation Safety Services	8
	15	Satisfy Requirements for Aviation Advisory Services	8
Cost	16	Airborne Infrastructure Cost	9
	17	Ground / Satellite Infrastructure Cost	4
	18	Technology Maturation & Standards Cost	1
Risk	19	Spectrum Availability & Compatibility	9
	20	Technical Maturity / Readiness Level (TRL)	1
	21	Standardization Status	1
	22	Global Harmonization Risk	3
	23	Certification Complexity	3
	24	Susceptible to Wide Outage / Long MTTR	3
	25	Ease of Transition	3
		TOTAL WEIGHT	***100***

Figure 376 – Weighting Factors for Relative Importance of Evaluation Criteria

However, it should be noted that the weighting factors are heavily dependent upon each aviation stakeholder’s perspective and other weightings may be appropriate. For example, the technical performance criterion #12 (i.e., whether the candidate technology is installable on a given class of aircraft) may actually be a showstopper for some aviation stakeholders (e.g., aircraft operator of small UAVs that may not be able to readily install HF or GEO SATCOM equipment on their aircraft).

29.4 Total Relative Candidate Score and Priority Ranking Process

The communication candidates were evaluated for their ability support the ATM communication needs in all the various flight domains, including surface, terminal area, enroute, oceanic/remote, and polar. The assessments were done for each individual flight domain, as well as for combinations of flight domains including the combinations for: 1) surface, terminal area, and enroute; 2) oceanic, remote, and polar; and 3) all flight domains.

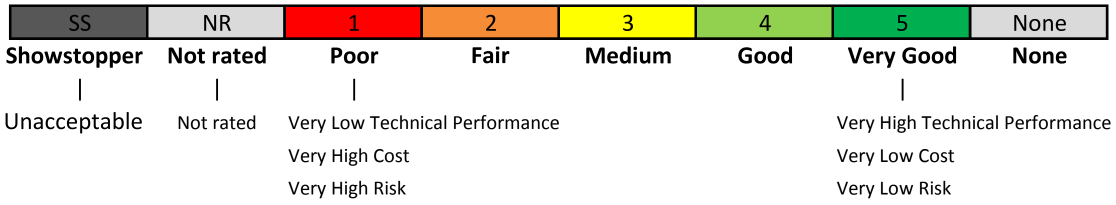
In each of these assessments, the individual ratings from the evaluations across each criterion were multiplied by the weighting factor associated with the criterion and these individual products were summed over all the evaluation criteria to obtain a “total score” for each candidate. These total scores were used to prioritize the communications candidates in the various flight domains under investigation, whereby a higher weighted “total score” for a given candidate represents a higher priority evaluation for the communications candidate in that flight domain. The results of these assessments are presented in Section 30.

30 EVALUATION AND PRIORITIZATION OF THE COMMUNICATIONS CANDIDATES

The section provides an evaluation of the future communications systems candidates and identifies the most promising candidates to support operations in various flight domains.

The process used to evaluate and prioritize the candidates includes evaluating each A-A and A-G communication candidate across the set of 25 evaluation criteria (as identified and described in Sections 29.1 and 29.2) to characterize the technical performance, relative cost, and relative risk of potentially using the candidate to support NAS ATM applications. The individual ratings from each of the evaluations across the set of 25 evaluation criteria are then weighted by the relative importance weighting factors associated with each criterion (see Section 29.3) and summed to obtain a “weighted total score” for each candidate. These weighted total scores were used to prioritize the communications candidates in the various flight domains under investigation. A higher weighted total score for a given candidate represents a higher priority communications candidate in that flight domain.

Figure 305 provides the legend used to color code the figures that present the individual ratings for each evaluation criterion for all the candidate assessments presented in this section of the report. This color legend corresponds with the rating scales for the candidate evaluation criteria that are defined in Section 29.2.



SS	NR	1	2	3	4	5	None
Showstopper	**Not rated**	**Poor**	**Fair**	**Medium**	**Good**	**Very Good**	**None**
Unacceptable	Not rated	Very Low Technical Performance Very High Cost Very High Risk				Very High Technical Performance Very Low Cost Very Low Risk	

Figure 377 – Legend: Score to Color Coding

The subsections below provide the results of the evaluations for each of the A-A and A-G communication candidates in single and multiple flight domains as follows:

- Single Airspace Flight Domain Evaluations
  1. Surface
  2. Terminal Area
  3. Enroute
  4. Oceanic / Remote
  5. Polar
- Multiple Airspace Flight Domains Evaluations
  1. Combined Surface, Terminal Area, and Enroute
  2. Combined Oceanic, Remote, and Polar
  3. Combined All Flight Domains
- Summary of Evaluation Results
- Assessment of Evaluation Results

30.1 Evaluation of Aircraft-to-Aircraft Communication Candidates

The section provides an evaluation of the future communications systems A-A candidates and identifies the most promising candidates to support operations in various flight domains.

30.1.1 Single Airspace A-A Candidate Evaluations

Figure 378 to Figure 382 provide the assessment results for the evaluation of the twelve A-A communication candidates in the single flight domains of: 1) airport surface, 2) terminal area, 3) enroute, 4) oceanic/remote, and 5) polar (respectively).

30.1.2 Multiple Airspace A-A Candidate Evaluations

Figure 383 to Figure 385 provide the assessment results for the evaluation of the twelve A-A communication candidates in the multiple flight domains of: 1) airport surface, terminal area, and enroute; 2) oceanic, remote, and polar; and 3) all flight domains (respectively).

Notes for A-A evaluation matrices provided in Figure 378 to Figure 385:

Note 1: Ratings of "None" for Ground / Satellite Infrastructure Cost is very good (no cost). In summing the "Total Scores" for the candidates, a "None" rating was treated as equivalent to a rating of "5".

Note 2: The S-band candidate will embrace the future potential availability of cellular technology to support A-A communications.

Note 3: LEO SATCOM could evolve to very low cost evolutions of Teledesic-type broadband architectures that potentially could have hundreds to thousands of low cost pico-satellites in their constellations to deliver very high bandwidth services at very low cost.

Note 4: Optical SATCOM may service high altitude aircraft.

Note 5: To support very high altitude communication services as might be needed by space vehicles (e.g., space planes), GEO SATCOM may contain a subsystem to support such high altitude users.

Airport Surface Flight Domain

				Ratings for Air-to-Air Candidates											
				1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
	#	Criteria Weight (%)	Evaluation Criteria	VHF	UHF	L-Band	S-Band	C-Band	X-Band	Optical	Hybrid RF/ Optical	LEO SATCOM	GEO SATCOM	MEO SATCOM	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	4	3	3	2	2	2	5	4	5	4
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	4	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	4	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	4	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	4	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	4	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	4	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	1	2	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	4	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	4	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	3	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	1	2	1
	13	5	Ability to Support Broadcast Comms.	5	5	5	5	4	4	1	2	2	4	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	5	5	3	1	2	3	1	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	5	5	5	4	3	3	3	2	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	4	3	1	1	3	2	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	2	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	4	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	5	2	2	2	5	3	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	5	2	1	1	4	4	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	3	2	3
	22	3	Global Harmonization Risk	5	2	5	3	5	3	2	2	5	4	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	4	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	1	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	3	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*107*	*97*	*107*	*80*	*65*	*69*	*93*	*78*	*81*	*77*
		100	*Candidate Weighted Total Score*	*429*	*378*	*435*	*394*	*434*	*327*	*257*	*276*	*371*	*291*	*315*	*290*
			Candidate Priority in this Assessment	***3***	***5***	***1***	***4***	***2***	***7***	***12***	***11***	***6***	***9***	***8***	***10***

Figure 378 – A-A Candidate Evaluation: Single Flight Domain – Surface (APT)

Terminal Area Flight Domain

Ratings for Air-to-Air Candidates

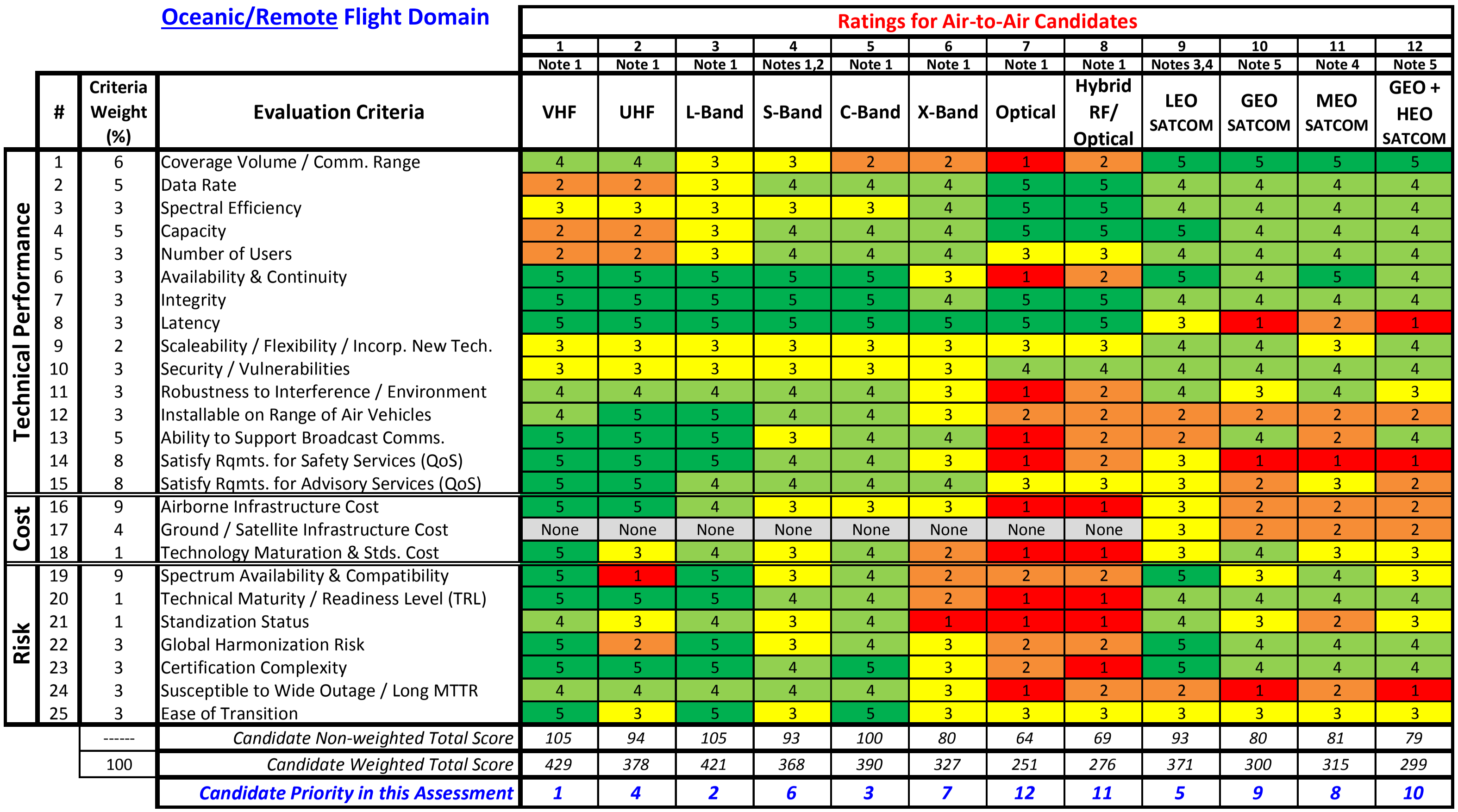
	#	Criteria Weight (%)	Evaluation Criteria	1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
				VHF	**UHF**	**L-Band**	**S-Band**	**C-Band**	**X-Band**	**Optical**	**Hybrid RF/ Optical**	**LEO SATCOM**	**GEO SATCOM**	**MEO SATCOM**	**GEO + HEO SATCOM**
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	4	3	2	2	1	2	5	4	5	4
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	4	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	4	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	4	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	4	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	4	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	4	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	2	2	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	4	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	4	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	3	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	1	2	1
	13	5	Ability to Support Broadcast Comms.	5	5	5	5	4	4	1	2	2	4	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	5	5	3	1	2	3	1	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	5	5	5	4	3	3	3	2	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	4	3	1	1	3	2	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	2	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	4	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	4	2	2	2	5	3	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	5	2	1	1	4	4	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	3	2	3
	22	3	Global Harmonization Risk	5	2	5	3	5	3	2	2	5	4	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	4	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	1	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	3	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*107*	*97*	*105*	*80*	*64*	*69*	*93*	*79*	*81*	*78*
		100	*Candidate Weighted Total Score*	*429*	*378*	*435*	*394*	*419*	*327*	*251*	*276*	*371*	*294*	*315*	*293*
			Candidate Priority in this Assessment	***2***	***5***	***1***	***4***	***3***	***7***	***12***	***11***	***6***	***9***	***8***	***10***

Figure 379 – A-A Candidate Evaluation: Single Flight Domain – Terminal Area (TMA)

EnRoute Flight Domain

				Ratings for Air-to-Air Candidates											
				1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
	#	**Criteria Weight (%)**	**Evaluation Criteria**	**VHF**	**UHF**	**L-Band**	**S-Band**	**C-Band**	**X-Band**	**Optical**	**Hybrid RF/ Optical**	**LEO SATCOM**	**GEO SATCOM**	**MEO SATCOM**	**GEO + HEO SATCOM**
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	4	3	2	2	1	2	5	4	5	4
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	4	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	4	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	4	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	4	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	4	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	4	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	2	2	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	4	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	4	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	3	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	2	2	2
	13	5	Ability to Support Broadcast Comms.	5	5	5	3	4	4	1	2	2	4	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	5	5	3	1	2	3	1	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	5	5	5	4	3	3	3	2	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	3	3	1	1	3	2	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	2	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	4	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	4	2	2	2	5	3	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	5	2	1	1	4	4	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	3	2	3
	22	3	Global Harmonization Risk	5	2	5	3	5	3	2	2	5	4	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	4	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	1	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	3	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*107*	*95*	*104*	*80*	*64*	*69*	*93*	*80*	*81*	*79*
		100	*Candidate Weighted Total Score*	*429*	*378*	*435*	*384*	*410*	*327*	*251*	*276*	*371*	*297*	*315*	*296*
			Candidate Priority in this Assessment	***2***	***5***	***1***	***4***	***3***	***7***	***12***	***11***	***6***	***9***	***8***	***10***

Figure 380 – A-A Candidate Evaluation: Single Flight Domain – Enroute (ENR)



Oceanic/Remote Flight Domain

Ratings for Air-to-Air Candidates

	#	Criteria Weight (%)	Evaluation Criteria	VHF	UHF	L-Band	S-Band	C-Band	X-Band	Optical	Hybrid RF/ Optical	LEO SATCOM	GEO SATCOM	MEO SATCOM	GEO + HEO SATCOM
				1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	3	3	2	2	1	2	5	5	5	5
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	4	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	4	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	4	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	4	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	4	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	4	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	1	2	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	4	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	4	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	3	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	2	2	2
	13	5	Ability to Support Broadcast Comms.	5	5	5	3	4	4	1	2	2	4	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	4	4	3	1	2	3	1	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	4	4	4	4	3	3	3	2	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	3	3	1	1	3	2	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	2	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	4	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	4	2	2	2	5	3	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	4	2	1	1	4	4	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	3	2	3
	22	3	Global Harmonization Risk	5	2	5	3	4	3	2	2	5	4	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	4	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	1	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	3	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*105*	*93*	*100*	*80*	*64*	*69*	*93*	*80*	*81*	*79*
		100	*Candidate Weighted Total Score*	*429*	*378*	*421*	*368*	*390*	*327*	*251*	*276*	*371*	*300*	*315*	*299*
			Candidate Priority in this Assessment	***1***	***4***	***2***	***6***	***3***	***7***	***12***	***11***	***5***	***9***	***8***	***10***

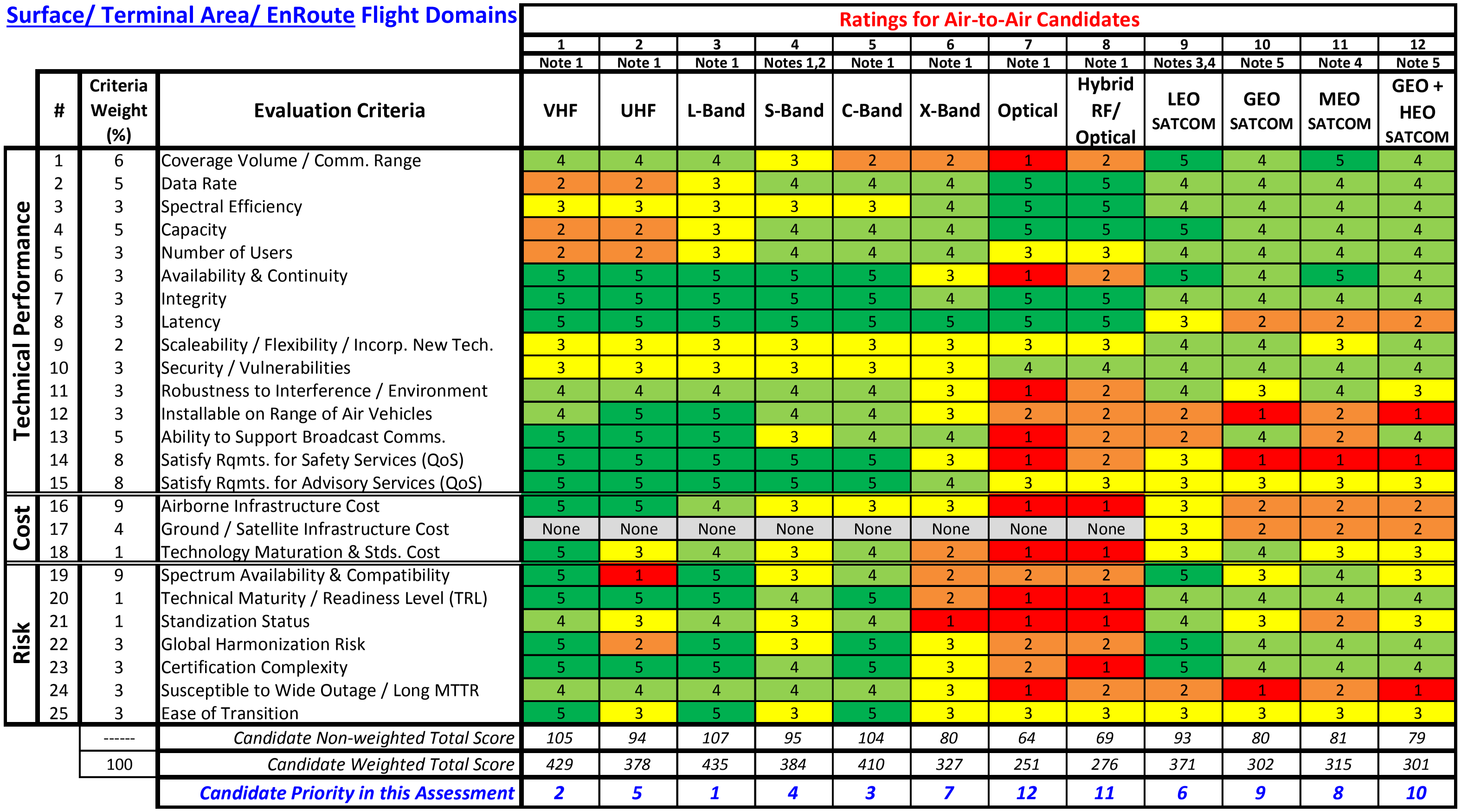
Figure 381 – A-A Candidate Evaluation: Single Flight Domain – Oceanic/Remote

Polar Flight Domain

Ratings for Air-to-Air Candidates

	#	Criteria Weight (%)	Evaluation Criteria	VHF	UHF	L-Band	S-Band	C-Band	X-Band	Optical	Hybrid RF/ Optical	LEO SATCOM	GEO SATCOM	MEO SATCOM	GEO + HEO SATCOM
				1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	3	3	2	2	1	2	5	SS	5	5
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	NR	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	NR	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	NR	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	NR	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	NR	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	NR	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	NR	2	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	NR	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	NR	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	NR	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	NR	2	2
	13	5	Ability to Support Broadcast Comms.	5	5	5	3	4	4	1	2	2	NR	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	4	4	3	1	2	3	NR	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	4	4	4	4	3	3	3	NR	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	3	3	1	1	3	NR	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	NR	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	NR	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	4	2	2	2	5	NR	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	4	2	1	1	4	NR	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	NR	2	3
	22	3	Global Harmonization Risk	5	2	5	3	4	3	2	2	5	NR	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	NR	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	NR	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	NR	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*105*	*93*	*100*	*80*	*64*	*69*	*93*	*0*	*81*	*79*
		100	*Candidate Weighted Total Score*	*429*	*378*	*421*	*368*	*390*	*327*	*251*	*276*	*371*	*0*	*315*	*299*
			Candidate Priority in this Assessment	***1***	***4***	***2***	***6***	***3***	***7***	***11***	***10***	***5***	***---***	***8***	***9***

