

A Study of Future Communications Concepts and Technologies for the National Airspace System—Part III

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Abstract— The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) is investigating current and anticipated wireless communications concepts and technologies that the National Airspace System (NAS) may need in the next 50 years. NASA has awarded three NASA Research Announcements (NAR) studies with the objective to determine the most promising candidate technologies for air-to-air and air-to-ground data exchange and analyze their suitability in a post-NextGen NAS environment. This paper will present progress made in the studies and describe the communications challenges and opportunities that have been identified as part of the study.

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1. INTRODUCTION

NASA's NextGen Concepts and Technology Development (CTD) Project integrates solutions for a safe, efficient and high-capacity airspace system through joint research efforts and partnerships with other government agencies. The CTD Project is one of two within NASA's Airspace Systems Program and is managed by the NASA Ames Research Center. Research within the CTD Project is in support the 2011 NASA Strategic Plan Sub-Goal 4.1: Develop innovative solutions and advanced technologies, through a balanced research portfolio, to improve current and future air transportation. The focus of CTD is on developing capabilities in traffic flow management, dynamic airspace configuration, separation assurance, super

density operations, and airport surface operations. Important to its research is the development of human/automation information requirements and decision-making guidelines for human-human and human-machine airport decision-making. Airborne separation, oceanic in-trail climb/descent and interval management applications depend on location and intent information of surrounding aircraft. ADS-B has been proposed to provide the information exchange, but other candidates such as satellite-based receivers, broadband or airborne internet, and cellular communications are possible candidate's. For further information, the CTD project plan can be found at: http://www.aeronautics.nasa.gov/pdf/ctd_project_plan_2011_508.pdf

In the Spring of 2012, NASA Ames Research Center issued an amendment (CTD1 Subtopic 3) entitled: "Technology Candidates for Air-to-Air and Air-to-Ground Data Exchange" calling for proposals to NASA Research Announcement (NRA) "Research Opportunities in Aeronautics", NNH11ZEA001N. Future applications such as airborne separation, oceanic in-trail climb/descent and interval management depend on the location and intent information of the surrounding aircraft with respect to an aircraft. Presently, Automatic Dependent Surveillance Broadcast (ADS-B) technology has been proposed to provide that information. However, satellite-based communications, broadband or airborne internet, and cellular communications have also been proposed as possible candidates. The purpose of this solicitation was to identify the air-to-air and air-to-ground communication methods for NextGen and beyond NextGen operations. The specific goals are as follows:

1. Identify existing or emerging technology candidates (and their integration), including but not limited to ADS-B, suitable for air-to-air and air-to-ground communications over a NAS modernization horizon of 50 years.
2. Quantify the functional attributes and characteristics of each candidate, including (but not limited to)

communications range, bandwidth, latency, integrity, reliability, and security.

3. Map the technology candidates to specific air traffic management applications where they will be most beneficial and cost effective.
4. Identify the infrastructure and architecture needs of the potential technologies for air-to-air and air-to-ground exchange.
5. Identify rough magnitude cost estimates, or relative cost comparisons, and any technological characteristics such as bandwidth, and reliability.
6. Provide assessment of how these technologies could be used for air traffic management applications including but not limited to airborne separation and interval management.
7. Identify vulnerabilities and security issues and mitigation of any proposed concepts.

The proposer was asked to identify current and future technologies that would be useful for air-to air and air-to-ground information exchange related to air traffic management applications. This was an exploratory NRA subtopic and there was flexibility for the proposer to select an appropriate approach. The anticipated duration was 24 months from the date of the award. The outcomes, deliverables, and, schedule were defined as follows:

1. A report