Figure 382 – A-A Candidate Evaluation: Single Flight Domain – Polar

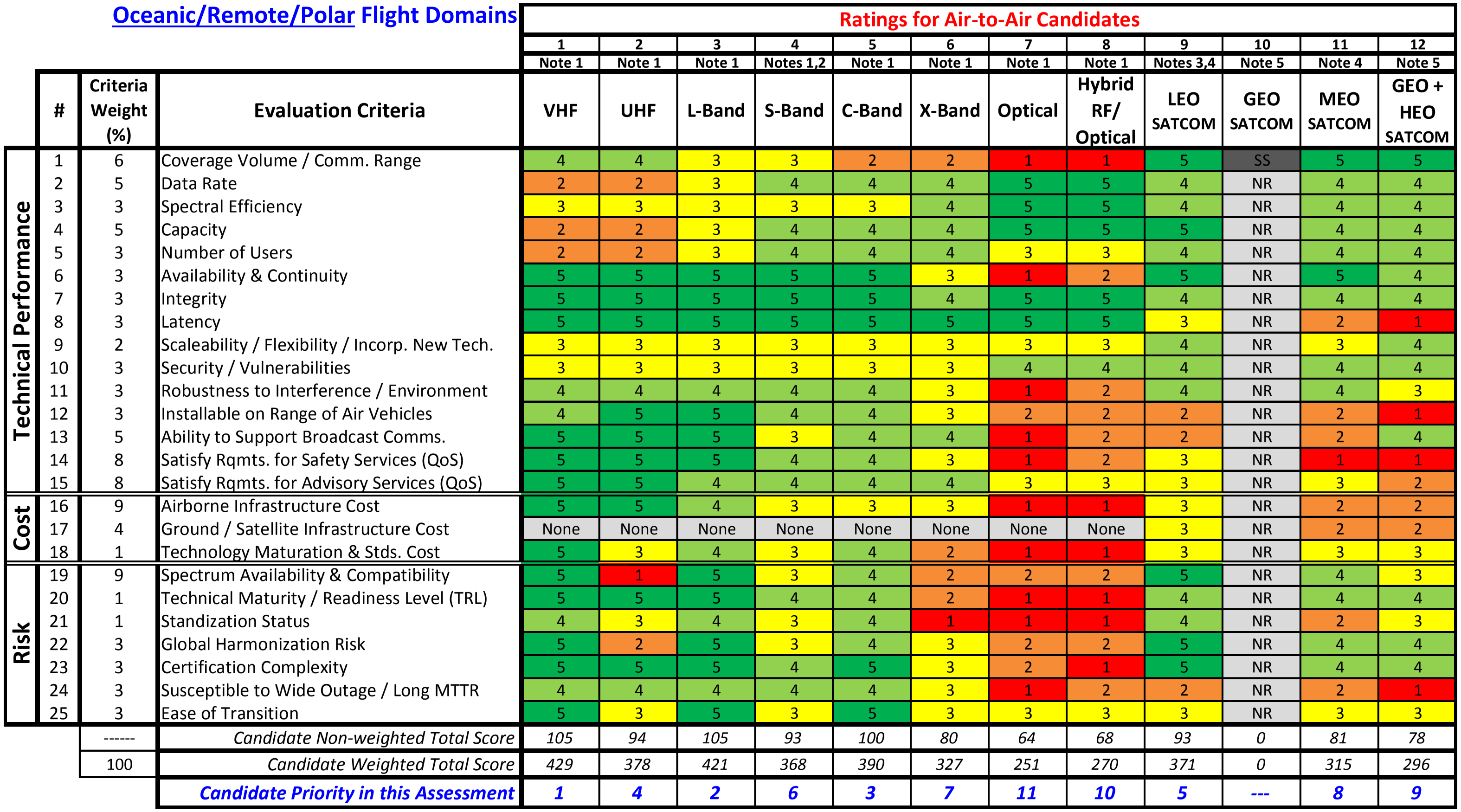


Surface/ Terminal Area/ EnRoute Flight Domains

Ratings for Air-to-Air Candidates

				1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
	#	**Criteria Weight (%)**	**Evaluation Criteria**	**VHF**	**UHF**	**L-Band**	**S-Band**	**C-Band**	**X-Band**	**Optical**	**Hybrid RF/ Optical**	**LEO SATCOM**	**GEO SATCOM**	**MEO SATCOM**	**GEO + HEO SATCOM**
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	4	3	2	2	1	2	5	4	5	4
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	4	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	4	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	4	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	4	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	4	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	4	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	2	2	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	4	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	4	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	3	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	1	2	1
	13	5	Ability to Support Broadcast Comms.	5	5	5	3	4	4	1	2	2	4	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	5	5	3	1	2	3	1	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	5	5	5	4	3	3	3	3	3	3
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	3	3	1	1	3	2	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	2	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	4	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	4	2	2	2	5	3	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	5	2	1	1	4	4	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	3	2	3
	22	3	Global Harmonization Risk	5	2	5	3	5	3	2	2	5	4	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	4	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	1	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	3	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*107*	*95*	*104*	*80*	*64*	*69*	*93*	*80*	*81*	*79*
		100	*Candidate Weighted Total Score*	*429*	*378*	*435*	*384*	*410*	*327*	*251*	*276*	*371*	*302*	*315*	*301*
			Candidate Priority in this Assessment	***2***	***5***	***1***	***4***	***3***	***7***	***12***	***11***	***6***	***9***	***8***	***10***

Figure 383 – A-A Candidate Evaluation: Multiple Flight Domains – APT / TMA / ENR



			Oceanic/Remote/Polar Flight Domains	Ratings for Air-to-Air Candidates											
				1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
	#	Criteria Weight (%)	Evaluation Criteria	VHF	UHF	L-Band	S-Band	C-Band	X-Band	Optical	Hybrid RF/ Optical	LEO SATCOM	GEO SATCOM	MEO SATCOM	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	3	3	2	2	1	1	5	SS	5	5
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	NR	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	NR	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	NR	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	NR	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	NR	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	NR	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	NR	2	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	NR	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	NR	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	NR	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	NR	2	1
	13	5	Ability to Support Broadcast Comms.	5	5	5	3	4	4	1	2	2	NR	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	4	4	3	1	2	3	NR	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	4	4	4	4	3	3	3	NR	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	3	3	1	1	3	NR	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	NR	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	NR	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	4	2	2	2	5	NR	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	4	2	1	1	4	NR	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	NR	2	3
	22	3	Global Harmonization Risk	5	2	5	3	4	3	2	2	5	NR	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	NR	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	NR	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	NR	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*105*	*93*	*100*	*80*	*64*	*68*	*93*	*0*	*81*	*78*
		100	*Candidate Weighted Total Score*	*429*	*378*	*421*	*368*	*390*	*327*	*251*	*270*	*371*	*0*	*315*	*296*
			Candidate Priority in this Assessment	***1***	***4***	***2***	***6***	***3***	***7***	***11***	***10***	***5***	***---***	***8***	***9***

Figure 384 – A-A Candidate Evaluation: Multiple Flight Domains – ORP

All Flight Domains

(Surface, Terminal Area, EnRoute, Oceanic, Remote, and Polar)

				Ratings for Air-to-Air Candidates											
				1	2	3	4	5	6	7	8	9	10	11	12
				Note 1	Note 1	Note 1	Notes 1,2	Note 1	Note 1	Note 1	Note 1	Notes 3,4	Note 5	Note 4	Note 5
	#	**Criteria Weight (%)**	**Evaluation Criteria**	**VHF**	**UHF**	**L-Band**	**S-Band**	**C-Band**	**X-Band**	**Optical**	**Hybrid RF/ Optical**	**LEO SATCOM**	**GEO SATCOM**	**MEO SATCOM**	**GEO + HEO SATCOM**
Technical Performance	1	6	Coverage Volume / Comm. Range	4	4	3	3	2	2	1	2	5	SS	5	5
	2	5	Data Rate	2	2	3	4	4	4	5	5	4	NR	4	4
	3	3	Spectral Efficiency	3	3	3	3	3	4	5	5	4	NR	4	4
	4	5	Capacity	2	2	3	4	4	4	5	5	5	NR	4	4
	5	3	Number of Users	2	2	3	4	4	4	3	3	4	NR	4	4
	6	3	Availability & Continuity	5	5	5	5	5	3	1	2	5	NR	5	4
	7	3	Integrity	5	5	5	5	5	4	5	5	4	NR	4	4
	8	3	Latency	5	5	5	5	5	5	5	5	3	NR	2	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	3	3	3	3	3	3	3	3	4	NR	3	4
	10	3	Security / Vulnerabilities	3	3	3	3	3	3	4	4	4	NR	4	4
	11	3	Robustness to Interference / Environment	4	4	4	4	4	3	1	2	4	NR	4	3
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	3	NR	3	2
	13	5	Ability to Support Broadcast Comms.	5	5	5	3	4	4	1	2	2	NR	2	4
	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	4	4	3	1	2	3	NR	2	2
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	4	4	4	4	3	3	3	NR	3	2
Cost	16	9	Airborne Infrastructure Cost	5	5	4	3	3	3	1	1	3	NR	2	2
	17	4	Ground / Satellite Infrastructure Cost	None	None	None	None	None	None	None	None	3	NR	2	2
	18	1	Technology Maturation & Stds. Cost	5	3	4	3	4	2	1	1	3	NR	3	3
Risk	19	9	Spectrum Availability & Compatibility	5	1	5	3	4	2	2	2	5	NR	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	4	2	1	1	4	NR	4	4
	21	1	Standization Status	4	3	4	3	4	1	1	1	4	NR	2	3
	22	3	Global Harmonization Risk	5	2	5	3	4	3	2	2	5	NR	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	NR	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	NR	2	1
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	NR	3	3
		------	*Candidate Non-weighted Total Score*	*105*	*94*	*105*	*93*	*100*	*80*	*64*	*69*	*94*	*0*	*83*	*80*
		100	*Candidate Weighted Total Score*	*429*	*378*	*421*	*368*	*390*	*327*	*251*	*276*	*374*	*0*	*326*	*307*
			Candidate Priority in this Assessment	***1***	***4***	***2***	***6***	***3***	***7***	***11***	***10***	***5***	***---***	***8***	***9***

Figure 385 – A-A Candidate Evaluation: Multiple Flt. Domains – APT / TMA / ENR / ORP

30.1.3 Prioritization of the A-A Candidates

Based upon the evaluations and rankings provided in Sections 30.1.1 and 30.1.2, Figure 386 and Figure 387 provide prioritized ranked lists of the A-A communication candidates for single airspace and multiple airspace flight domains, respectively. Figure 388 and Figure 389 provide the same results, but also include the weighted total scores for the communication candidates for each of the flight domains under investigation.

A-A Communication Candidate Rankings

Single Airspace Flight Domains

Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar
1	L-Band	L-Band	L-Band	VHF	VHF
2	C-Band	VHF	VHF	L-Band	L-Band
3	VHF	C-Band	C-Band	C-Band	C-Band
4	S-Band	S-Band	S-Band	UHF	UHF
5	UHF	UHF	UHF	LEO SATCOM	LEO SATCOM
6	LEO SATCOM	LEO SATCOM	LEO SATCOM	S-Band	S-Band
7	X-Band	X-Band	X-Band	X-Band	X-Band
8	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO + HEO SATCOM
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	Hybrid RF/ Optical
11	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Optical
12	Optical	Optical	Optical	Optical	#N/A

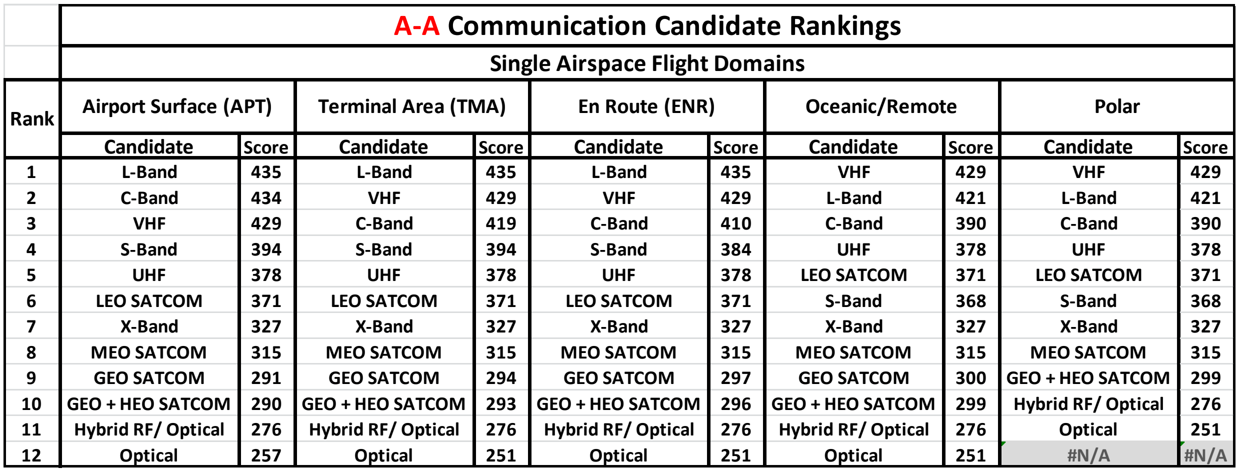
Figure 386 – A-A Candidate Prioritization for Single Flight Domains

A-A Communication Candidate Rankings

Multiple Airspace Flight Domains

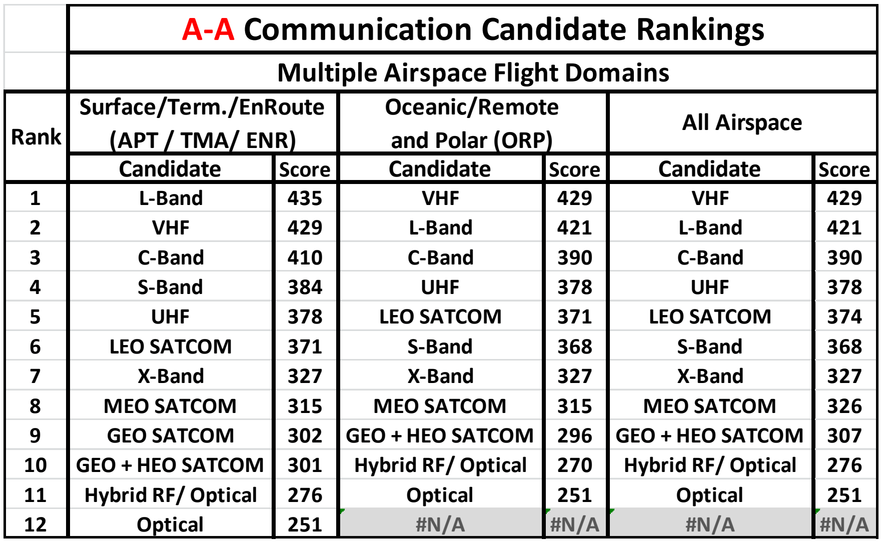
Rank	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace
1	L-Band	VHF	VHF
2	VHF	L-Band	L-Band
3	C-Band	C-Band	C-Band
4	S-Band	UHF	UHF
5	UHF	LEO SATCOM	LEO SATCOM
6	LEO SATCOM	S-Band	S-Band
7	X-Band	X-Band	X-Band
8	MEO SATCOM	MEO SATCOM	MEO SATCOM
9	GEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM
10	GEO + HEO SATCOM	Hybrid RF/ Optical	Hybrid RF/ Optical
11	Hybrid RF/ Optical	Optical	Optical
12	Optical	#N/A	#N/A

Figure 387 – A-A Candidate Prioritization for Multiple Flight Domains



	A-A Communication Candidate Rankings									
	Single Airspace Flight Domains									
Rank	Airport Surface (APT)		Terminal Area (TMA)		En Route (ENR)		Oceanic/Remote		Polar	
	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score
1	L-Band	435	L-Band	435	L-Band	435	VHF	429	VHF	429
2	C-Band	434	VHF	429	VHF	429	L-Band	421	L-Band	421
3	VHF	429	C-Band	419	C-Band	410	C-Band	390	C-Band	390
4	S-Band	394	S-Band	394	S-Band	384	UHF	378	UHF	378
5	UHF	378	UHF	378	UHF	378	LEO SATCOM	371	LEO SATCOM	371
6	LEO SATCOM	371	LEO SATCOM	371	LEO SATCOM	371	S-Band	368	S-Band	368
7	X-Band	327	X-Band	327	X-Band	327	X-Band	327	X-Band	327
8	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315
9	GEO SATCOM	291	GEO SATCOM	294	GEO SATCOM	297	GEO SATCOM	300	GEO + HEO SATCOM	299
10	GEO + HEO SATCOM	290	GEO + HEO SATCOM	293	GEO + HEO SATCOM	296	GEO + HEO SATCOM	299	Hybrid RF/ Optical	276
11	Hybrid RF/ Optical	276	Hybrid RF/ Optical	276	Hybrid RF/ Optical	276	Hybrid RF/ Optical	276	Optical	251
12	Optical	257	Optical	251	Optical	251	Optical	251	#N/A	#N/A

Figure 388 – A-A Candidate Prioritization for Single Flight Domains (with Scores)



	A-A Communication Candidate Rankings					
	Multiple Airspace Flight Domains					
Rank	Surface/Term./EnRoute (APT / TMA/ ENR)		Oceanic/Remote and Polar (ORP)		All Airspace	
	Candidate	Score	Candidate	Score	Candidate	Score
1	L-Band	435	VHF	429	VHF	429
2	VHF	429	L-Band	421	L-Band	421
3	C-Band	410	C-Band	390	C-Band	390
4	S-Band	384	UHF	378	UHF	378
5	UHF	378	LEO SATCOM	371	LEO SATCOM	374
6	LEO SATCOM	371	S-Band	368	S-Band	368
7	X-Band	327	X-Band	327	X-Band	327
8	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	326
9	GEO SATCOM	302	GEO + HEO SATCOM	296	GEO + HEO SATCOM	307
10	GEO + HEO SATCOM	301	Hybrid RF/ Optical	270	Hybrid RF/ Optical	276
11	Hybrid RF/ Optical	276	Optical	251	Optical	251
12	Optical	251	#N/A	#N/A	#N/A	#N/A

Figure 389 – A-A Candidate Prioritization for Multiple Flight Domains (with Scores)

Note for Figure 386 to Figure 389: "#NA" stands for "Not Applicable." Each "#NA" entry indicates that of the 12 A-A communications candidates being evaluated, a candidate has been given a showstopper (SS) [i.e., unacceptable] rating for the flight domain(s) under investigation and thus is not included in the ranked list of candidates.

30.1.4 Discussion of A-A Candidates Prioritization Results

The A-A Candidates prioritization results across all single flight domains and multiple flight domains indicate that L-band, VHF, and C-band candidates scored at essentially the same highest tier of priority. The highest tier A-A candidates scored well with high technical performance, low cost, and low risk across all flight domains. There are slight numerical weighted score differences among the candidates, which are not significant in this initial prioritization. These three highest tier candidates are capable of providing an Actual Communications Performance (ACP) quality of service commensurate with meeting the RCP for most of the envisioned long-term NAS ATM safety and advisory applications that require A-A communications.

The middle tier of A-A candidates include UHF, S-band, LEO SATCOM, and X-band. The candidates in this tier generally have high scores for some of the evaluation criteria, but have at least one category of performance, cost, or risk that were not evaluated as well as the highest tier of candidates

The lowest tier of A-A candidates include MEO SATCOM, GEO SATCOM, GEO + HEO SATCOM, hybrid RF/Optical, and Optical. The candidates in this lowest tier generally scored low in at least two evaluation areas of performance, cost, or risk. Furthermore, the performance of the candidates in this tier typically only meets RCP for a subset of the long-term ATM applications that require A-A communications. For example, the candidates in this lowest tier would not generally support ADS-B surveillance safety applications for aircraft in close proximity to one another. However, these candidates tend to offer some of the highest communications BW and could be very useful for a subset of ATM applications (e.g., advisory applications for the exchange of weather radar information) that require A-A high BW communications on some aircraft platforms.

While this study has attempted to appropriately prioritize the communication candidates in a manner consistent with the expected long-term NAS communication needs while balancing the collective interests of all the aviation stakeholders, it should be noted that the candidate prioritizations are subject to change when different evaluation criteria, assumptions, communications requirements, or weighting factors are used in the assessment process.

30.2 Evaluation of Aircraft-to-Ground Communication Candidates

The section provides an evaluation of the future communications systems A-G candidates and identifies the most promising candidates to support operations in various flight domains.

30.2.1 Single Airspace A-G Candidate Evaluations

Figure 390 to Figure 394 provide the assessment results for the evaluation of the nineteen A-G communication candidates in the single flight domains of: 1) airport surface, 2) terminal area, 3) enroute, 4) oceanic/remote, and 5) polar (respectively).

30.2.2 Multiple Airspace A-G Candidate Evaluations

Figure 395 to Figure 397 provide the assessment results for the evaluation of the nineteen A-G communication candidates in the multiple flight domains of: 1) airport surface, terminal area, and enroute; 2) oceanic, remote, and polar; and 3) all flight domains (respectively).

Notes for A-G evaluation matrices provided in Figure 390 to Figure 401:

Note 1: *HF Candidate viewed as "showstopper" from coverage issues on the airport surface and in the terminal area.*

Note 2: *Hopping candidates add significant complexity and reduce available capacity. They are viewed as a "showstopper" for providing A-G coverage on the airport surface, in the terminal area, and enroute flight domains.*

Note 3: Optical candidates viewed as "showstopper" for A-G communications resulting from coverage issues in the enroute, oceanic/remote, and polar flight domains.

Note 4: While the cellular ground infrastructure cost is high, the cost burden to the aviation community is "low" as the cost is assumed to be spread among many terrestrial users.

Note 5: LEO SATCOM could evolve to very low cost evolutions of Teledesic-type broadband architectures that potentially could have hundreds to thousands of low cost pico-satellites in their constellations to deliver very high bandwidth services at very low cost.

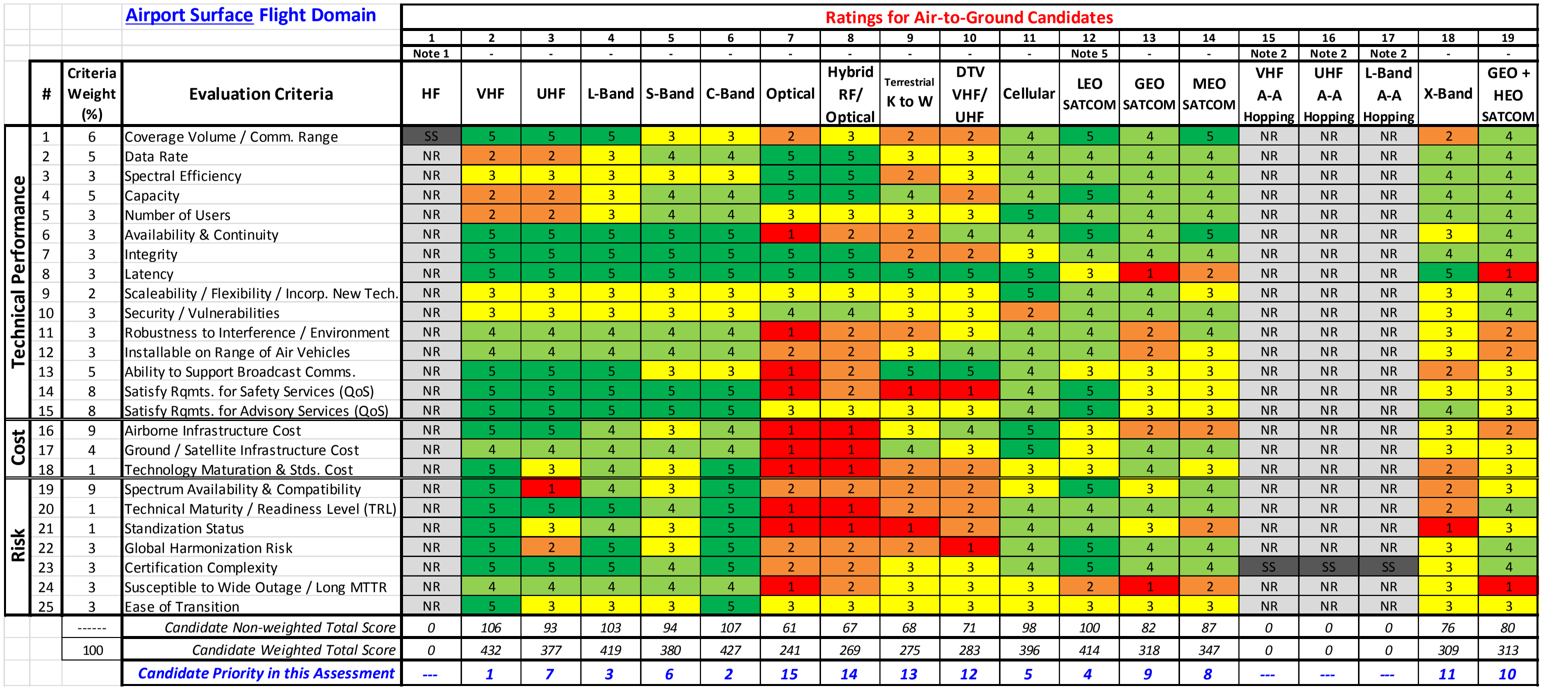
Note 6: Optical SATCOM may service high altitude aircraft.

Note 7: To support very high altitude communication services as might be needed by space vehicles (e.g., space planes), GEO SATCOM may contain a subsystem to support such high altitude users.

Note 8: LOS terrestrial candidates were deemed a "showstopper" or infeasible from a cost standpoint to implement the ground infrastructure to obtain coverage in oceanic, remote, and polar airspace flight domains (assuming insufficient island coverage).

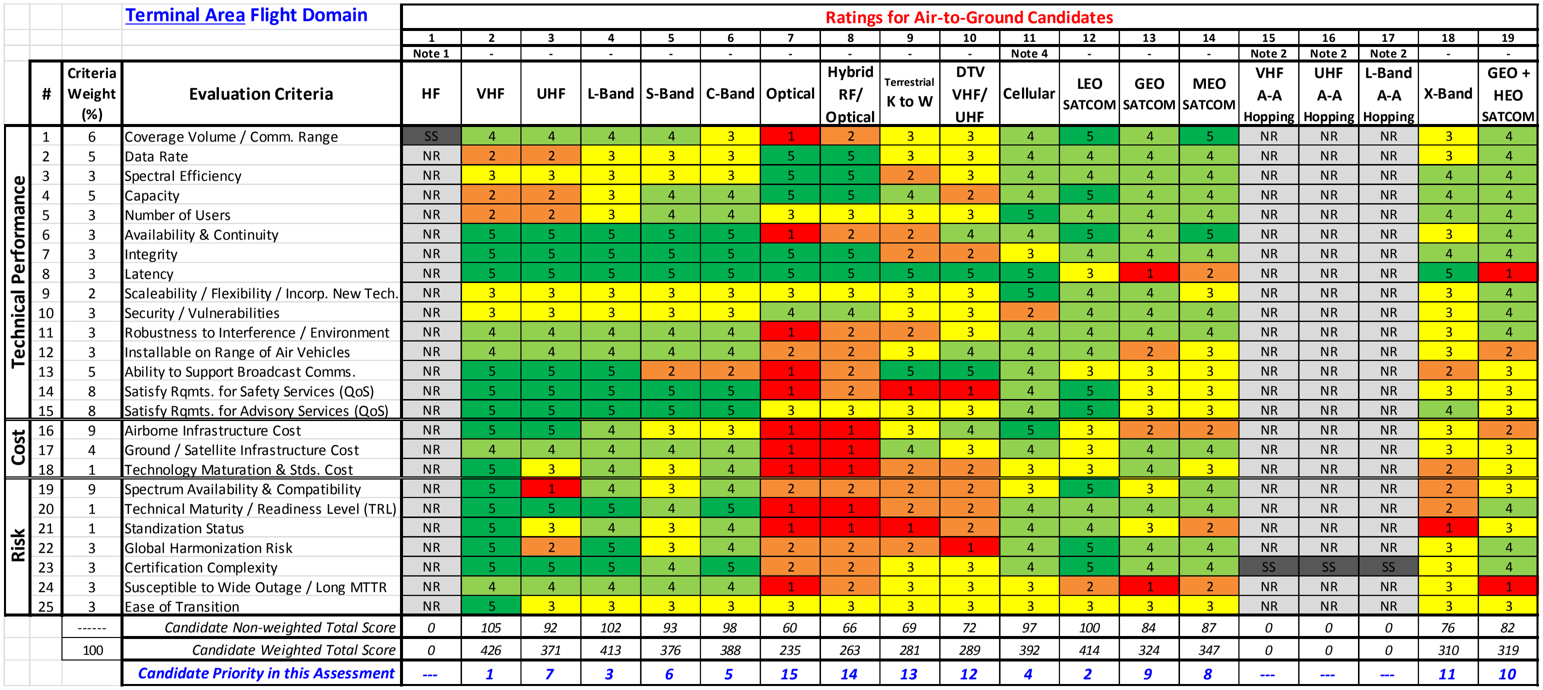
Note 9: HF communications represents a diverse backup (e.g., robust to different interference / environmental events) to the primary (preferred) SATCOM A-G candidates in oceanic, remote, and polar airspace.

Note 10: This assessment assumes GEO SATCOM coverage within ~+/- 70 degrees latitude (i.e., provides no coverage at the poles). Hybrid solutions are possible that would provide polar coverage including, for example, the GEO + HEO SATCOM (see A-G candidate #19) and GEO + LEO SATCOM.



			Airport Surface Flight Domain	Ratings for Air-to-Ground Candidates																		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Note 1	-	-	-	-	-	-	-	-	-	-	Note 5	-	-	Note 2	Note 2	Note 2	-	-
	#	Criteria Weight (%)	Evaluation Criteria	HF	VHF	UHF	L-Band	S-Band	C-Band	Optical	Hybrid RF/ Optical	Terrestrial K to W	DTV VHF/ UHF	Cellular	LEO SATCOM	GEO SATCOM	MEO SATCOM	VHF A-A Hopping	UHF A-A Hopping	L-Band A-A Hopping	X-Band	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	SS	5	5	5	3	3	2	3	2	2	4	5	4	5	NR	NR	NR	2	4
	2	5	Data Rate	NR	2	2	3	4	4	5	5	3	3	4	4	4	4	NR	NR	NR	4	4
	3	3	Spectral Efficiency	NR	3	3	3	3	3	5	5	2	3	4	4	4	4	NR	NR	NR	4	4
	4	5	Capacity	NR	2	2	3	4	4	5	5	4	2	4	5	4	4	NR	NR	NR	4	4
	5	3	Number of Users	NR	2	2	3	4	4	3	3	3	3	5	4	4	4	NR	NR	NR	4	4
	6	3	Availability & Continuity	NR	5	5	5	5	5	1	2	2	4	4	5	4	5	NR	NR	NR	3	4
	7	3	Integrity	NR	5	5	5	5	5	5	5	2	2	3	4	4	4	NR	NR	NR	4	4
	8	3	Latency	NR	5	5	5	5	5	5	5	5	5	5	3	1	2	NR	NR	NR	5	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	NR	3	3	3	3	3	3	3	3	3	5	4	4	3	NR	NR	NR	3	4
	10	3	Security / Vulnerabilities	NR	3	3	3	3	3	4	4	3	3	2	4	4	4	NR	NR	NR	3	4
	11	3	Robustness to Interference / Environment	NR	4	4	4	4	4	1	2	2	3	4	4	2	4	NR	NR	NR	3	2
	12	3	Installable on Range of Air Vehicles	NR	4	4	4	4	4	2	2	3	4	4	4	2	3	NR	NR	NR	3	2
	13	5	Ability to Support Broadcast Comms.	NR	5	5	5	3	3	1	2	5	5	4	3	3	3	NR	NR	NR	2	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	NR	5	5	5	5	5	1	2	1	1	4	5	3	3	NR	NR	NR	3	3
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	NR	5	5	5	5	5	3	3	3	3	4	5	3	3	NR	NR	NR	4	3
Cost	16	9	Airborne Infrastructure Cost	NR	5	5	4	3	4	1	1	3	4	5	3	2	2	NR	NR	NR	3	2
	17	4	Ground / Satellite Infrastructure Cost	NR	4	4	4	4	4	1	1	4	3	5	3	4	4	NR	NR	NR	3	3
	18	1	Technology Maturation & Stds. Cost	NR	5	3	4	3	5	1	1	2	2	3	3	4	3	NR	NR	NR	2	3
Risk	19	9	Spectrum Availability & Compatibility	NR	5	1	4	3	5	2	2	2	2	3	5	3	4	NR	NR	NR	2	3
	20	1	Technical Maturity / Readiness Level (TRL)	NR	5	5	5	4	5	1	1	2	2	4	4	4	4	NR	NR	NR	2	4
	21	1	Standization Status	NR	5	3	4	3	5	1	1	1	2	4	4	3	2	NR	NR	NR	1	3
	22	3	Global Harmonization Risk	NR	5	2	5	3	5	2	2	2	1	4	5	4	4	NR	NR	NR	3	4
	23	3	Certification Complexity	NR	5	5	5	4	5	2	2	3	3	4	5	4	4	SS	SS	SS	3	4
	24	3	Susceptible to Wide Outage / Long MTTR	NR	4	4	4	4	4	1	2	3	3	3	2	1	2	NR	NR	NR	3	1
	25	3	Ease of Transition	NR	5	3	3	3	5	3	3	3	3	3	3	3	3	NR	NR	NR	3	3
		------	*Candidate Non-weighted Total Score*	*0*	*106*	*93*	*103*	*94*	*107*	*61*	*67*	*68*	*71*	*98*	*100*	*82*	*87*	*0*	*0*	*0*	*76*	*80*
		100	*Candidate Weighted Total Score*	*0*	*432*	*377*	*419*	*380*	*427*	*241*	*269*	*275*	*283*	*396*	*414*	*318*	*347*	*0*	*0*	*0*	*309*	*313*
			Candidate Priority in this Assessment	***---***	***1***	***7***	***3***	***6***	***2***	***15***	***14***	***13***	***12***	***5***	***4***	***9***	***8***	***---***	***---***	***---***	***11***	***10***

Figure 390 – A-G Candidate Evaluation: Single Flight Domain – Surface (APT)



			Terminal Area Flight Domain	**Ratings for Air-to-Ground Candidates**																		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Note 1	-	-	-	-	-	-	-	-	-	Note 4	-	-	-	Note 2	Note 2	Note 2	-	-
	#	Criteria Weight (%)	Evaluation Criteria	HF	VHF	UHF	L-Band	S-Band	C-Band	Optical	Hybrid RF/ Optical	Terrestrial K to W	DTV VHF/ UHF	Cellular	LEO SATCOM	GEO SATCOM	MEO SATCOM	VHF A-A Hopping	UHF A-A Hopping	L-Band A-A Hopping	X-Band	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	SS	4	4	4	4	3	1	2	3	3	4	5	4	5	NR	NR	NR	3	4
	2	5	Data Rate	NR	2	2	3	3	3	5	5	3	3	4	4	4	4	NR	NR	NR	3	4
	3	3	Spectral Efficiency	NR	3	3	3	3	3	5	5	2	3	4	4	4	4	NR	NR	NR	4	4
	4	5	Capacity	NR	2	2	3	4	4	5	5	4	2	4	5	4	4	NR	NR	NR	4	4
	5	3	Number of Users	NR	2	2	3	4	4	3	3	3	3	5	4	4	4	NR	NR	NR	4	4
	6	3	Availability & Continuity	NR	5	5	5	5	5	1	2	2	4	4	5	4	5	NR	NR	NR	3	4
	7	3	Integrity	NR	5	5	5	5	5	5	5	2	2	3	4	4	4	NR	NR	NR	4	4
	8	3	Latency	NR	5	5	5	5	5	5	5	5	5	5	3	1	2	NR	NR	NR	5	1
	9	2	Scaleability / Flexibility / Incorp. New Tech.	NR	3	3	3	3	3	3	3	3	3	5	4	4	3	NR	NR	NR	3	4
	10	3	Security / Vulnerabilities	NR	3	3	3	3	3	4	4	3	3	2	4	4	4	NR	NR	NR	3	4
	11	3	Robustness to Interference / Environment	NR	4	4	4	4	4	1	2	2	3	4	4	4	4	NR	NR	NR	3	4
	12	3	Installable on Range of Air Vehicles	NR	4	4	4	4	4	2	2	3	4	4	4	2	3	NR	NR	NR	3	2
	13	5	Ability to Support Broadcast Comms.	NR	5	5	5	2	2	1	2	5	5	4	3	3	3	NR	NR	NR	2	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	NR	5	5	5	5	5	1	2	1	1	4	5	3	3	NR	NR	NR	3	3
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	NR	5	5	5	5	5	3	3	3	3	4	5	3	3	NR	NR	NR	4	3
Cost	16	9	Airborne Infrastructure Cost	NR	5	5	4	3	3	1	1	3	4	5	3	2	2	NR	NR	NR	3	2
	17	4	Ground / Satellite Infrastructure Cost	NR	4	4	4	4	4	1	1	4	3	4	3	4	4	NR	NR	NR	3	3
	18	1	Technology Maturation & Stds. Cost	NR	5	3	4	3	4	1	1	2	2	3	3	4	3	NR	NR	NR	2	3
Risk	19	9	Spectrum Availability & Compatibility	NR	5	1	4	3	4	2	2	2	2	3	5	3	4	NR	NR	NR	2	3
	20	1	Technical Maturity / Readiness Level (TRL)	NR	5	5	5	4	5	1	1	2	2	4	4	4	4	NR	NR	NR	2	4
	21	1	Standization Status	NR	5	3	4	3	4	1	1	1	2	4	4	3	2	NR	NR	NR	1	3
	22	3	Global Harmonization Risk	NR	5	2	5	3	4	2	2	2	1	4	5	4	4	NR	NR	NR	3	4
	23	3	Certification Complexity	NR	5	5	5	4	5	2	2	3	3	4	5	4	4	SS	SS	SS	3	4
	24	3	Susceptible to Wide Outage / Long MTTR	NR	4	4	4	4	4	1	2	3	3	3	2	1	2	NR	NR	NR	3	1
	25	3	Ease of Transition	NR	5	3	3	3	3	3	3	3	3	3	3	3	3	NR	NR	NR	3	3
		------	*Candidate Non-weighted Total Score*	*0*	*105*	*92*	*102*	*93*	*98*	*60*	*66*	*69*	*72*	*97*	*100*	*84*	*87*	*0*	*0*	*0*	*76*	*82*
		100	*Candidate Weighted Total Score*	*0*	*426*	*371*	*413*	*376*	*388*	*235*	*263*	*281*	*289*	*392*	*414*	*324*	*347*	*0*	*0*	*0*	*310*	*319*
			Candidate Priority in this Assessment	***---***	***1***	***7***	***3***	***6***	***5***	***15***	***14***	***13***	***12***	***4***	***2***	***9***	***8***	***---***	***---***	***---***	***11***	***10***

Figure 391 – A-G Candidate Evaluation: Single Flight Domain – Terminal Area (TMA)

EnRoute Flight Domain

Ratings for Air-to-Ground Candidates

				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				-	-	-	-	-	-	Note 3	Note 3	-	-	Note 4	Notes 5,6	Notes 6,7	Note 6	Note 2	Note 2	Note 2	-	Note 6
	#	Criteria Weight (%)	Evaluation Criteria	HF	VHF	UHF	L-Band	S-Band	C-Band	Optical	Hybrid RF/ Optical	Terrestrial K to W	DTV VHF/ UHF	Cellular	LEO SATCOM	GEO SATCOM	MEO SATCOM	VHF A-A Hopping	UHF A-A Hopping	L-Band A-A Hopping	X-Band	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	3	4	4	4	4	3	SS	SS	2	3	4	5	5	5	NR	NR	NR	3	5
	2	5	Data Rate	1	2	2	3	3	3	NR	NR	3	3	4	4	4	4	NR	NR	NR	4	4
	3	3	Spectral Efficiency	1	3	3	3	3	3	NR	NR	2	3	4	5	4	5	NR	NR	NR	3	4
	4	5	Capacity	1	2	2	3	3	3	NR	NR	3	2	4	5	3	4	NR	NR	NR	3	3
	5	3	Number of Users	1	3	3	3	3	3	NR	NR	3	3	5	5	3	4	NR	NR	NR	3	3
	6	3	Availability & Continuity	1	5	5	5	5	4	NR	NR	3	4	4	5	3	5	NR	NR	NR	3	3
	7	3	Integrity	3	5	5	5	4	4	NR	NR	2	2	3	3	3	3	NR	NR	NR	3	3
	8	3	Latency	4	5	5	5	5	5	NR	NR	5	5	5	3	2	3	NR	NR	NR	5	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	2	3	3	3	3	3	NR	NR	3	3	5	3	3	3	NR	NR	NR	3	3
	10	3	Security / Vulnerabilities	4	3	3	3	3	3	NR	NR	3	3	3	4	4	4	NR	NR	NR	3	4
	11	3	Robustness to Interference / Environment	2	4	4	4	4	3	NR	NR	2	3	4	5	5	5	NR	NR	NR	3	5
	12	3	Installable on Range of Air Vehicles	2	4	4	4	4	4	NR	NR	3	4	4	4	2	4	NR	NR	NR	3	2
	13	5	Ability to Support Broadcast Comms.	1	5	5	5	2	2	NR	NR	5	5	4	3	3	3	NR	NR	NR	2	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	2	5	5	5	4	4	NR	NR	1	1	3	5	4	4	NR	NR	NR	2	4
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	1	5	5	5	5	5	NR	NR	3	3	4	5	4	4	NR	NR	NR	4	4
Cost	16	9	Airborne Infrastructure Cost	1	5	5	4	4	3	NR	NR	2	3	4	3	2	2	NR	NR	NR	3	2
	17	4	Ground / Satellite Infrastructure Cost	5	4	3	3	3	3	NR	NR	4	3	5	3	5	4	NR	NR	NR	2	3
	18	1	Technology Maturation & Stds. Cost	5	5	3	4	3	2	NR	NR	2	2	3	3	3	3	NR	NR	NR	2	3
Risk	19	9	Spectrum Availability & Compatibility	4	5	1	4	3	4	NR	NR	2	2	3	5	3	4	NR	NR	NR	2	3
	20	1	Technical Maturity / Readiness Level (TRL)	3	5	5	5	4	3	NR	NR	2	2	4	4	4	4	NR	NR	NR	2	4
	21	1	Standization Status	4	5	3	4	3	4	NR	NR	1	2	4	4	3	2	NR	NR	NR	1	3
	22	3	Global Harmonization Risk	1	5	2	3	3	4	NR	NR	2	1	4	5	4	4	NR	NR	NR	3	4
	23	3	Certification Complexity	3	5	5	4	4	4	NR	NR	3	3	4	5	4	4	SS	SS	SS	3	4
	24	3	Susceptible to Wide Outage / Long MTTR	2	4	4	4	4	4	NR	NR	3	3	3	2	1	2	NR	NR	NR	3	1
	25	3	Ease of Transition	1	5	4	4	3	3	NR	NR	3	3	3	5	4	4	NR	NR	NR	3	4
		------	*Candidate Non-weighted Total Score*	*58*	*106*	*93*	*99*	*89*	*86*	*0*	*0*	*67*	*71*	*97*	*103*	*85*	*93*	*0*	*0*	*0*	*71*	*83*
		100	*Candidate Weighted Total Score*	*213*	*429*	*373*	*403*	*362*	*352*	*0*	*0*	*264*	*280*	*382*	*424*	*342*	*375*	*0*	*0*	*0*	*289*	*334*
			Candidate Priority in this Assessment	***14***	***1***	***6***	***3***	***7***	***8***	***---***	***---***	***13***	***12***	***4***	***2***	***9***	***5***	***---***	***---***	***---***	***11***	***10***

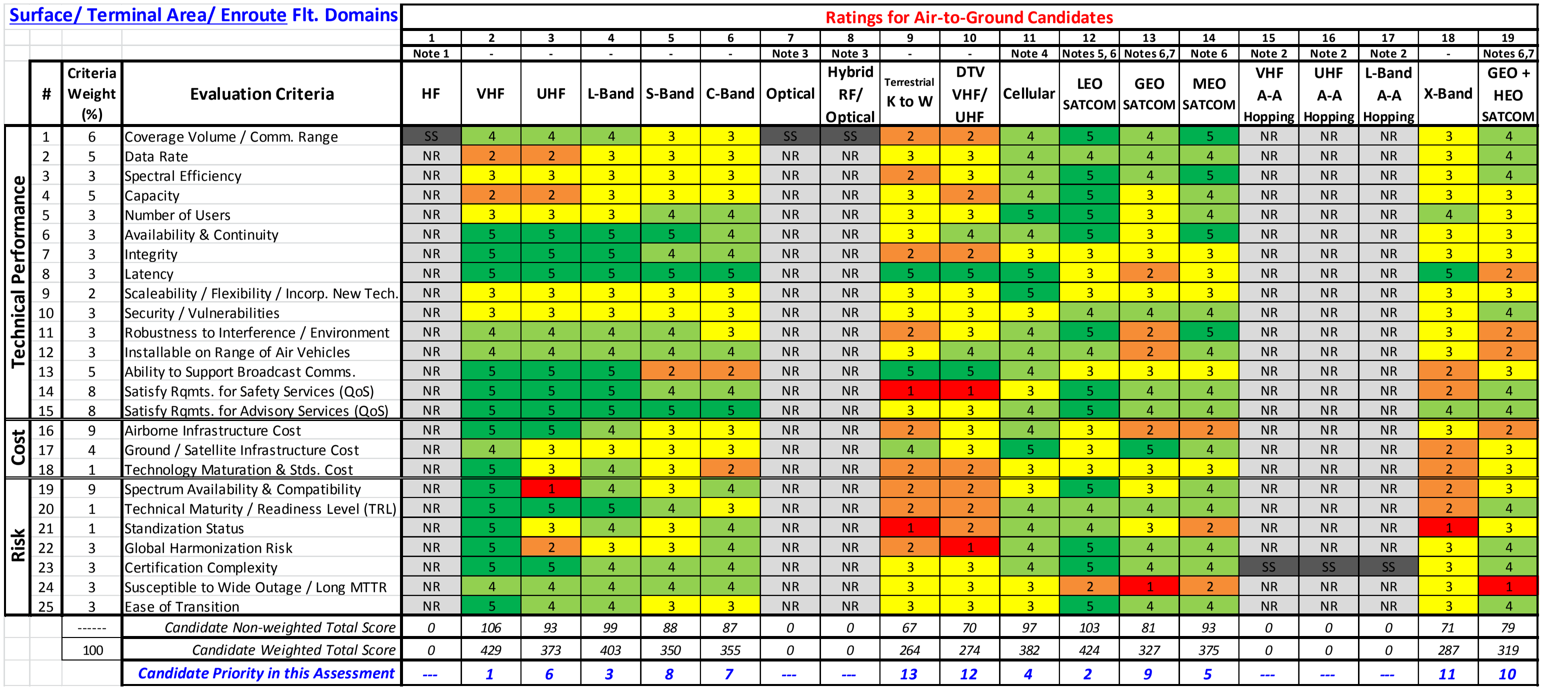
Figure 392 – A-G Candidate Evaluation: Single Flight Domain – Enroute (ENR)

			Oceanic/Remote Flight Domain	**Ratings for Air-to-Ground Candidates**																		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Note 9	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Notes 5,6	Notes 6,7	Note 6	-	-	-	Note 8	Notes 6,7
	#	**Criteria Weight (%)**	**Evaluation Criteria**	**HF**	**VHF**	**UHF**	**L-Band**	**S-Band**	**C-Band**	**Optical**	**Hybrid RF/ Optical**	**Terrestrial K to W**	**DTV VHF/ UHF**	**Cellular**	**LEO SATCOM**	**GEO SATCOM**	**MEO SATCOM**	**VHF A-A Hopping**	**UHF A-A Hopping**	**L-Band A-A Hopping**	**X-Band**	**GEO + HEO SATCOM**
Technical Performance	1	6	Coverage Volume / Comm. Range	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	5	5	2	2	2	NR	5
	2	5	Data Rate	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	4	4	2	2	3	NR	4
	3	3	Spectral Efficiency	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	4	5	3	3	4	NR	4
	4	5	Capacity	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	3	4	2	2	2	NR	3
	5	3	Number of Users	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	3	4	3	3	3	NR	3
	6	3	Availability & Continuity	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	3	5	2	2	2	NR	3
	7	3	Integrity	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	3	3	3	3	3	NR	3
	8	3	Latency	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	2	3	4	4	4	NR	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	3	3	2	2	2	NR	3
	10	3	Security / Vulnerabilities	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	4	4	2	2	2	NR	4
	11	3	Robustness to Interference / Environment	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	5	5	3	3	4	NR	5
	12	3	Installable on Range of Air Vehicles	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	2	4	4	4	4	NR	2
	13	5	Ability to Support Broadcast Comms.	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	3	3	1	1	1	NR	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	4	4	2	2	2	NR	4
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	4	4	3	3	3	NR	4
Cost	16	9	Airborne Infrastructure Cost	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	2	2	2	4	4	4	NR	2
	17	4	Ground / Satellite Infrastructure Cost	4	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	2	4	2	4	4	4	SS	2
	18	1	Technology Maturation & Stds. Cost	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	3	3	3	3	3	NR	3
Risk	19	9	Spectrum Availability & Compatibility	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	3	4	3	3	3	NR	3
	20	1	Technical Maturity / Readiness Level (TRL)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	4	4	3	3	3	NR	4
	21	1	Standization Status	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	3	2	3	2	2	NR	3
	22	3	Global Harmonization Risk	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	4	4	2	2	2	NR	4
	23	3	Certification Complexity	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	4	4	3	3	3	NR	4
	24	3	Susceptible to Wide Outage / Long MTTR	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	2	3	4	4	4	NR	2
	25	3	Ease of Transition	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	4	4	2	2	2	NR	4
		------	*Candidate Non-weighted Total Score*	*78*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*102*	*85*	*92*	*69*	*68*	*71*	*0*	*83*
		100	*Candidate Weighted Total Score*	*309*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*414*	*341*	*370*	*274*	*273*	*284*	*0*	*333*
			Candidate Priority in this Assessment	***5***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***1***	***3***	***2***	***7***	***8***	***6***	***---***	***4***

Figure 393 – A-G Candidate Evaluation: Single Flight Domain – Oceanic/Remote

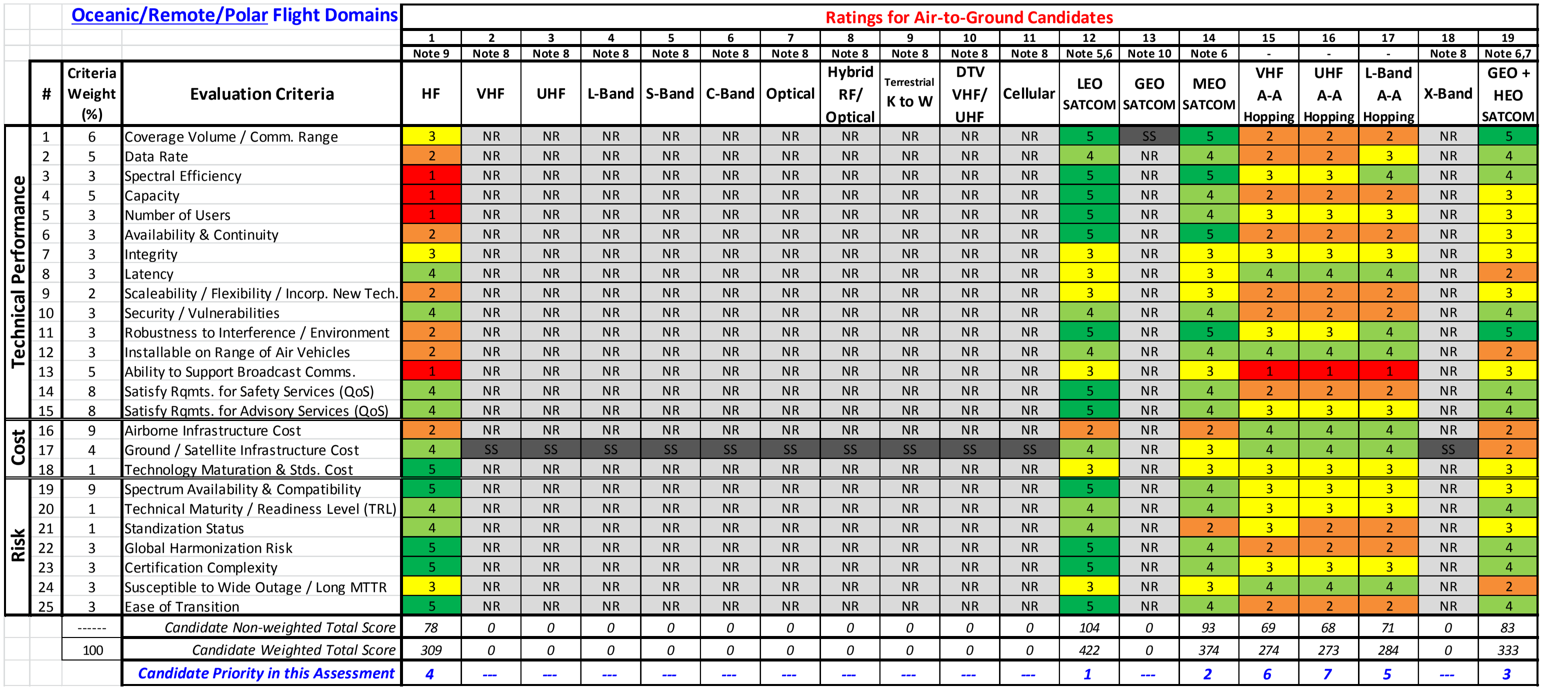
			Polar Flight Domain	**Ratings for Air-to-Ground Candidates**																		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Note 9	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Notes 5,6	Note 10	Note 6	-	-	-	Note 8	Notes 6,7
	#	**Criteria Weight (%)**	**Evaluation Criteria**	**HF**	**VHF**	**UHF**	**L-Band**	**S-Band**	**C-Band**	**Optical**	**Hybrid RF/ Optical**	**Terrestrial K to W**	**DTV VHF/ UHF**	**Cellular**	**LEO SATCOM**	**GEO SATCOM**	**MEO SATCOM**	**VHF A-A Hopping**	**UHF A-A Hopping**	**L-Band A-A Hopping**	**X-Band**	**GEO + HEO SATCOM**
Technical Performance	1	6	Coverage Volume / Comm. Range	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	SS	5	2	2	2	NR	5
	2	5	Data Rate	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	2	2	3	NR	4
	3	3	Spectral Efficiency	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	3	3	4	NR	4
	4	5	Capacity	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	3
	5	3	Number of Users	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	3
	6	3	Availability & Continuity	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	2	2	2	NR	3
	7	3	Integrity	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	3	3	3	NR	3
	8	3	Latency	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	2	2	2	NR	3
	10	3	Security / Vulnerabilities	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	2	2	2	NR	4
	11	3	Robustness to Interference / Environment	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	3	3	4	NR	5
	12	3	Installable on Range of Air Vehicles	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	4	4	4	NR	2
	13	5	Ability to Support Broadcast Comms.	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	1	1	1	NR	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	4
Cost	16	9	Airborne Infrastructure Cost	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	2	NR	2	4	4	4	NR	2
	17	4	Ground / Satellite Infrastructure Cost	4	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	2	NR	2	4	4	4	SS	2
	18	1	Technology Maturation & Stds. Cost	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	3	3	3	NR	3
Risk	19	9	Spectrum Availability & Compatibility	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	3
	20	1	Technical Maturity / Readiness Level (TRL)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	3	3	3	NR	4
	21	1	Standization Status	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	2	3	2	2	NR	3
	22	3	Global Harmonization Risk	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
	23	3	Certification Complexity	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	4
	24	3	Susceptible to Wide Outage / Long MTTR	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	2
	25	3	Ease of Transition	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
		------	*Candidate Non-weighted Total Score*	*78*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*102*	*0*	*92*	*69*	*68*	*71*	*0*	*83*
		100	*Candidate Weighted Total Score*	*309*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*414*	*0*	*370*	*274*	*273*	*284*	*0*	*333*
			Candidate Priority in this Assessment	***4***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***1***	***---***	***2***	***6***	***7***	***5***	***---***	***3***

Figure 394 – A-G Candidate Evaluation: Single Flight Domain – Polar



Surface/ Terminal Area/ Enroute Flt. Domains				Ratings for Air-to-Ground Candidates																		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Note 1	-	-	-	-	-	Note 3	Note 3	-	-	Note 4	Notes 5, 6	Notes 6,7	Note 6	Note 2	Note 2	Note 2	-	Notes 6,7
	#	Criteria Weight (%)	Evaluation Criteria	HF	VHF	UHF	L-Band	S-Band	C-Band	Optical	Hybrid RF/ Optical	Terrestrial K to W	DTV VHF/ UHF	Cellular	LEO SATCOM	GEO SATCOM	MEO SATCOM	VHF A-A Hopping	UHF A-A Hopping	L-Band A-A Hopping	X-Band	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	SS	4	4	4	3	3	SS	SS	2	2	4	5	4	5	NR	NR	NR	3	4
	2	5	Data Rate	NR	2	2	3	3	3	NR	NR	3	3	4	4	4	4	NR	NR	NR	3	4
	3	3	Spectral Efficiency	NR	3	3	3	3	3	NR	NR	2	3	4	5	4	5	NR	NR	NR	3	4
	4	5	Capacity	NR	2	2	3	3	3	NR	NR	3	2	4	5	3	4	NR	NR	NR	3	3
	5	3	Number of Users	NR	3	3	3	4	4	NR	NR	3	3	5	5	3	4	NR	NR	NR	4	3
	6	3	Availability & Continuity	NR	5	5	5	5	4	NR	NR	3	4	4	5	3	5	NR	NR	NR	3	3
	7	3	Integrity	NR	5	5	5	4	4	NR	NR	2	2	3	3	3	3	NR	NR	NR	3	3
	8	3	Latency	NR	5	5	5	5	5	NR	NR	5	5	5	3	2	3	NR	NR	NR	5	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	NR	3	3	3	3	3	NR	NR	3	3	5	3	3	3	NR	NR	NR	3	3
	10	3	Security / Vulnerabilities	NR	3	3	3	3	3	NR	NR	3	3	3	4	4	4	NR	NR	NR	3	4
	11	3	Robustness to Interference / Environment	NR	4	4	4	4	3	NR	NR	2	3	4	5	2	5	NR	NR	NR	3	2
	12	3	Installable on Range of Air Vehicles	NR	4	4	4	4	4	NR	NR	3	4	4	4	2	4	NR	NR	NR	3	2
	13	5	Ability to Support Broadcast Comms.	NR	5	5	5	2	2	NR	NR	5	5	4	3	3	3	NR	NR	NR	2	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	NR	5	5	5	4	4	NR	NR	1	1	3	5	4	4	NR	NR	NR	2	4
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	NR	5	5	5	5	5	NR	NR	3	3	4	5	4	4	NR	NR	NR	4	4
Cost	16	9	Airborne Infrastructure Cost	NR	5	5	4	3	3	NR	NR	2	3	4	3	2	2	NR	NR	NR	3	2
	17	4	Ground / Satellite Infrastructure Cost	NR	4	3	3	3	3	NR	NR	4	3	5	3	5	4	NR	NR	NR	2	3
	18	1	Technology Maturation & Stds. Cost	NR	5	3	4	3	2	NR	NR	2	2	3	3	3	3	NR	NR	NR	2	3
Risk	19	9	Spectrum Availability & Compatibility	NR	5	1	4	3	4	NR	NR	2	2	3	5	3	4	NR	NR	NR	2	3
	20	1	Technical Maturity / Readiness Level (TRL)	NR	5	5	5	4	3	NR	NR	2	2	4	4	4	4	NR	NR	NR	2	4
	21	1	Standization Status	NR	5	3	4	3	4	NR	NR	1	2	4	4	3	2	NR	NR	NR	1	3
	22	3	Global Harmonization Risk	NR	5	2	3	3	4	NR	NR	2	1	4	5	4	4	NR	NR	NR	3	4
	23	3	Certification Complexity	NR	5	5	4	4	4	NR	NR	3	3	4	5	4	4	SS	SS	SS	3	4
	24	3	Susceptible to Wide Outage / Long MTTR	NR	4	4	4	4	4	NR	NR	3	3	3	2	1	2	NR	NR	NR	3	1
	25	3	Ease of Transition	NR	5	4	4	3	3	NR	NR	3	3	3	5	4	4	NR	NR	NR	3	4
		------	*Candidate Non-weighted Total Score*	*0*	*106*	*93*	*99*	*88*	*87*	*0*	*0*	*67*	*70*	*97*	*103*	*81*	*93*	*0*	*0*	*0*	*71*	*79*
		100	*Candidate Weighted Total Score*	*0*	*429*	*373*	*403*	*350*	*355*	*0*	*0*	*264*	*274*	*382*	*424*	*327*	*375*	*0*	*0*	*0*	*287*	*319*
			Candidate Priority in this Assessment	***---***	***1***	***6***	***3***	***8***	***7***	***---***	***---***	***13***	***12***	***4***	***2***	***9***	***5***	***---***	***---***	***---***	***11***	***10***

Figure 395 – A-G Candidate Evaluation: Multiple Flight Domains – APT / TMA / ENR



			Oceanic/Remote/Polar Flight Domains	Ratings for Air-to-Ground Candidates																		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Note 9	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 5,6	Note 10	Note 6	-	-	-	Note 8	Note 6,7
	#	Criteria Weight (%)	Evaluation Criteria	HF	VHF	UHF	L-Band	S-Band	C-Band	Optical	Hybrid RF/ Optical	Terrestrial K to W	DTV VHF/ UHF	Cellular	LEO SATCOM	GEO SATCOM	MEO SATCOM	VHF A-A Hopping	UHF A-A Hopping	L-Band A-A Hopping	X-Band	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	SS	5	2	2	2	NR	5
	2	5	Data Rate	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	2	2	3	NR	4
	3	3	Spectral Efficiency	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	3	3	4	NR	4
	4	5	Capacity	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	3
	5	3	Number of Users	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	3
	6	3	Availability & Continuity	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	2	2	2	NR	3
	7	3	Integrity	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	3	3	3	NR	3
	8	3	Latency	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	2	2	2	NR	3
	10	3	Security / Vulnerabilities	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	2	2	2	NR	4
	11	3	Robustness to Interference / Environment	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	3	3	4	NR	5
	12	3	Installable on Range of Air Vehicles	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	4	4	4	NR	2
	13	5	Ability to Support Broadcast Comms.	1	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	1	1	1	NR	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	4
Cost	16	9	Airborne Infrastructure Cost	2	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	2	NR	2	4	4	4	NR	2
	17	4	Ground / Satellite Infrastructure Cost	4	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	4	NR	3	4	4	4	SS	2
	18	1	Technology Maturation & Stds. Cost	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	3	3	3	NR	3
Risk	19	9	Spectrum Availability & Compatibility	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	3
	20	1	Technical Maturity / Readiness Level (TRL)	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	3	3	3	NR	4
	21	1	Standization Status	4	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	2	3	2	2	NR	3
	22	3	Global Harmonization Risk	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
	23	3	Certification Complexity	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	4
	24	3	Susceptible to Wide Outage / Long MTTR	3	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	2
	25	3	Ease of Transition	5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
		------	*Candidate Non-weighted Total Score*	*78*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*104*	*0*	*93*	*69*	*68*	*71*	*0*	*83*
		100	*Candidate Weighted Total Score*	*309*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*422*	*0*	*374*	*274*	*273*	*284*	*0*	*333*
			Candidate Priority in this Assessment	***4***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***1***	***---***	***2***	***6***	***7***	***5***	***---***	***3***

Figure 396 – A-G Candidate Evaluation: Multiple Flight Domains – ORP

All Flight Domains

(Surface, Terminal Area, EnRoute, Oceanic, Remote, and Polar)

Ratings for Air-to-Ground Candidates

	#	Criteria Weight (%)	Evaluation Criteria	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
				Note 1	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Note 8	Notes 5,6	Note 10	Note 6	-	-	-	Note 8	Notes 6,7
				HF	VHF	UHF	L-Band	S-Band	C-Band	Optical	Hybrid RF/ Optical	Terrestrial K to W	DTV VHF/ UHF	Cellular	LEO SATCOM	GEO SATCOM	MEO SATCOM	VHF LOS and A-A Hopping	UHF LOS and A-A Hopping	L-Band LOS &A-A Hopping	X-Band	GEO + HEO SATCOM
Technical Performance	1	6	Coverage Volume / Comm. Range	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	5	SS	5	3	3	3	SS	5
	2	5	Data Rate	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	2	2	3	NR	4
	3	3	Spectral Efficiency	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	3	3	4	NR	4
	4	5	Capacity	SS	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	3	NR	3
	5	3	Number of Users	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	3
	6	3	Availability & Continuity	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	3	3	3	NR	3
	7	3	Integrity	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	3
	8	3	Latency	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	2
	9	2	Scaleability / Flexibility / Incorp. New Tech.	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	3	3	3	NR	3
	10	3	Security / Vulnerabilities	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	3	3	3	NR	4
	11	3	Robustness to Interference / Environment	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	5	4	4	4	NR	2
	12	3	Installable on Range of Air Vehicles	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	4	4	4	NR	2
	13	5	Ability to Support Broadcast Comms.	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	3	3	3	NR	3
	14	8	Satisfy Rqmts. for Safety Services (QoS)	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	4	4	4	NR	4
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	5	5	5	NR	4
Cost	16	9	Airborne Infrastructure Cost	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	2	NR	2	5	5	5	NR	2
	17	4	Ground / Satellite Infrastructure Cost	NR	SS	SS	SS	SS	SS	SS	SS	SS	SS	SS	2	NR	2	4	4	4	SS	2
	18	1	Technology Maturation & Stds. Cost	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	3
Risk	19	9	Spectrum Availability & Compatibility	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	2	4	NR	3
	20	1	Technical Maturity / Readiness Level (TRL)	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	4	3	3	3	NR	4
	21	1	Standization Status	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	4	NR	2	3	3	3	NR	3
	22	3	Global Harmonization Risk	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
	23	3	Certification Complexity	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	2	2	2	NR	4
	24	3	Susceptible to Wide Outage / Long MTTR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	3	NR	3	4	4	4	NR	2
	25	3	Ease of Transition	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	5	NR	4	3	3	3	NR	4
		------	*Candidate Non-weighted Total Score*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*102*	*0*	*92*	*83*	*82*	*87*	*0*	*80*
		100	*Candidate Weighted Total Score*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*414*	*0*	*370*	*346*	*337*	*368*	*0*	*324*
			Candidate Priority in this Assessment	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***---***	***1***	***---***	***2***	***4***	***5***	***3***	***---***	***6***

Figure 397 – A-G Candidate Evaluation: Multiple Flt. Domains – APT / TMA / ENR / ORP

30.2.3 Prioritization A-G Candidates

Based upon the evaluations and rankings provided in Sections 30.2.1 and 30.2.2, Figure 398 and Figure 399 provide the prioritized ranked lists of the A-G communication candidates for single airspace and multiple airspace flight domains, respectively. Figure 400 and Figure 401 provide the same results, but also include the weighted total scores for the communication candidates for each of the flight domains under investigation.

<u>Note for the following figures</u>: "#NA" stands for "Not Applicable." Each "#NA" entry indicates that of the 12 A-A and 19 A-G communications candidates being evaluated, a candidate has been given a showstopper (SS) [i.e., unacceptable] rating for the flight domain(s) under investigation and thus is not included in the ranked list of candidates.

	A-G Communication Candidate Rankings				
	Single Airspace Flight Domains				
Rank	**Airport Surface (APT)**	**Terminal Area (TMA)**	**En Route (ENR)**	**Oceanic/Remote**	**Polar**
1	**VHF**	**VHF**	**VHF**	**LEO SATCOM**	**LEO SATCOM**
2	**C-Band**	**LEO SATCOM**	**LEO SATCOM**	**MEO SATCOM**	**MEO SATCOM**
3	**L-Band**	**L-Band**	**L-Band**	**GEO SATCOM**	**GEO + HEO SATCOM**
4	**LEO SATCOM**	**Cellular**	**Cellular**	**GEO + HEO SATCOM**	**HF**
5	**Cellular**	**C-Band**	**MEO SATCOM**	**HF**	**L-Band A-A Hopping**
6	**S-Band**	**S-Band**	**UHF**	**L-Band A-A Hopping**	**VHF A-A Hopping**
7	**UHF**	**UHF**	**S-Band**	**VHF A-A Hopping**	**UHF A-A Hopping**
8	**MEO SATCOM**	**MEO SATCOM**	**C-Band**	**UHF A-A Hopping**	#N/A
9	**GEO SATCOM**	**GEO SATCOM**	**GEO SATCOM**	#N/A	#N/A
10	**GEO + HEO SATCOM**	**GEO + HEO SATCOM**	**GEO + HEO SATCOM**	#N/A	#N/A
11	**X-Band**	**X-Band**	**X-Band**	#N/A	#N/A
12	**DTV VHF/ UHF**	**DTV VHF/ UHF**	**DTV VHF/ UHF**	#N/A	#N/A
13	**Terrestrial K to W**	**Terrestrial K to W**	**Terrestrial K to W**	#N/A	#N/A
14	**Hybrid RF/ Optical**	**Hybrid RF/ Optical**	**HF**	#N/A	#N/A
15	**Optical**	**Optical**	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A

Figure 398 – A-G Candidate Prioritization for Single Flight Domains

	A-G Communication Candidate Rankings		
	Multiple Airspace Flight Domains		
Rank	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace
1	VHF	LEO SATCOM	LEO SATCOM
2	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	GEO + HEO SATCOM	L-Band LOS & A-A Hop
4	Cellular	HF	VHF LOS & A-A Hop
5	MEO SATCOM	L-Band A-A Hopping	UHF LOS & A-A Hop
6	UHF	VHF A-A Hopping	GEO + HEO SATCOM
7	C-Band	UHF A-A Hopping	#N/A
8	S-Band	#N/A	#N/A
9	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	#N/A	#N/A
14	#N/A	#N/A	#N/A
15	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A

Figure 399 – A-G Candidate Prioritization for Multiple Flight Domains

	A-G Communication Candidate Rankings									
	Single Airspace Flight Domains									
Rank	Airport Surface (APT)		Terminal Area (TMA)		En Route (ENR)		Oceanic/Remote		Polar	
	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score
1	VHF	432	VHF	426	VHF	429	LEO SATCOM	414	LEO SATCOM	414
2	C-Band	427	LEO SATCOM	414	LEO SATCOM	424	MEO SATCOM	370	MEO SATCOM	370
3	L-Band	419	L-Band	413	L-Band	403	GEO SATCOM	341	GEO + HEO SATCOM	333
4	LEO SATCOM	414	Cellular	392	Cellular	382	GEO + HEO SATCOM	333	HF	309
5	Cellular	396	C-Band	388	MEO SATCOM	375	HF	309	L-Band A-A Hopping	284
6	S-Band	380	S-Band	376	UHF	373	L-Band A-A Hopping	284	VHF A-A Hopping	274
7	UHF	377	UHF	371	S-Band	362	VHF A-A Hopping	274	UHF A-A Hopping	273
8	MEO SATCOM	347	MEO SATCOM	347	C-Band	352	UHF A-A Hopping	273	#N/A	#N/A
9	GEO SATCOM	318	GEO SATCOM	324	GEO SATCOM	342	#N/A	#N/A	#N/A	#N/A
10	GEO + HEO SATCOM	313	GEO + HEO SATCOM	319	GEO + HEO SATCOM	334	#N/A	#N/A	#N/A	#N/A
11	X-Band	309	X-Band	310	X-Band	289	#N/A	#N/A	#N/A	#N/A
12	DTV VHF/ UHF	283	DTV VHF/ UHF	289	DTV VHF/ UHF	280	#N/A	#N/A	#N/A	#N/A
13	Terrestrial K to W	275	Terrestrial K to W	281	Terrestrial K to W	264	#N/A	#N/A	#N/A	#N/A
14	Hybrid RF/ Optical	269	Hybrid RF/ Optical	263	HF	213	#N/A	#N/A	#N/A	#N/A
15	Optical	241	Optical	235	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Figure 400 – A-G Candidate Prioritization for Single Flight Domains (with Scores)

	A-G Communication Candidate Rankings					
	Multiple Airspace Flight Domains					
Rank	**Surface/Term./EnRoute (APT / TMA/ ENR)**		**Oceanic/Remote and Polar (ORP)**		**All Airspace**	
	Candidate	**Score**	**Candidate**	**Score**	**Candidate**	**Score**
1	VHF	429	LEO SATCOM	422	LEO SATCOM	414
2	LEO SATCOM	424	MEO SATCOM	374	MEO SATCOM	370
3	L-Band	403	GEO + HEO SATCOM	333	L-Band LOS & A-A	368
4	Cellular	382	HF	309	VHF LOS & A-A Hop	346
5	MEO SATCOM	375	L-Band A-A Hopping	284	UHF LOS & A-A Hop	337
6	UHF	373	VHF A-A Hopping	274	GEO + HEO SATCOM	324
7	C-Band	355	UHF A-A Hopping	273	#N/A	#N/A
8	S-Band	350	#N/A	#N/A	#N/A	#N/A
9	GEO SATCOM	327	#N/A	#N/A	#N/A	#N/A
10	GEO + HEO SATCOM	319	#N/A	#N/A	#N/A	#N/A
11	X-Band	287	#N/A	#N/A	#N/A	#N/A
12	DTV VHF/ UHF	274	#N/A	#N/A	#N/A	#N/A
13	Terrestrial K to W	264	#N/A	#N/A	#N/A	#N/A
14	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Figure 401 – A-G Candidate Prioritization for Multiple Flight Domains (with Scores)

30.2.4 Discussion of A-G Candidates Prioritization Results

The subsections below discuss the results from the A-G prioritization. While this study has attempted to appropriately prioritize the communication candidates in a manner consistent with the expected long-term NAS communication needs while balancing the collective interests of all the aviation stakeholders, it should be noted that the candidate prioritizations are subject to change when different evaluation criteria, assumptions, communications requirements, or weighting factors are used in the assessment process.

30.2.4.1 Airport Surface, Terminal Area, and Enroute Flight Domains

The A-G Candidates prioritization results applicable to the airport surface, terminal area, and enroute flight domains generally prioritize VHF, L-band, LEO SATCOM, and cellular candidates in the top tier. These A-G candidates scored well in terms of high technical performance, low cost, and low risk. These candidates (evaluated with expected future improvements and maturation over the study 50-year time horizon) tend to be capable of providing actual communications performance commensurate with meeting the RCP for most of the envisioned long-term ATM applications. Evaluating these candidates as they are today, would result in higher cost associated with LEO SATCOM and higher risk associated with using cellular systems for safety services. It is envisioned that over time that LEO SATCOM will become very high performance and very low cost with Teledesic-style LEO constellations containing hundreds to thousands of pico-satellites and cellular networks will become robust to support aviation safety services communications.

The middle tier of candidates applicable to the airport surface, terminal area, and enroute flight domains are UHF, S-band, and C-band. This tier of candidates has some desirable characteristics of the top tier of candidates, but these candidates generally have at least one area of either performance, cost, or risk where they are not evaluated as well as the highest tier of candidates.

The lowest tier of candidates applicable to the airport surface, terminal area, and enroute flight domains include X-band, MEO SATCOM, GEO SATCOM, GEO + HEO SATCOM, DTV VHF/UHF, Terrestrial K to W band, Hybrid RF/Optical, and Optical. The candidates in this lowest tier usually evaluated low in at least two evaluation categories of performance, cost, or risk. Furthermore, the actual communications performances of the candidates in this tier typically only meet the RCP for a small subset of the envisioned long-term ATM applications.

30.2.4.2 Oceanic, Remote, and Polar Flight Domains

The top tier of A-G candidates applicable to the oceanic, remote, and polar flight domains include LEO and MEO SATCOM. These candidates were evaluated very high relative to the other alternatives against the measures of high technical performance, low cost, and low risk. They also could meet the A-G communications RCP to enable a broad range of the identified long-term ATM safety and advisory applications.

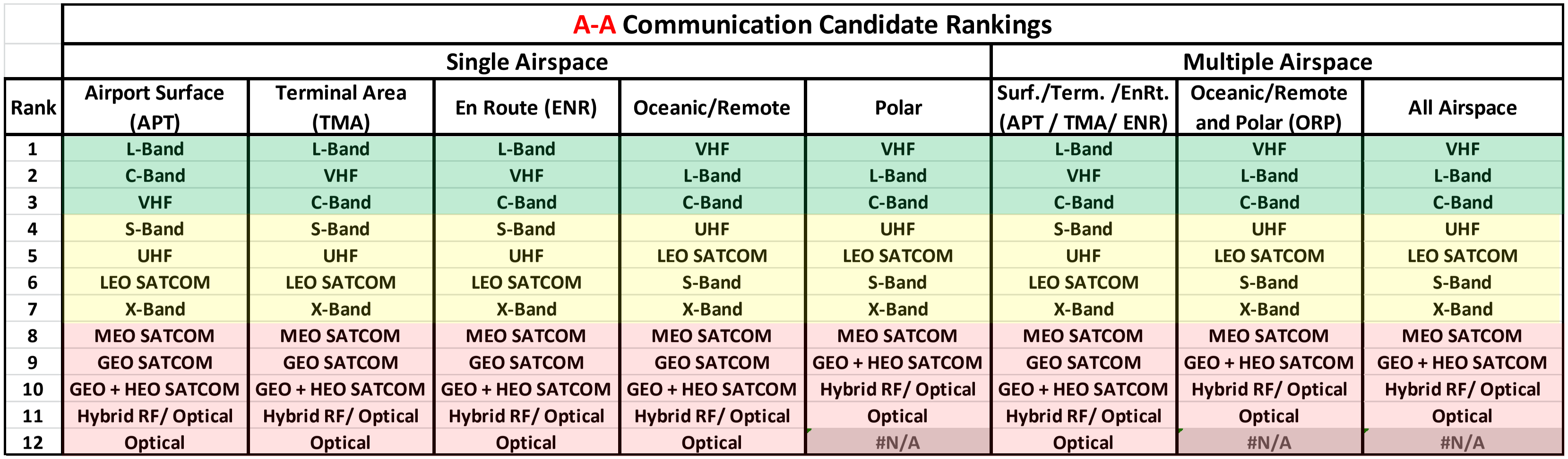
The middle tier of A-G candidates include the GEO SATCOM (for oceanic/remote not including polar) or GEO + HEO (when including polar coverage) and HF. These candidates could meet the ATM application RCP, but have shortfalls primarily in a number of areas [e.g., capacity for HF, and cost for GEO and GEO + HEO SATCOM].

The lowest tier of A-G candidates include those that achieve long range A-G communications using aircraft-to-aircraft LOS communications that hop between intervening aircraft. These candidates include VHF A-A hopping, UHF A-A hopping, and L-band A-A hopping. They ranked low in a number of performance areas [e.g., coverage volume /availability /continuity as the hopping candidates rely on having good aircraft relative geometry to be able to route the communications (via LOS A-A) to close the long range A-G communications link].

While HF and the hopping candidates tended to be evaluated lower than the SATCOM alternatives to support ATM applications that require A-G communications in oceanic, remote, and polar flight domains, it will likely remain important from safety and security perspectives to maintain a backup / alternate means of A-G communications to the primary means of communications (likely SATCOM) in these flight domains. HF or the hopping alternatives provide a diverse technical means to SATCOM for achieving long range A-G communications.

30.3 Communication Candidates Prioritization Results Summary

This subsection contains figures that summarize the prioritization of the communication candidates resulting from the analyses that were presented in Sections 30.1 and 30.2. Figure 402 and Figure 403 provide a prioritized list of the A-A communication candidates by flight domain (with and without the weighted total scores, respectively). Similarly, Figure 404 and Figure 405 provide a prioritized list of the A-G communication candidates by flight domain. In these figures, the colored shading of green, yellow, and red indicate the top, middle, and lowest tier candidates (respectively) across multiple flight domains as described in Section 30.1.4 for A-A and Section 30.2.4 for A-G candidates.

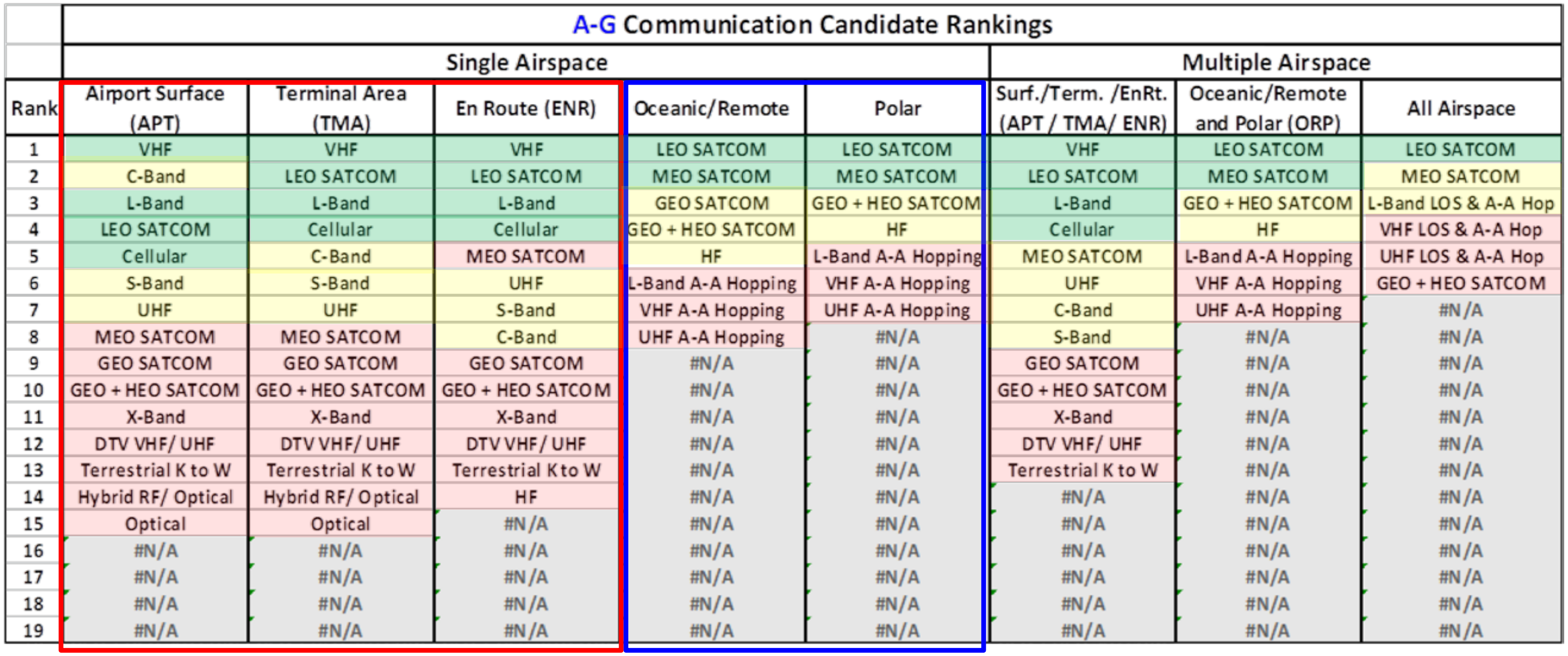


	A-A Communication Candidate Rankings							
	Single Airspace					Multiple Airspace		
Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace
1	L-Band	L-Band	L-Band	VHF	VHF	L-Band	VHF	VHF
2	C-Band	VHF	VHF	L-Band	L-Band	VHF	L-Band	L-Band
3	VHF	C-Band	C-Band	C-Band	C-Band	C-Band	C-Band	C-Band
4	S-Band	S-Band	S-Band	UHF	UHF	S-Band	UHF	UHF
5	UHF	UHF	UHF	LEO SATCOM	LEO SATCOM	UHF	LEO SATCOM	LEO SATCOM
6	LEO SATCOM	LEO SATCOM	LEO SATCOM	S-Band	S-Band	LEO SATCOM	S-Band	S-Band
7	X-Band	X-Band	X-Band	X-Band	X-Band	X-Band	X-Band	X-Band
8	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM	MEO SATCOM
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO SATCOM	GEO + HEO SATCOM	GEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	Hybrid RF/ Optical	GEO + HEO SATCOM	Hybrid RF/ Optical	Hybrid RF/ Optical
11	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Hybrid RF/ Optical	Optical	Hybrid RF/ Optical	Optical	Optical
12	Optical	Optical	Optical	Optical	#N/A	Optical	#N/A	#N/A

Figure 402 – A-A Candidate Prioritization Summary (w/o Scores)

	A-A Communication Candidate Rankings															
	Single Airspace										Multiple Airspace					
Rank	Airport Surface (APT)		Terminal Area (TMA)		En Route (ENR)		Oceanic/Remote		Polar		Surface/Term./EnRoute (APT / TMA/ ENR)		Oceanic/Remote and Polar (ORP)		All Airspace	
	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score
1	L-Band	435	L-Band	435	L-Band	435	VHF	429	VHF	429	L-Band	435	VHF	429	VHF	429
2	C-Band	434	VHF	429	VHF	429	L-Band	421	L-Band	421	VHF	429	L-Band	421	L-Band	421
3	VHF	429	C-Band	419	C-Band	410	C-Band	390	C-Band	390	C-Band	410	C-Band	390	C-Band	390
4	S-Band	394	S-Band	394	S-Band	384	UHF	378	UHF	378	S-Band	384	UHF	378	UHF	378
5	UHF	378	UHF	378	UHF	378	LEO SATCOM	371	LEO SATCOM	371	UHF	378	LEO SATCOM	371	LEO SATCOM	374
6	LEO SATCOM	371	LEO SATCOM	371	LEO SATCOM	371	S-Band	368	S-Band	368	LEO SATCOM	371	S-Band	368	S-Band	368
7	X-Band	327	X-Band	327	X-Band	327	X-Band	327	X-Band	327	X-Band	327	X-Band	327	X-Band	327
8	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	315	MEO SATCOM	326
9	GEO SATCOM	291	GEO SATCOM	294	GEO SATCOM	297	GEO SATCOM	300	GEO + HEO SATCOM	299	GEO SATCOM	302	GEO + HEO SATCOM	296	GEO + HEO SATCOM	307
10	GEO + HEO SATCOM	290	GEO + HEO SATCOM	293	GEO + HEO SATCOM	296	GEO + HEO SATCOM	299	Hybrid RF/ Optical	276	GEO + HEO SATCOM	301	Hybrid RF/ Optical	270	Hybrid RF/ Optical	276
11	Hybrid RF/ Optical	276	Hybrid RF/ Optical	276	Hybrid RF/ Optical	276	Hybrid RF/ Optical	276	Optical	251	Hybrid RF/ Optical	276	Optical	251	Optical	251
12	Optical	257	Optical	251	Optical	251	Optical	251	#N/A	#N/A	Optical	251	#N/A	#N/A	#N/A	#N/A

Figure 403 – A-A Candidate Prioritization Summary (with Weighted Scores)

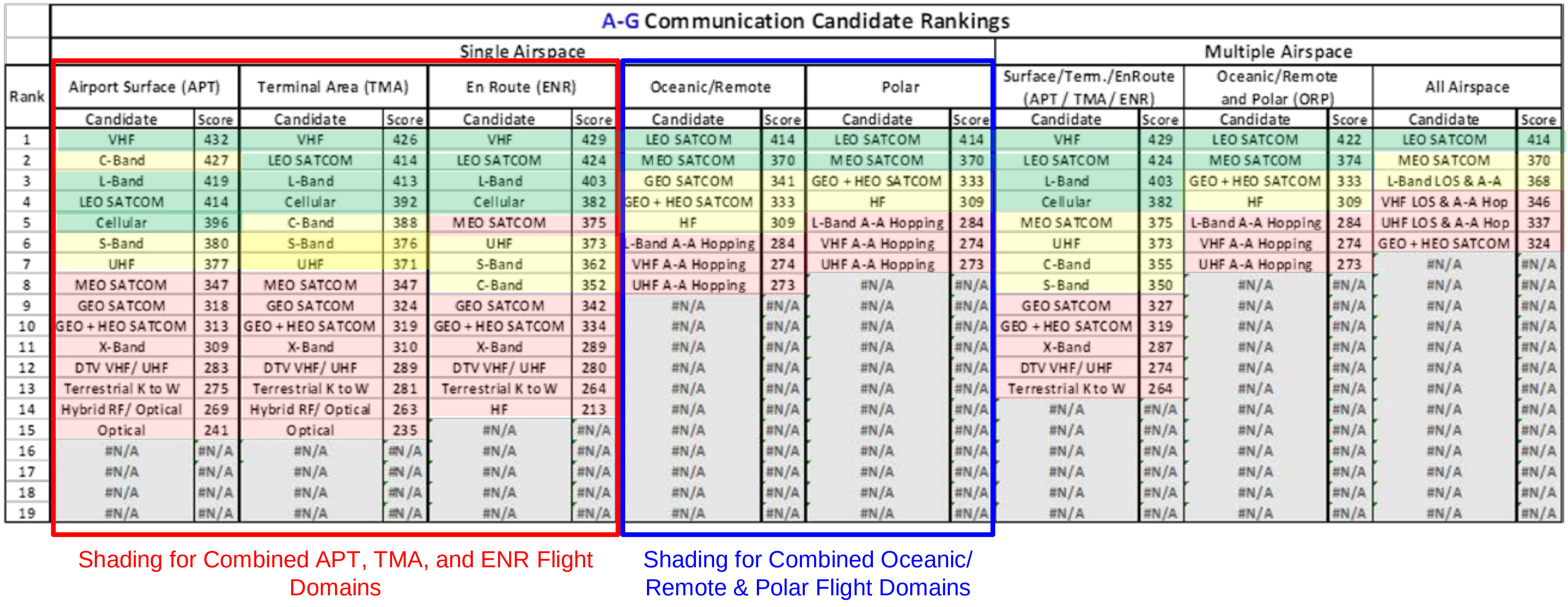


	A-G Communication Candidate Rankings							
	Single Airspace					Multiple Airspace		
Rank	Airport Surface (APT)	Terminal Area (TMA)	En Route (ENR)	Oceanic/Remote	Polar	Surf./Term. /EnRt. (APT / TMA/ ENR)	Oceanic/Remote and Polar (ORP)	All Airspace
1	VHF	VHF	VHF	LEO SATCOM	LEO SATCOM	VHF	LEO SATCOM	LEO SATCOM
2	C-Band	LEO SATCOM	LEO SATCOM	MEO SATCOM	MEO SATCOM	LEO SATCOM	MEO SATCOM	MEO SATCOM
3	L-Band	L-Band	L-Band	GEO SATCOM	GEO + HEO SATCOM	L-Band	GEO + HEO SATCOM	L-Band LOS & A-A Hop
4	LEO SATCOM	Cellular	Cellular	GEO + HEO SATCOM	HF	Cellular	HF	VHF LOS & A-A Hop
5	Cellular	C-Band	MEO SATCOM	HF	L-Band A-A Hopping	MEO SATCOM	L-Band A-A Hopping	UHF LOS & A-A Hop
6	S-Band	S-Band	UHF	L-Band A-A Hopping	VHF A-A Hopping	UHF	VHF A-A Hopping	GEO + HEO SATCOM
7	UHF	UHF	S-Band	VHF A-A Hopping	UHF A-A Hopping	C-Band	UHF A-A Hopping	#N/A
8	MEO SATCOM	MEO SATCOM	C-Band	UHF A-A Hopping	#N/A	S-Band	#N/A	#N/A
9	GEO SATCOM	GEO SATCOM	GEO SATCOM	#N/A	#N/A	GEO SATCOM	#N/A	#N/A
10	GEO + HEO SATCOM	GEO + HEO SATCOM	GEO + HEO SATCOM	#N/A	#N/A	GEO + HEO SATCOM	#N/A	#N/A
11	X-Band	X-Band	X-Band	#N/A	#N/A	X-Band	#N/A	#N/A
12	DTV VHF/ UHF	DTV VHF/ UHF	DTV VHF/ UHF	#N/A	#N/A	DTV VHF/ UHF	#N/A	#N/A
13	Terrestrial K to W	Terrestrial K to W	Terrestrial K to W	#N/A	#N/A	Terrestrial K to W	#N/A	#N/A
14	Hybrid RF/ Optical	Hybrid RF/ Optical	HF	#N/A	#N/A	#N/A	#N/A	#N/A
15	Optical	Optical	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Shading for Combined APT, TMA, and ENR Flight Domains

Shading for Combined Oceanic/ Remote & Polar Flight Domains

Figure 404 – A-G Candidate Prioritization Summary (w/o Scores)



	A-G Communication Candidate Rankings																	
	Single Airspace										Multiple Airspace							
Rank	Airport Surface (APT)		Terminal Area (TMA)		En Route (ENR)		Oceanic/Remote		Polar		Surface/Term./EnRoute (APT / TMA / ENR)		Oceanic/Remote and Polar (ORP)		All Airspace	
	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score	Candidate	Score
1	VHF	432	VHF	426	VHF	429	LEO SATCOM	414	LEO SATCOM	414	VHF	429	LEO SATCOM	422	LEO SATCOM	414
2	C-Band	427	LEO SATCOM	414	LEO SATCOM	424	MEO SATCOM	370	MEO SATCOM	370	LEO SATCOM	424	MEO SATCOM	374	MEO SATCOM	370
3	L-Band	419	L-Band	413	L-Band	403	GEO SATCOM	341	GEO + HEO SATCOM	333	L-Band	403	GEO + HEO SATCOM	333	L-Band LOS & A-A	368
4	LEO SATCOM	414	Cellular	392	Cellular	382	GEO + HEO SATCOM	333	HF	309	Cellular	382	HF	309	VHF LOS & A-A Hop	346
5	Cellular	396	C-Band	388	MEO SATCOM	375	HF	309	L-Band A-A Hopping	284	MEO SATCOM	375	L-Band A-A Hopping	284	UHF LOS & A-A Hop	337
6	S-Band	380	S-Band	376	UHF	373	L-Band A-A Hopping	284	VHF A-A Hopping	274	UHF	373	VHF A-A Hopping	274	GEO + HEO SATCOM	324
7	UHF	377	UHF	371	S-Band	362	VHF A-A Hopping	274	UHF A-A Hopping	273	C-Band	355	UHF A-A Hopping	273	#N/A	#N/A
8	MEO SATCOM	347	MEO SATCOM	347	C-Band	352	UHF A-A Hopping	273	#N/A	#N/A	S-Band	350	#N/A	#N/A	#N/A	#N/A
9	GEO SATCOM	318	GEO SATCOM	324	GEO SATCOM	342	#N/A	#N/A	#N/A	#N/A	GEO SATCOM	327	#N/A	#N/A	#N/A	#N/A
10	GEO + HEO SATCOM	313	GEO + HEO SATCOM	319	GEO + HEO SATCOM	334	#N/A	#N/A	#N/A	#N/A	GEO + HEO SATCOM	319	#N/A	#N/A	#N/A	#N/A
11	X-Band	309	X-Band	310	X-Band	289	#N/A	#N/A	#N/A	#N/A	X-Band	287	#N/A	#N/A	#N/A	#N/A
12	DTV VHF/ UHF	283	DTV VHF/ UHF	289	DTV VHF/ UHF	280	#N/A	#N/A	#N/A	#N/A	DTV VHF/ UHF	274	#N/A	#N/A	#N/A	#N/A
13	Terrestrial K to W	275	Terrestrial K to W	281	Terrestrial K to W	264	#N/A	#N/A	#N/A	#N/A	Terrestrial K to W	264	#N/A	#N/A	#N/A	#N/A
14	Hybrid RF/ Optical	269	Hybrid RF/ Optical	263	HF	213	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
15	Optical	241	Optical	235	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
16	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
17	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
18	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
19	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Shading for Combined APT, TMA, and ENR Flight Domains

Shading for Combined Oceanic/ Remote & Polar Flight Domains

Figure 405 – A-G Candidate Prioritization Summary (with Weighted Scores)

31 APPLICATIONS FEASIBLE WITH THE MOST PROMISING CANDIDATES

The section of the report identifies which of the long-term NextGen communications-enabled ATM applications are feasible with the most promising candidates. Where appropriate, references have been provided to previously submitted study reports that have identified and described the applications and straw man required communications performance (RCP) needed to enable each application in the various airspaces.

31.1 Applications and RCP

A set of 52 long-term ATM applications enabled by A-A and/or A-G communications were identified and described in Section 25.2. Figure 406 lists the applications that were identified. The set of long-term applications has been partitioned into eight groupings, including: 1) Surface Operations, 2) Surface / Terminal Area Operations, 3) Time Based Flow Management (TBFM), 4) Collaborative Air Traffic Management (CATM), 5) Separation, 6) Performance-Based Navigation (PBN), 7) Weather and NAS Flight Information Services, and 8) Other Applications / Multiple Flight Phases.

During the first part of this study, straw man Required Communications Performance (RCP) values necessary to support a broad range of ATM applications were identified (see Section 13), including many of the long-range ATM applications identified in Figure 406. The straw man RCP identified the required communications performance to support communications, navigation, and surveillance functions. *As an example, the RCP for a navigation function may define the communication requirements associated with the data broadcast function of the GNSS local area augmentation system, whereas the RCP for a surveillance function may include the communications requirements for data communications associated with ADS-B, ADS-R, and TIS-B.*

	Application #	Application / Capability
Surface Operations	1	Data Sharing
	2	Surface SA (SURF in aircraft, APT for ATC)
	3	Revised PDC via DataComm
	4	Improved Efficiency of Taxiing Operations
Surface / Terminal Area Operations	5	Ground-based Runway and/or Taxiway Alerting
	6	Simultaneous Runway Operations
	7	Closely Spaced Parallel Runway Operations (CSPO)
	8	Converging and Intersecting Runway Operations
	9	Surface SA with Indications & Alerts (SURF IA)
	10	Optimized Profile Descent (OPD)
	11	Optimized Climb
	12	Tailored Arrivals and Departures
	13	Wake Turbulence Mitigation for Arrivals / Departures
	14	GNSS/GBAS Cat. I/II/III Precision Approach
	15	Multiple Glide Slope Angle Approaches
TBFM	16	Metering/Merging/Spacing (Enroute and Terminal)
	17	Ground-Based Interval Management (GIM) (ADS-B)
	18	Delegated Interval (DI) / Interval Management
CATM	19	Flight Planning Feedback
	20	Dynamic Aircraft Rerouting - TFM
	21	Enhanced NAS Modeling, Prediction, and Planning
	22	Collaborative Decision Making (CDM)
Separation	23	Delegated Separation (DS)
	24	Airborne Self Separation (e.g., AFR)
	25	In Trail Procedures (ITP) Domestic
	26	In Trail Procedures (ITP) Oceanic / Remote / Polar
	27	Reduced Separation for Domestic Airspace
	28	Reduced Separation for Oceanic / Remote / Polar
PBN / Reduced AC Separation	29	Advanced PBN
	30	PBN including Airspace Redesign
	31	Reduced Oceanic/Remote RNP
	32	Reduced Domestic RNP
	33	Enroute PBN
Wx & Flt. Info.	34	Flight Information Services (FIS)
	35	Weather Information Services (WIS)
	36	Weather Technology in the Cockpit (WTIC)
Other Apps. / Multiple Flight Phases	37	Data Link Clearances
	38	AOC / FOC Communications
	39	Airborne Access to SWIM (AAtS)
	40	4D Trajectory Based Operations (TBO)
	41	Gate-to-Gate TBO
	42	ADS-B Air-to-Air
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.
	46	UAS in the NAS
	47	ACAS-X
	48	Traffic Situational Awareness with Alerts (TSAA)
	49	Continuous Cruise Climb/Descent
	50	Traffic Aware Strategic Aircrew Request (TASAR)
	51	Dynamic Weather Reroute
	52	New DataComm Applications

Figure 406 – List of Long-Term ATM Applications

31.2 Identification of Applications that are Feasible with the Communication Candidates

Figure 128 summarizes the A-A and A-G communication technology candidates by their ability to provide a quality of service commensurate with satisfying the required communications performance for some of the long-term NAS ATM applications identified as a function of the airspace environment. This figure is a notional simplification. Some candidates can support ATM applications in other airspace (e.g., MEO SATCOM can also support A-G communications in surface and terminal airspace environments).

		Airspace				
#	Communications Candidates	Surface	Terminal	En Route	Oceanic/Remote	Polar
A-A	Air-to-Air (A-A) Communications Candidates					
1	VHF A-A	X	X	X	X	X
2	UHF A-A	X	X	X	X	X
3	L-Band A-A	X	X	X	X	X
4	S-Band A-A	X	X	X	X	X
5	C-Band A-A	X	X	X	X	X
6	X-Band A-A	X	X	X	X	X
7	Optical A-A	X	X	X	X	X
8	Hybrid RF/Optical A-A	X	X	X	X	X
9	LEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	X
10	GEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	
11	MEO SATCOM A-A (One Hop through Satellite)	X	X	X	X	X
12	GEO + HEO SATCOM A-A (One Hop through Sat.)	X	X	X	X	X
A-G	Air-to-Ground (A-G) Communication Candidates					
1	HF A-G				X	X
2	VHF A-G	X	X	X		
3	UHF A-G	X	X	X		
4	L-Band A-G	X	X	X		
5	S-Band A-G	X	X	X		
6	C-Band A-G	X	X	X		
7	Optical A-G	X	X			
8	Hybrid RF/Optical A-G	X	X	X		
9	Terrestrial K to W Band Network (e.g., Ku Band QualComm+)	X	X	X		
10	DTV VHF/UHF Network	X	X	X		
11	Cellular Network (e.g., Aircell)	X	X	X		
12	LEO SATCOM Network (e.g., Iridium Next+)	X	X	X	X	X
13	GEO SATCOM Network with global / regional / spot beams (e.g., Inmarsat Global Xpress+, Viasat I, Hughes NextGen, Broadcast Sat. TV+)			X	X	
14	MEO SATCOM Network (e.g. GlobalStar+)			X	X	X
15	VHF A-A Hopping for long range A-G Com.				X	X
16	UHF A-A Hopping for long range A-G Com.				X	X
17	L-Band A-A Hopping for long range A-G Com.				X	X
18	X-Band A-G	X	X			
19	GEO + HEO SATCOM Network	X	X	X	X	X

Figure 407 – Notional Communication Candidates to Airspace Mapping

Figure 309 to Figure 313 identify the specific ATM applications from the list in Figure 406 that are feasible using the various A-A and A-G communications candidates. Applications have been deemed to be feasible to be supported by a communications candidate when the Actual Communications Performance (ACP) is expected to be sufficient to satisfy the RCP necessary to enable conducting the long-term ATM application in the identified airspace domain.

These figures are partitioned by applications intended to be used in the various different flight domains, whereby: Figure 309 is for the airport surface domain, Figure 310 (page 436) is for the surface/terminal area domain, Figure 311 (page 437) is for the enroute domain, Figure 312 (page 438) is for the oceanic and remote domain, and Figure 313 (page 438) is for the polar domain.

In all of these figures, the numbers in the “Air-to-Air Candidate Mapping” columns refer to the A-A candidates as numbered and identified in Figure 128 and are colored in “**red**”. Similarly, the numbers identified in the “Air-to-Ground Candidate Mapping” columns refer to the A-G candidates as numbered and identified in Figure 128 and are colored in “**blue**”.

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	**#**	**Application / Capability**	**RCP**	**Required Com. To Support Surv.**	**RCP**	**Required Com. To Support Surv.**	**Required Com. To Support Nav.**
Surface / APT	1	Data Sharing	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 18	---	---
	2	Surface SA (SURF in aircraft, APT for ATC)	---	1, 2, 3, 4, 5, 6	---	---	---
	3	Revised PDC via DataComm	---	---	2, 3, 4, 5, 6, 7, 8, 18	---	---
	4	Improved Efficiency of Taxiing Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	2, 3, 4, 5, 6, 18	---
	5	Ground-based Runway and/or Taxiway Alerting	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	9	Surface SA with Indications & Alerts (SURF IA)	---	1, 2, 3, 4, 5, 6	---	---	---
	19	Flight Planning Feedback	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 18, 19	---	---
	34	Flight Information Services (FIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	35	Weather Information Services (WIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	37	Data Link Clearances	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	38	AOC / FOC Communications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	41	Gate-to-Gate TBO	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	42	ADS-B Air-to-Air	---	1, 2, 3, 4, 5, 6	---	---	---
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	---	---	---	2, 3, 4, 5, 6, 18	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 18, 19	---	---
	46	UAS in the NAS	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	52	New DataComm Applications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---

Figure 408 – Surface / APT: Applications Feasible with Communications Candidates

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	#	Application / Capability	RCP	Required Com. To Support Surv.	RCP	Required Com. To Support Surv.	Required Com. To Support Nav.
Surface/ Terminal Area	2	Surface SA (SURF in aircraft, APT for ATC)	---	1, 2, 3, 4, 5, 6	---	---	---
	5	Ground-based Runway and/or Taxiway Alerting	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	6	Simultaneous Runway Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	7	Closely Spaced Parallel Runway Operations (CSPO)	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	8	Converging and Intersecting Runway Operations	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	9	Surface SA with Indications & Alerts (SURF IA)	---	1, 2, 3, 4, 5, 6	---	---	---
	10	Optimized Profile Descent (OPD)	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	11	Optimized Climb	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	12	Tailored Arrivals and Departures	---	---	2, 3, 4, 5, 6, 12, 18	2, 3, 4, 5, 6, 18	---
	13	Wake Turbulence Mitigation for Arrivals / Departures	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	14	GNSS/GBAS Cat. I/II/III Precision Approach	---	---	2, 3, 4, 5, 6, 18	2, 3, 4, 5, 6, 18	2, 3, 4, 5, 6, 18
	15	Multiple Glide Slope Angle Approaches	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	16	Metering/Merging/Spacing	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	---	2, 3, 4, 5, 6, 18	---
	22	Collaborative Decision Making (CDM)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	34	Flight Information Services (FIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	35	Weather Information Services (WIS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	37	Data Link Clearances	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	---	---
	38	AOC / FOC Communications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	---	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	42	ADS-B Air-to-Air	---	1, 2, 3, 4, 5, 6	---	---	---
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	---	---	---	2, 3, 4, 5, 6, 18	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 18, 19	---	---
	46	UAS in the NAS	---	1, 2, 3, 4, 5, 6	2, 3, 4, 5, 6, 7, 8, 12, 18	2, 3, 4, 5, 6, 18	---
	47	ACAS-X	---	1, 2, 3, 4, 5, 6	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3, 4, 5, 6	---	2, 3, 4, 5, 6, 18	---
	52	New DataComm Applications	---	---	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 18, 19	---	---

Figure 409 – Surface / Terminal: Candidates that Meet Application Needs

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	#	Application / Capability	RCP	Required Com. To Support Surv.	RCP	Required Com. To Support Surv.	Required Com. To Support Nav.
Enroute Domestic	16	Metering/Merging/Spacing	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	2, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14, 19	---	---
	22	Collaborative Decision Making (CDM)	---	---	2, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	25	In Trail Procedures (ITP) Domestic	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	27	Reduced Separation for Domestic Airspace	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	29	Advanced PBN	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	30	PBN including Airspace Redesign	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	32	Reduced Domestic RNP	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	33	Enroute PBN	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	34	Flight Information Services (FIS)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	35	Weather Information Services (WIS)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	37	Data Link Clearances	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	38	AOC / FOC Communications	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	42	ADS-B Air-to-Air	---	1, 2, 3	---	---	---
	43	ADS-B / TIS-B / ADS-R Air-to-Ground / Ground-to-Air	---	---	---	2, 3, 4, 5, 6	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	46	UAS in the NAS	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	47	ACAS-X	---	1, 2, 3	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3	---	2, 3, 4, 5, 6	---
	49	Continuous Cruise Climb/Descent	---	1, 2, 3	2, 3, 4, 5, 6, 12, 13, 14, 19	2, 3, 4, 5, 6	---
	50	Traffic Aware Strategic Aircrew Request (TASAR)	---	1, 2, 3	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---
	51	Dynamic Weather Reroute	---	---	2, 3, 4, 5, 6, 12, 13, 14, 19	---	---
	52	New DataComm Applications	---	---	2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 19	---	---

Figure 410 – Enroute: Candidates that Meet Application Needs

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	#	Application / Capability	RCP	Required Com. To Support Surv.	RCP	Required Com. To Support Surv.	Required Com. To Support Nav.
Enroute Oceanic / Remote	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	22	Collaborative Decision Making (CDM)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	26	In Trail Procedures (ITP)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	28	Reduced Separation for Oceanic / Remote	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	29	Advanced PBN	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	30	PBN including Airspace Redesign	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	31	Reduced Oceanic/Remote RNP	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	34	Flight Information Services (FIS)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	35	Weather Information Services (WIS)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	37	Data Link Clearances	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	38	AOC / FOC Communications	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	42	ADS-B Air-to-Air	---	1, 2, 3	---	---	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	46	UAS in the NAS					
	47	ACAS-X	---	1, 2, 3	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3	---	1, 12, 13, 14, 15, 16, 17, 19	---
	49	Continuous Cruise Climb/Descent	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	1, 12, 13, 14, 15, 16, 17, 19	---
	50	Traffic Aware Strategic Aircrew Request (TASAR)	---	1, 2, 3	1, 12, 13, 14, 15, 16, 17, 19	---	---
	51	Dynamic Weather Reroute	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---
	52	New DataComm Applications	---	---	1, 12, 13, 14, 15, 16, 17, 19	---	---

Figure 411 – Oceanic/Remote: Candidates that Meet Application Needs

			Air-to-Air Candidate Mapping		Air-to-Ground Candidate Mapping		
Airspace	#	Application / Capability	RCP	Required Com. To Support Surv.	RCP	Required Com. To Support Surv.	Required Com. To Support Nav.
Polar	17	Ground-Based Interval Management (GIM) (ADS-B)	---	---	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	18	Delegated Interval (DI) / Interval Management	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	20	Dynamic Aircraft Rerouting - TFM	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	21	Enhanced NAS Modeling, Prediction, and Planning	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	22	Collaborative Decision Making (CDM)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	23	Delegated Separation (DS)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	24	Airborne Self Separation (e.g., AFR)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	26	In Trail Procedures (ITP)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	28	Reduced Separation for Oceanic / Remote	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	29	Advanced PBN	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	30	PBN including Airspace Redesign	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	31	Reduced Oceanic/Remote RNP	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	34	Flight Information Services (FIS)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	35	Weather Information Services (WIS)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	36	Weather Technology in the Cockpit (WTIC)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	37	Data Link Clearances	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	38	AOC / FOC Communications	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	39	Airborne Access to SWIM (AAtS)	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	40	4D Trajectory Based Operations (TBO)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	42	ADS-B Air-to-Air	---	1, 2, 3	---	---	---
	44	Aircraft-to-Aircraft (A-A) Exchange of Sensed Info.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	---	---	---	---
	45	Aircraft-to-Ground (A-G) Exchange of Sensed Info.	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	46	UAS in the NAS					
	47	ACAS-X	---	1, 2, 3	---	---	---
	48	Traffic Situational Awareness with Alerts (TSAA)	---	1, 2, 3	---	1, 12, 14, 15, 16, 17, 19	---
	49	Continuous Cruise Climb/Descent	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	1, 12, 14, 15, 16, 17, 19	---
	50	Traffic Aware Strategic Aircrew Request (TASAR)	---	1, 2, 3	1, 12, 14, 15, 16, 17, 19	---	---
	51	Dynamic Weather Reroute	---	---	1, 12, 14, 15, 16, 17, 19	---	---
	52	New DataComm Applications	---	---	1, 12, 14, 15, 16, 17, 19	---	---

Figure 412 – Polar: Candidates that Meet Application Needs

32 PHASE 5 – INTERIM STUDY FINDINGS

The section of the report summarizes the interim study findings and provides a conclusion to the fifth phase of the study.

32.1 Summary of Phase 5 Interim Study Findings

Phase 5 of the study describes the findings from:

- identifying criteria for prioritizing the list of communication technology candidates from most promising to least promising,
- using the criteria to identify the most promising technology alternatives, and
- identifying which of the applications are feasible with the most promising technology candidates.

Twenty five (25) evaluation criteria as given in Figure 366 (on page 505) have been identified for the purposes of evaluating and prioritizing the communication candidates. These 25 criteria encompass a broad range of factors that have been used to evaluate the technical performance, cost, and risk of the various candidates. Descriptions of the evaluation criteria, rating scales, and weighting factors are provided in Section 29.

The twelve A-A and nineteen A-G communication candidates were analyzed for their ability to support the ATM communication needs in all the various flight domains, including surface, terminal area, enroute, oceanic/remote, and polar. The assessments were done for each of the five individual flight domains, as well as for three combinations of multiple flight domains consisting of: 1) surface, terminal area, and enroute; 2) oceanic, remote, and polar; and 3) all flight domains. These assessments resulted in the completion of 16 evaluation matrices, 8 for the A-A candidates and 8 for the A-G candidates; one evaluation matrix for each of the flight domain(s) under investigation as are provided in Section 30. In each of these assessments, the individual ratings from the evaluations across each criterion were multiplied by the weighting factor associated with the criterion and summed over all the evaluation criteria to obtain a "total score" for each candidate in each of the flight domain(s) under investigation. These total scores were then used to prioritize the communications candidates by flight domain, whereby a higher total weighted score represents a higher priority candidate in the flight domain(s) under investigation.

Figure 403 (on page 549) summarizes the prioritized ranking of the identified A-A communication candidates by flight domain. Similarly, Figure 405 (on page 551) summarizes the prioritized ranking of the identified A-G candidates. Section 31 of this report identifies which of the identified 52 long-term NextGen and beyond NAS applications are feasible with the various A-A and A-G communications candidates.

While this study has attempted to appropriately prioritize the communication candidates in a manner consistent with the expected long-term NAS communication needs while balancing the collective interests of all the aviation stakeholders, it should be noted that these candidate prioritizations are subject to change when different evaluation criteria, assumptions, communications requirements, or weighting factors are used in the assessment process.

32.2 Interim Study Report Conclusion

This concludes the description of Phase 5 of the study (presented in Sections 29 to 32 of this report) which was originally documented in the fifth in a series of five interim reports that were completed during the execution of this study to identify and evaluate air-to-air and air-to-ground candidates for meeting the long-term evolving needs of the National Airspace System during the modernization time horizon of 50 years.

An additional follow-on study is being planned to further identify and evaluate communications candidates for use in very low and low altitude UAS Air Traffic Management applications. Beyond this follow-on investigation, additional R&D is recommended to more comprehensively evaluate the air-to-air and air-to-ground communication candidates for meeting the long-term needs of the National Airspace System in a cost effective manner.

33 STUDY CONCLUSIONS AND RECOMMENDATIONS

This section provides a conclusion to the study and provides recommendations for additional studies relevant to future NAS communications.

33.1 Study Conclusion

The Next Generation and beyond air transportation system will require a secure, efficient, flexible, scalable, and robust communications system along with a fault tolerant infrastructure. The modernization of NAS communications outlined by NextGen and SESAR initiates the evolutionary path towards a data centric environment that will enable significant performance gains, cost reductions, and capacity increases to support the needs of aircraft operators, service providers, and airspace users.

This report has described the results of a two-year study made by employees of Rockwell Collins under NRA contract to NASA. The study team has identified, investigated, and evaluated communications technologies and their architectures, cost, security performance, spectrum, technology maturity, and viability as well as identified and assessed the ability of the communications technologies to meet the future NAS communications needs by evaluating the candidates against a set of potential future more demanding air traffic management applications.

While no one single communications data link technology can meet all the expected future A-A and A-G communications requirements for the NAS, the outlook to be able to address the NAS communications needs gaps is very optimistic. RF bands already allocated for aviation use can be improved by invoking a long term evolutionary process to update (e.g., VHF Comm) and re-allocate CNS aviation spectrum (e.g., DME and VOR) to meet the evolving needs of the NAS through more efficient use of the spectrum. Additionally, LOS air-to-ground and SATCOM communications in the L through W bands may offer the opportunity for spatial orthogonal spectrum sharing. While spectrum sharing presents many technical, regulatory, political, and certification challenges today, these barriers are expected to be broken down in the future.

Use of bands from C through W suitable for short and medium range communications promise small array antenna technologies that readily can be readily installed on most aircraft including UAVs. Over the next 50 years SATCOM system providers are anticipated to populate most of the remaining orbital options as the demand for mobile broadband surges. Low latency and very low cost, high bandwidth satellite communications that include switching and processing onboard the satellite will enable new applications, including beyond line of sight aircraft-to-aircraft communications to enable, for example, improved real-time flight optimization. Many of the new communications candidates could, if matured and implemented, bring significant enhancements to surface and terminal area communications (e.g., extended AeroMACS / WiMAX).

A combination of various communication technologies will be needed to address the diverse aeronautical communications requirements across all the operational flight domains. A key enabler to achieving modernization in a cost effective manner is through the use of advanced software defined radio systems capable of integrating multiple capabilities and delivering a high degree of flexibility and cost savings to all users.

The implementation of future systems that can meet aviation's demands for reliable and efficient communications will require a coordinated and well managed distributed investment that balances the cost of airborne, ground, and satellite components. Cost analysis and benefit investigation reveals the potential to take advantage of commercial communication networks to meet the communications needs for many applications rather than implementing custom aviation communications solutions. Aviation will likely have a difficult time acquiring significantly more spectrum allocations and will need to modernize their CNS systems to be more spectrally efficient to meet future demands. Technology advances will enable more efficient use of spectrum. Systems should be designed to better accommodate change. Additionally, this study has identified that modernization of communications infrastructure will require coordinated synchronization of operational improvements with technology deployments to maximize benefits.

33.2 Recommendations for Additional Study

Additional R&D is recommended to more comprehensively identify and evaluate communication candidates for meeting the long-term needs of the NAS. It is important that such studies are done within the next few years to ensure that the planned investments to upgrade the NAS communications are on a path that is consistent with meeting the long-term needs. Specific areas of recommended additional study are identified in the following subsections.

33.2.1 Future Study Recommendation: Communications to Support UAS in the NAS Operations

Unmanned Aircraft Systems (UAS) may have a far-reaching impact on future CNS and ATM systems. Therefore, it is recommended that a detailed study be initiated as soon as possible to assess the impact of low (below ≈1200 feet) and very low (below ≈400 feet) altitude UAS on future CNS and ATM systems. Such a study should consider a range of possible UAS concepts of operation and operational environments (e.g., remote places, suburbs, densely populated areas, major cities with tall buildings), and the possibility of harmonization strategies for UAS command and control links with traditional ATC communications as well as the general integration of UAS information used for situational awareness of the pilots and controllers.

33.2.2 Future Study Recommendation: NAS 2065 Concept of Operations

The required long-term NAS aeronautical communications needs are highly dependent upon the operating environments, intended applications, and number of users that need to be supported in all of the various operating environments. There are many different visions for how the NAS will change over a 50 year modernization time period, including for example those characterized as: a) modest evolution (e.g., less than 3X growth in the number of aircraft operations with modest introduction of new vehicles into the airspace), b) moderate evolution (e.g., 3X to 10X growth, perhaps with a few new vehicles to integrate into the airspace), and c) aggressive evolution (e.g., 10X to 1000X or more growth, with a significant growth in UAVs and personal aircraft that need to be integrated into the NAS). Furthermore, the operating paradigm of the ATM system has a large role in the number and types of communications needed [e.g., from air traffic controllers that are actively “controlling” flight trajectories, to air traffic managers that are delegating trajectory control within specified limits with management oversight, to autonomous self separation where ATM is distributed among the airspace users]. The communications needed highly depend upon the future state of the NAS. It is important to identify the NAS communications needed to support a range of possible NAS future states.

A NAS 2065 study should be initiated with the objectives of:

- Developing several (nominally 3) long-term NAS ConOps visions that bound the range for how the NAS may evolve over the next 50 years,

- Developing the CNS requirements to support the range of long-term NAS ConOps visions, and
- Developing and analyzing CNS technologies / infrastructure / architectures capable of meeting the CNS requirements associated with the range of long-term visions.

33.2.3 Future Study Recommendation: Dynamic Spectrum Allocation

RF spectrum is a very limited finite resource that is essential to aviation and demand for it is increasing over time from both aviation and non-aviation users. A study should be undertaken to: a) analyze the availability of spectrum to support aeronautical applications, b) identify how aviation can more efficiently utilize spectrum, and c) develop a technical approach for dynamic, on demand, allocation of spectrum.

33.2.4 Future Study Recommendation: Dynamic Communications Routing

The aviation network of the future needs to be capable of dynamically transferring information across multiple communications connectivity alternatives and support simultaneous traffic flows in a manner that meets the various required quality of service requirements appropriate to the applications being supported. To meet the communications quality of service needs for the NAS, future aeronautical networks must support sophisticated dynamic communications routing that they can converge quickly with little system overhead. A study to identify robust routing algorithms appropriate for aviation applications and standardization should be undertaken. The study should encompass the management of multiple links for seem less inter-link handovers and leverage currently evolving IP mobility standards.

33.2.5 Future Study Recommendation: Radical NAS Operational Concepts CNS Impact Study

A study should be initiated to identify and investigate radically different NAS operational concepts and determine how such concepts of operation would impact the NAS CNS requirements and identify CNS technologies and systems including infrastructure and architecture needed to realize the identified radically different operational concepts. Examples of radically different operational concepts that could be subjects of further study include:

- Autonomous Flight Rules (AFR) self separation
- Elimination of “all” ground Air Traffic Control for distributed aircraft-centric ATM
- Processing free aircraft (i.e., virtually all processing is done on the ground)
- Widespread use of personal aircraft that can take off from virtually anywhere
- Time of arrival-based Air Traffic Management

33.2.6 Future Study Recommendation: NAS CNS Security

The initial security analysis completed as part of this study provides a high level assessment of the security vulnerabilities, threats, risks, and potential mitigations for NAS communications. A future study should be undertaken to expand this initial analysis to more fully address the security vulnerabilities, threats, and risks to future aeronautical CNS systems and to expand upon and define a set of recommended mitigation strategies. Additional research and development into aviation security vulnerabilities, threats, risks, and mitigations that take into account the full set of stakeholder issues and holistically address the NAS security challenges (more than just communications security) is needed. Finding security solutions that will be viable for all aviation stakeholders will be a challenge. Research needs to be completed to more fully develop measures of security performance that could be incorporated (if appropriate) into the specified levels of required CNS performance [i.e., Required Communications Performance (RCP), Required Navigation Performance (RNP), and Required Surveillance Performance (RSP)].

34 APPENDIX A: LIST OF ACRONYMS AND ABBREVIATIONS

Acronym or Abbreviation	**Definition**
A-A	Aircraft-to-Aircraft
A-G	Aircraft-to-Ground
A-G-S	Airborne / Ground / Satellite
AAtS	Airborne Access to SWIM
ABAS	Aircraft Based Augmentation System
AC or A/C	Aircraft
ACAD	Assured Collision Avoidance Distance
ACARS	Aircraft Communications Addressing and Reporting System
ACAS	Airborne Collision Avoidance System, or AirCraft Analytical System
ACAS-X	Airborne Collision Avoidance System – Next Generation
ACL	Application Capability Level
ACP	Actual Communications Performance, or Audio Control Panel
ADC	Analog-to-Digital Converter
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
ADF	Automatic Direction Finding
AEEC	Airlines Electronic Engineering Committee
AeroMACS	Aeronautical Mobile Airport Communications System
AFB	Air Force Base
AFR	Autonomous Flight Rules
AGL	Above Ground Level
AIAA	American Institute of Aeronautics and Astronautics
AIM	Aircraft Information Management, or Aeronautical Information Management System
AIRB	Basic Airborne Situational Awareness
AIRMET	Airmen’s Meteorological Information
AIS	Aeronautical Information Services
ALE	Airborne Link Establishment
ALRT	Alert
AM	Amplitude Modulation
AMCS	Aeronautical Mobile Communications Services
AMS(R)S	Aeronautical Mobile-Satellite (Route) Services
ANSD	Assured Normal Separation Distance
ANSP	Air Navigation Service Providers
ANTARES	AeroNauTicAl REsources Satellite-based
AOC	Aeronautical Operational Control
APNT	Alternative PNT
Approx.	Approximate
APT	Airport, or Airport Surface Situational Awareness Application for ATC
AR	Authorization Required (e.g., RNP AR)
ARINC	Aeronautical Radio Incorporated

Acronym or Abbreviation	**Definition**
ARNS	Aeronautical Radio Navigation Service
ARR	Arrival
ARTCC	Air Route Traffic Control Center
ASAS	Aircraft Separation Assistance System
ASIC	Application Specific Integrated Circuit
ASS	Aircraft Self Separation
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
ATCSCC	Air Traffic Control System Command Center
ATIS	Automated Terminal Information System
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
ATOP	Advanced Technologies & Oceanic Procedures
ATPA	Automated Terminal Proximity Alert
ATS	Air Traffic Services, or Air Transport Systems
ATSSA	ADS-B Traffic Surveillance Systems and Applications
AT&T	American Multinational Telecommunications Corporation, formerly known as American Telephone and Telegraph Company
AWS	Advanced Wireless Services
A(PROVISION)	Availability of the specified provision
A(USE)	Availability of Use
BEP	Back End Processor
BLOS	Beyond Line of Sight
BRS	Business and Regional Systems
C	Continuity
CAA	Civil Aviation Authorities
CAASD	Center for Advanced Aviation System Development
CAT I	Category I Precision Approach
CAT II	Category II Precision Approach
CAT III	Category III Precision Approach
CATM	Collaborative Air Traffic Management
CAVS	CDTI-Assisted Visual Separation
CAZ	Conflict Avoidance Zone
CD	Conflict Detection
CDA	Continuous Descent Approach
CDM	Collaborative Decision Making
CDMA	Code Division Multiple Access
CDTI	Cockpit Display of Traffic Information
CDZ	Conflict Detection Zone
CEDS	CDTI Enabled Delegated Separation
CMU	Communications Management Unit
CNPC	Control Non-Payload Communications
CO and CS	Contracting Officer
COCR	Communications Operating Concept and Requirements
Co-I	Co-Investigator

Acronym or Abbreviation	**Definition**
Com50	Communications 50 Year Study
comm	Communications
ConOps	Concept of Operations
CONUS	Continental United States
COTR	Contracting Officer Technical Representative
COTS	Commercial Off The Shelf
CP	Conflict Prediction
CPDLC	Controller-Pilot Data Link Communications
CPFSK	Continuous Phase Frequency Shift Keying
CPL	Coupler
CR	Conflict Resolution
CRC	Cyclic Redundancy Check
CSPA	Closely Spaced Parallel Approach
CSPO	Closely Spaced Parallel approach Operation
CSPR	Closely Spaced Parallel Runway
CSS	Common Support Services
CTAF	Common Traffic Advisory Frequency
D	Dimensional
D8PSK	Differential 8-state Phase Shift Keying
DACS	Digital Access Carrier System
DARPA	Defense Advanced Research Products Agency
DASC	Digital Avionics Systems Conference
DATIS	Digital Automated Terminal Information System
DCSPA	Dependent Closely Space Parallel Approach
DEP	Departure
DGPS	Differential GPS
DI	Delegated Interval
DM	Downlink Message
DME	Distance Measuring Equipment
DMS	Data link Management System
DoD	Department of Defense
DoHS	Department of Homeland Security
DOS	Denial of Service
DOT	Department of Transportation
DPSK	Differential Phase Shift Keying
DRNP	Dynamic RNP
DS	Delegated Separation
DSB	Double Side Band
DSB-AM	Double Side Band-Amplitude Modulation
DSR	Direct Sampling Radio
DSP	Data Link Service Provider
DWR	Dynamic Weather Rerouting
EFB	Electronic Flight Bag
EFVS	Enhanced Flight Vision System
EGNOS	European Geostationary Navigation Overlay Service
EHF	Extremely High Frequency
ELF	Extremely Low Frequency

Acronym or Abbreviation	**Definition**
ELM	Extended Length Message
ELT	Emergency Locator Transmitter
EM	Electromagnetic
ENOB	Effective Number of Bits
ENR	Enroute
ER	Enroute
ERAM	EnRoute Automation Modernization
ES	Extended Squitter
ESA	European Space Agency
ET	Transaction Expiration Time
EUROCAE	European Organization for Civil Aviation Equipment
EVAcq	Enhanced Visual Acquisition
EVDO	Evolution Data Optimized (wireless network standard)
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FANS	Future Air Navigation System
FCC	Federal Communications Commission
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FEP	Front End Processor
FILGAPP	‘Filling the Gaps’ in GNSS Advanced Procedures and Operations
FIM	Flight-deck Interval Management
FIM-S	Flight-deck Interval Management-Spacing
FIM-DI	Flight-deck Interval Management-Delegated Interval
FIPS	Federal Information Processing Standards
FIS-B	Flight Information Services – Broadcast
FL	Forward Link
FLIPSY	Flight Plan Consistency
FOC	Flight Operational Control
FPGA	Field Programmable Gate Array
FPOA	Field Programmable Object Array
FSPL	Free Space Path Loss
FSS	Fixed Satellite Services, or Flight Service Station
ft	feet
F&E	Facilities and Equipment
G-A	Ground-to-Aircraft
GAMA	General Aviation Manufacturers Association
GEO	Geostationary Earth Orbit
GES	Ground-Earth Station
GFSK	Gaussian Frequency Shift Keying
GIM	Ground Interval Management
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema, or Global Navigation Satellite System
GLS	GNSS Landing System
GNSS	Global Navigation Satellite System

Acronym or Abbreviation	**Definition**
GPS	Global Positioning System
GRS	Glenn Research Center
GSM	Global System for Mobile communications
G/T	Antenna gain-to-noise temperature
H	High
HAP	High Altitude Platform
HEO	High Earth Orbit
HF	High Frequency
HFDL	High Frequency Data Link
HGA	High Gain Antenna
HMI	Hazardously Misleading Information, or Human Machine Interface
HPA	High Power Amplifier
HSPA	High Speed Packet Access
HST	High Speed Transceiver
HW	Hardware
Hz	Hertz
I	Integrity
I-3	Inmarsat – generation 3 satellites
I-4	Inmarsat – generation 4 satellites
I-5	Inmarsat – generation 5 satellites
IAF	Initial Approach Fix
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
iCNS	Integrated Communications, Navigation, and Surveillance
ICSPA	Independent Closely Space Parallel Approach
ID	Identifier
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFE	In Flight Entertainment
IFF	Identification Friend of Foe
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IM	Interval Management
IMC	Instrument Meteorological Conditions
IM DO	IM Departure Operations
IM DSA1	IM Dependent Staggered Approaches with One Target
IM DSA2	IM Dependent Staggered Approaches with Two Targets
IM PA	IM Dependent Paired Approach
Int.	Integration
IOC	Initial Operational Capability
IP	Internet Protocol
ISM	Industrial, Scientific, and Medical Bands
ISS	International & Services Solution
IT	Information Technology
ITP	In-Trail Procedure
ITU	International Telecommunications Union

Acronym or Abbreviation	**Definition**
ITU-R	ITU – Radio-communications Sector
ITU-T	ITU – Telecommunication Standardization Sector
IUPS	Integrated Uninterruptable Power Supply
IWP	Integrated Work Plan
JPDO	Joint Program Development Office
JPS	Journal Processing System
JHUAPL	Johns Hopkins University Applied Physics Laboratory
L	Low
L1	First Civil Frequency on GPS
L5	Second Civil Frequency on GPS
LAAS	Local Area Augmentation System
LEO	Low Earth Orbit
LED	Lead (aircraft)
LF	Low Frequency
LO	Local Oscillator
LOS	Line of Sight, or Loss of Service
LPV	Localizer Performance with Vertical guidance
LRRA	Low Range Radio Altimeter
LTE	Long Term Evolution
LUF	Lowest Usable Frequency
M	Moderate
MAC	Media Access Control
MASPS	Minimum Aviation System Performance Standards
MEO	Medium Earth Orbit
METAR	Meteorological Aviation Routine Weather Report
MF	Medium Frequency
MIMO	Multiple Input / Multiple Output
MISO	Multiple Input / Single Output
MIT	Massachusetts Institute of Technology
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standards
MPSK	M-ary Phase Shift Keying
MSK	Minimum Shift Keying
MSL	Mean Sea Level
MUF	Maximum Usable Frequency
NA (or #NA)	Not Applicable
NAC	NextGen Advisory Committee
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAID	Navigation Aid
NDB	Non-Directional Beacon
NEXRAD	Next-Generation Radar
NextGen	Next Generation, typically refers to the Next Generation Air Transportation System
NEXCOM	Next-Generation Communications
NEXTCOM	Next-Generation Air-to-Ground Communications

Acronym or Abbreviation	**Definition**
NIR	Network Interface Router
NIST	National Institute of Standards and Technology
NLR	Netherlands Aerospace Labs
NM	Nautical Mile
NMAC	Near Mid-Air Collision
NOTAM	Notice to Airmen
NPA	Non-Precision Approach (lateral guidance only)
NPRM	Notice of Proposed Rulemaking
NR	Not Rated
NRA	NASA Research Announcement
NTIA	National Telecommunications and Information Administration
NTO	New Technology Officer
NWP	NextGen Weather Processor
N/S	North/South
OAPM	Optimization of Airspace and Procedures in the Metroplex
OCXO	Oven-Controlled Crystal Oscillators
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OI	Operational Improvement
OMO	One-Minute Observations
OPD	Optimized Profile Descent
ORM	Operational Risk Management
OSED	Operational Services and Environmental Description
OSI	Open Systems Interconnection
PA	Precision Approach, or Prevention Advisory
PBN	Performance Based Navigation
PDC	Pre-Departure Clearance
PI	Principal Investigator
PIC	Pilot in Command
PIREP	Pilot Report
PLP	Physical Layer Pipe
PM	Program Manager
PNT	Position / Navigation / Timing
POA	Plain Old ACARS (i.e., protocols prior to VDL-M2)
PPM	Pulse Position Modulation
PP&C	Program Pricing and Control
PRN	Pseudo Random Noise
PSK	Phase Shift Keying
PSR	Primary Surveillance Radar
QAM	Quadrature Amplitude Modulation
QNT	Quint Networking Technology
RA	Resolution Advisory
RASP	Required ATM Services and Performance
RCP	Required Communication Performance
RCTP	Required Communication Technical Performance

Acronym or Abbreviation	**Definition**
RE&D	Research, Engineering, and Development
REF	Reference (Aircraft)
RESP	Response
Rev	Revision
RF	Radio Frequency
RFI	Radio Frequency Interference
RFU	Radio Frequency Unit
RL	Reverse Link
RMS	Root Mean Square
RNP	Required Navigation Performance
RNAV	Area Navigation
ROM	Rough Order of Magnitude
RSP	Required Surveillance Performance
RTA	Required Time of Arrival
RTCA	No longer an acronym, RTCA, Inc. is the name of a corporation, formerly named “Radio Technical Commission for Aeronautics”
RTSP	Required Total System Performance
RTU	Radio Tuning Unit
RVR	Runway Visual Range
RVSM	Reduced Vertical Separation Minima
RWY	Runway
Rx	Receive or Receiver
R&D	Research and Development
s	seconds
SAE	Society of Automotive Engineers
SARPs	Standards and Recommended Practices
SATCOM	Satellite Communications
SBAS	Satellite Based Augmentation System
SBD	Short Burst Data
SC	Special Committee, or Security Categorization
SCC	Satellite Communications Center
SDU	Satellite Data Unit
SESAR	Single European Sky ATM Research
SHF	Super High Frequency
SIA	Satellite Industry Association
SIGMET	Significant Meteorological Information
SIMO	Single Input / Multiple Output
SIS	Signal in space
SITA	Société Internationale de Télécommunications Aéronautiques
SLC	Switched Local Circuit
SLF	Super Low Frequency
SME	Subject Matter Expert
SMS	Short Message Service
SOC	Satellite Operations Center
SOIA	Simultaneous Offset Instrument Approach

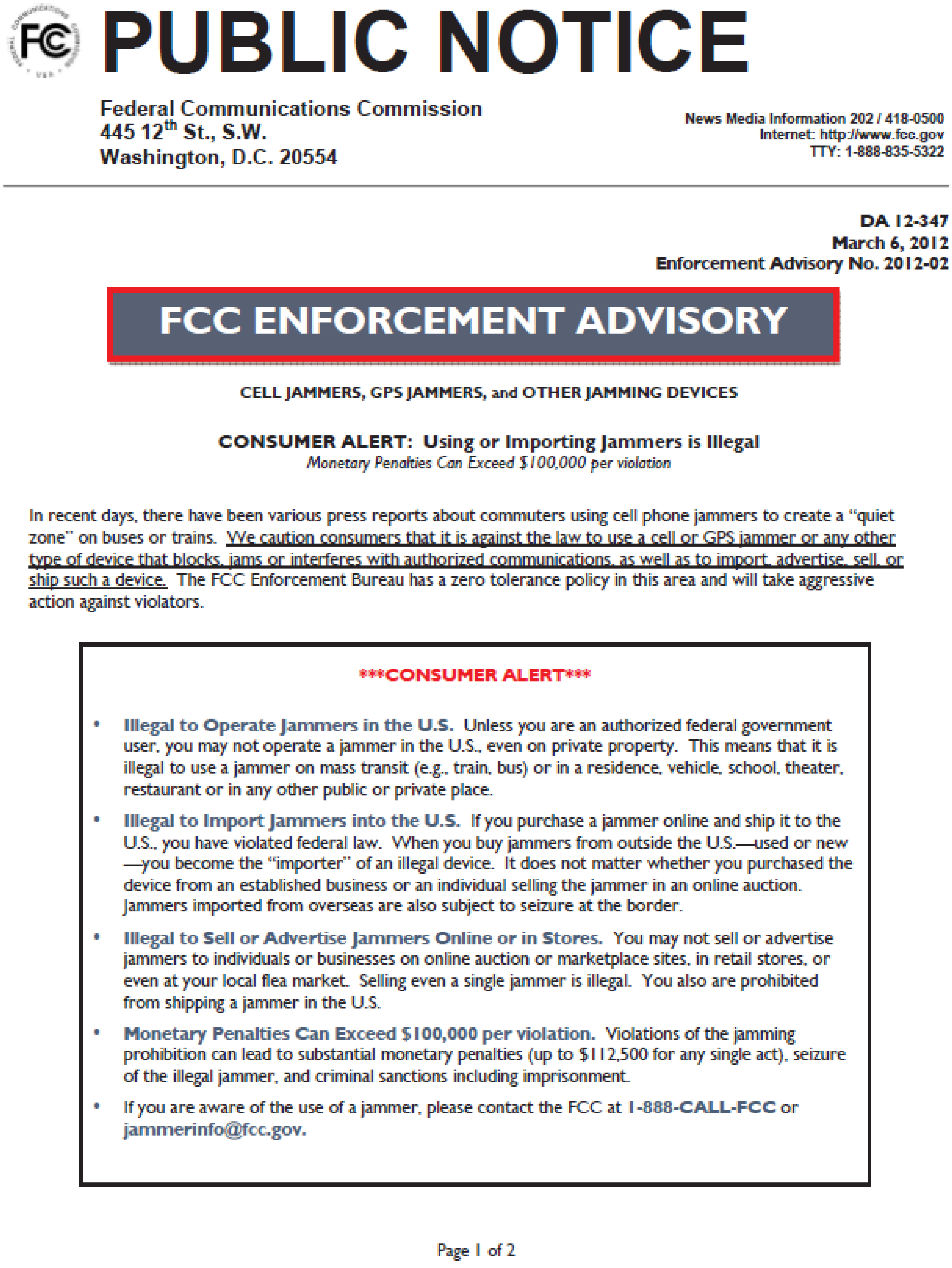
Acronym or Abbreviation	**Definition**
SOL	Safety of Life
SOW	Statement of Work
SP	Special Publication
SPR	Safety and Performance Requirements
SRT	Satellite Receiver/Transmitter
SS	Showstopper
SSB	Single Side Band
SSR	Secondary Surveillance Radar
STARS	Standard Terminal Automation Replacement System
STDMA	Self-organizing Time Division Multiple Access
SUA	Special Use Airspace
SURF	Surface Situational Awareness
SURF-IA	Surface Situational Awareness with Indications & Alerts
SV	Service Volume
SW	Software
SWaP	Size, Weight, and Power
SWaP + C	Size, Weight, and Power plus Cost
SWIM	System Wide Information Management
TA	Traffic Advisory
TAF	Terminal Aerodrome Forecast
TASAR	Traffic Aware Strategic Aircrew Request
TBO	Trajectory Based Operations
TBFM	Time Based Flow Management
TCAS	Traffic Alert and Collision Avoidance System
TCXO	Temperature Compensated Crystal Oscillators
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TFDM	Terminal Flight Data Manager
TFM	Trajectory Flow Management
TFMS	Traffic Flow Management System
THF	Tremendously High Frequency
TIS-B	Traffic Information Services - Broadcast
TLF	Tremendously Low Frequency
TM	Technical Monitor
TMA	Terminal Area
TMU	Trajectory Management Unit
TP	Technical Paper
TQL	Transmit Quality Level
TRACON	Terminal Radar Approach Control
TRL	Technology Readiness Level, or Trail Aircraft
TRN	Transaction
TSAA	Traffic Situational Awareness with Alerts
TSO	Technical Standard Order
TT	Transaction Time
TTA	Time to Alert
TTNT	Tactical Targeting Network Technology
Tx	Transmit or Transmitter

Acronym or Abbreviation	**Definition**
UAT	Universal Access Transceiver
UAS	Unmanned Air System
UAV	Unmanned Air Vehicle
UHF	Ultra High Frequency
ULF	Ultra Low Frequency
UM	Uplink Message
UNII	Unlicensed National Information Infrastructure
US	United States
UV	Ultra Violet
VDB	VHF Data Broadcast
VDL	VHF Data Link
VDL-M2	VHF Data Link – Mode 2
VDL-M4	VHF Data Link – Mode 4
VFR	Visual Flight Rules
VHDR	Very High Data Rate
VHF	Very High Frequency
VHFA	Very High Frequency Antenna
VLF	Very Low Frequency
VMC	Visual Meteorological Conditions
VoIP	Voice over IP
VOLMET	Volume Meteorological
VOR	VHF Omni-directional Range
VSA	Visual Separation on Approach
VSB	Vestigial Sideband Modulation
VTOL	Vertical Take Off and Landing (aircraft)
WAN	Wide Area Network
WATRS	West Atlantic Route System
WILCO	Will Comply
WiMAX	Worldwide Interoperability for Microwave Access
WIS	Weather Information Services
WG	Working Group
WTIC	Weather Technology In the Cockpit
Wx	Weather
WxR	Weather Radar
X.25	ITU-T standard protocol suite for packed switched WAN communications
ZIF	Zero Intermediate Frequency
1090ES	1090 MHz Extended Squitter
2D	Two Dimensional
2DT	Two Dimensional Trajectory
3D	Three Dimensional
3DT	Three Dimensional Trajectory
4D	Four Dimensional
4DT	Four Dimensional Trajectory
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation

35 APPENDIX B: PUBLIC NOTICE – FCC ENFORCEMENT ADVISORY FOR JAMMING DEVICES

This appendix provides a copy of the two page Federal Communications Commission (FCC) public notice regarding the enforcement for Jamming Devices dated March 6, 2012. See Figure 413 and Figure 414 (provided on the following two pages).

This notice is an FCC enforcement advisory informing the public that it is against the law to intentionally interfere with authorized communications, as well as to import, advertise, sell, or ship such devices. It is also to inform potential perpetrators that there may be substantial monetary penalties and criminal sanctions including imprisonment.



PUBLIC NOTICE

Federal Communications Commission
445 12th St., S.W.
Washington, D.C. 20554

News Media Information 202 / 418-0500
Internet: http://www.fcc.gov
TTY: 1-888-835-5322

DA 12-347
March 6, 2012
Enforcement Advisory No. 2012-02

FCC ENFORCEMENT ADVISORY

CELL JAMMERS, GPS JAMMERS, and OTHER JAMMING DEVICES

CONSUMER ALERT: Using or Importing Jammers is Illegal

Monetary Penalties Can Exceed $100,000 per violation

In recent days, there have been various press reports about commuters using cell phone jammers to create a "quiet zone" on buses or trains. We caution consumers that it is against the law to use a cell or GPS jammer or any other type of device that blocks, jams or interferes with authorized communications, as well as to import, advertise, sell, or ship such a device. The FCC Enforcement Bureau has a zero tolerance policy in this area and will take aggressive action against violators.

*****CONSUMER ALERT*****

- **Illegal to Operate Jammers in the U.S.** Unless you are an authorized federal government user, you may not operate a jammer in the U.S., even on private property. This means that it is illegal to use a jammer on mass transit (e.g., train, bus) or in a residence, vehicle, school, theater, restaurant or in any other public or private place.
- **Illegal to Import Jammers into the U.S.** If you purchase a jammer online and ship it to the U.S., you have violated federal law. When you buy jammers from outside the U.S.—used or new—you become the "importer" of an illegal device. It does not matter whether you purchased the device from an established business or an individual selling the jammer in an online auction. Jammers imported from overseas are also subject to seizure at the border.
- **Illegal to Sell or Advertise Jammers Online or in Stores.** You may not sell or advertise jammers to individuals or businesses on online auction or marketplace sites, in retail stores, or even at your local flea market. Selling even a single jammer is illegal. You also are prohibited from shipping a jammer in the U.S.
- **Monetary Penalties Can Exceed $100,000 per violation.** Violations of the jamming prohibition can lead to substantial monetary penalties (up to $112,500 for any single act), seizure of the illegal jammer, and criminal sanctions including imprisonment.
- If you are aware of the use of a jammer, please contact the FCC at **1-888-CALL-FCC** or **jammerinfo@fcc.gov.**

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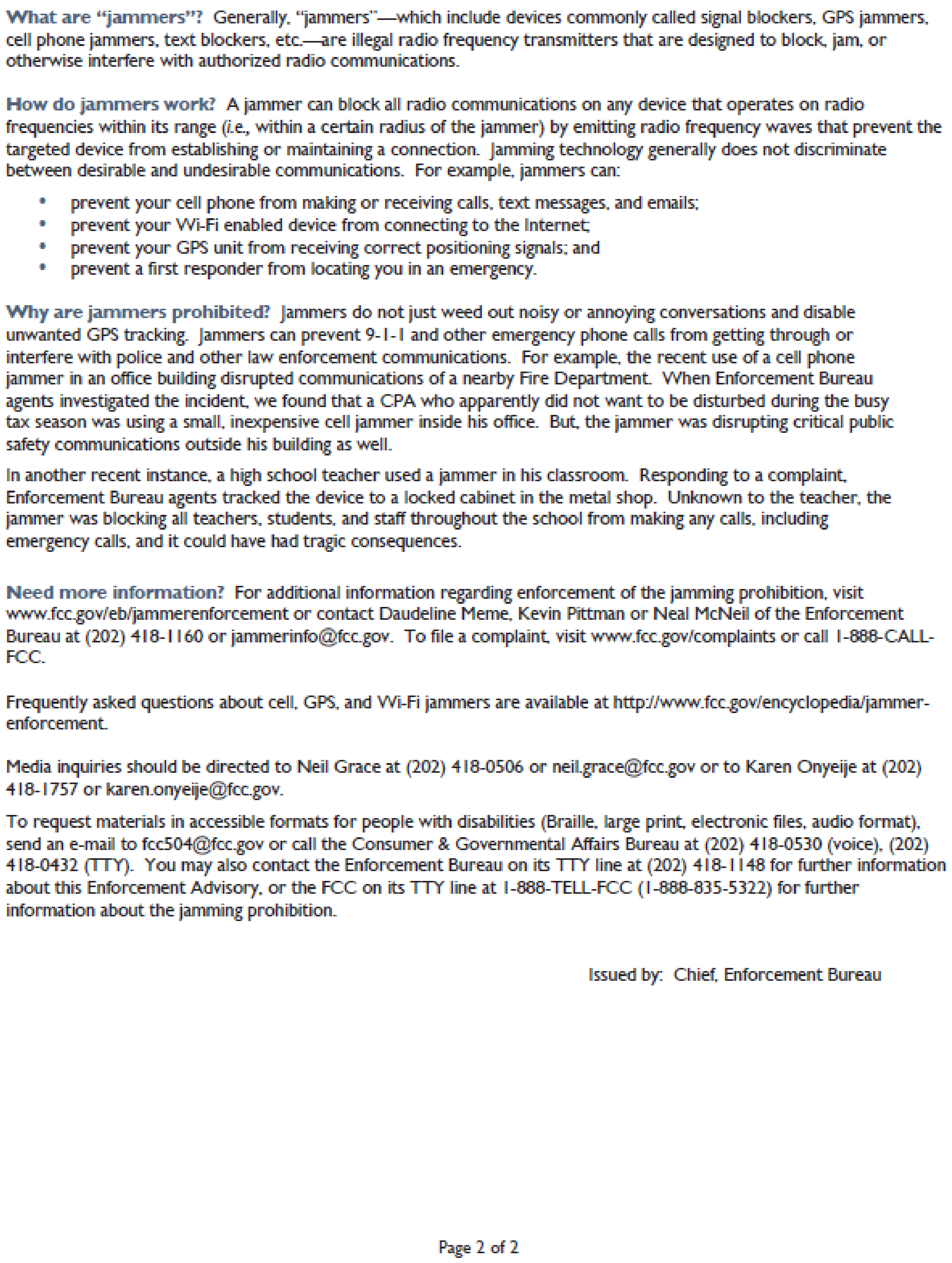
Figure 413 – FCC Public Notice on Jamming Devices (Page 1 of 2)



What are "jammers"? Generally, "jammers"—which include devices commonly called signal blockers, GPS jammers, cell phone jammers, text blockers, etc.—are illegal radio frequency transmitters that are designed to block, jam, or otherwise interfere with authorized radio communications.

How do jammers work? A jammer can block all radio communications on any device that operates on radio frequencies within its range (i.e., within a certain radius of the jammer) by emitting radio frequency waves that prevent the targeted device from establishing or maintaining a connection. Jamming technology generally does not discriminate between desirable and undesirable communications. For example, jammers can:

- prevent your cell phone from making or receiving calls, text messages, and emails;
- prevent your Wi-Fi enabled device from connecting to the Internet;
- prevent your GPS unit from receiving correct positioning signals; and
- prevent a first responder from locating you in an emergency.

Why are jammers prohibited? Jammers do not just weed out noisy or annoying conversations and disable unwanted GPS tracking. Jammers can prevent 9-1-1 and other emergency phone calls from getting through or interfere with police and other law enforcement communications. For example, the recent use of a cell phone jammer in an office building disrupted communications of a nearby Fire Department. When Enforcement Bureau agents investigated the incident, we found that a CPA who apparently did not want to be disturbed during the busy tax season was using a small, inexpensive cell jammer inside his office. But, the jammer was disrupting critical public safety communications outside his building as well.

In another recent instance, a high school teacher used a jammer in his classroom. Responding to a complaint, Enforcement Bureau agents tracked the device to a locked cabinet in the metal shop. Unknown to the teacher, the jammer was blocking all teachers, students, and staff throughout the school from making any calls, including emergency calls, and it could have had tragic consequences.

Need more information? For additional information regarding enforcement of the jamming prohibition, visit www.fcc.gov/eb/jammerenforcement or contact Daudeline Meme, Kevin Pittman or Neal McNeil of the Enforcement Bureau at (202) 418-1160 or jammerinfo@fcc.gov. To file a complaint, visit www.fcc.gov/complaints or call 1-888-CALL-FCC.

Frequently asked questions about cell, GPS, and Wi-Fi jammers are available at http://www.fcc.gov/encyclopedia/jammer-enforcement.

Media inquiries should be directed to Neil Grace at (202) 418-0506 or neil.grace@fcc.gov or to Karen Onyeije at (202) 418-1757 or karen.onyeije@fcc.gov.

To request materials in accessible formats for people with disabilities (Braille, large print, electronic files, audio format), send an e-mail to fcc504@fcc.gov or call the Consumer & Governmental Affairs Bureau at (202) 418-0530 (voice), (202) 418-0432 (TTY). You may also contact the Enforcement Bureau on its TTY line at (202) 418-1148 for further information about this Enforcement Advisory, or the FCC on its TTY line at 1-888-TELL-FCC (1-888-835-5322) for further information about the jamming prohibition.

Issued by: Chief, Enforcement Bureau

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Figure 414 – FCC Public Notice on Jamming Devices (Page 2 of 2)

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36 APPENDIX C: GPS VULNERABILITIES

This appendix overviews GPS vulnerabilities as described in an FAA report released in January 2007. The FAA, with the support of key subject matter experts, released a report entitled "Surveillance / Positioning Backup Strategy Alternatives Analysis" in January 2007. Section 3.1 of the aforementioned report characterized the vulnerabilities to GPS as summarized below.

This report categorized types of GPS vulnerabilities into the following categories:

- Unintentional interference
- Planned testing interference
- Radio Frequency Interference (RFI) from emerging technologies
- Intentional interference
- Sustainment issues
- Ionospheric effects
- System attack (ground, space)

The report indicated that based on past assessments as well as historical and anecdotal evidence, the potential impact and perceived likelihood of each of these vulnerabilities were assessed on a qualitative basis. The results of this assessment are presented in Figure 415. Also shown in the figure is an assessment of how certain factors, such as the introduction of GPS L5, and improved detection and location capabilities, could reduce the likelihood or the impact of these vulnerabilities. Likewise, factors such as increased dependency are also shown as drivers of potentially increased likelihoods or impacts.

Several conclusions, as documented in the FAA Surveillance / Positioning Backup report, were made based on the results of this assessment. First, GPS losses due to ground or space attack were assumed to fall outside the scope of any proposed FAA mitigation strategy, and should not be included in this evaluation as a requirement. Losses due to sustainment issues were considered by the team to be a policy issue. Losses due to unintentional or planned testing interference were considered to present the greatest risk (combination of likelihood and impact) to the NAS. Losses of GPS due to these types of vulnerabilities have been documented in the past, and will continue to occur in the future. Also, most mitigation strategies that could be implemented in the relatively near term that would mitigate these types of losses would also mitigate many other types, including ionospheric, RFI, and most types of likely intentional interference vulnerabilities. Therefore, the report concluded that GPS losses based on unintentional interference or planned testing interference should be the basis for the development of a backup strategy (as highlighted in bold in Figure 415).

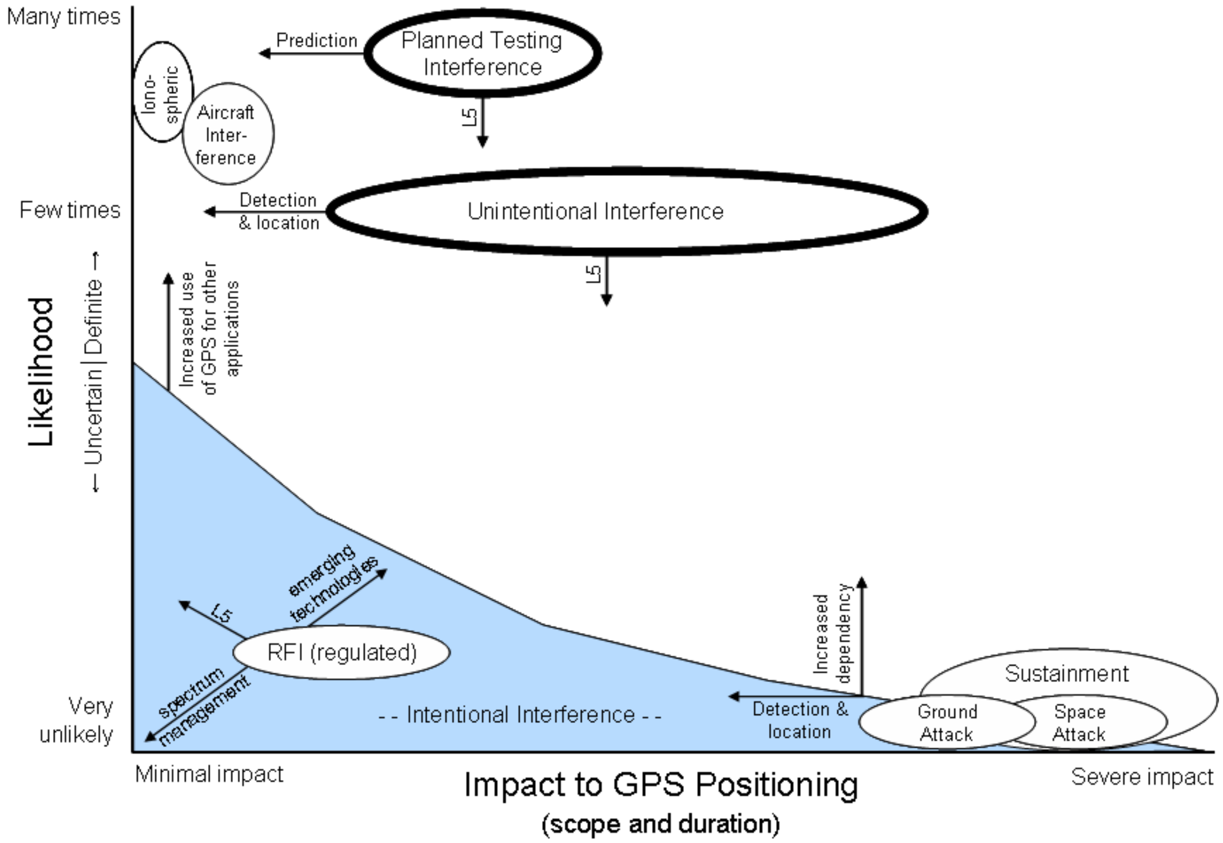

Figure 415 – GPS Vulnerabilities and Their Potential Risks

[Reference: "Surveillance / Positioning Backup Strategy Alternatives Analysis," FAA, January 8, 2007, page 6.]

In order assess the risk and to develop an effective mitigation strategies, the impact of a loss of GPS due to unintentional or planned testing interference needed to be quantified. Past assessments and historical evidence suggested that either type of interference could affect areas ranging anywhere from less than one to hundreds of nautical miles (NM) radius from the interference source, depending on many factors including source transmitting power and altitude of impacted aircraft. These interference events would not be limited to just certain locations in the U.S., and could therefore occur anywhere in the NAS. Given the wide range of possible impacts, the report identified a specific level of impact that was viewed as being both realistic and representative of a challenging condition, i.e., a loss of GPS covering an affected area of 40 - 60 NM in radius which is the typical area covered by a terminal radar today.

A realistic and representative duration of GPS loss was also. Based on historical and anecdotal evidence, losses due to planned testing interference occurred over relatively short periods (several hours) at a time, but repetitively over many days or weeks. Losses due to unintentional interference tended to be more continuous in nature, have lasted anywhere from a few hours to several weeks. Given the wide range in durations of past events, tempered with an assumption of improving detection and location capabilities over time, the report concluded that 3 - 4 days was a realistic and representative duration of a loss of GPS.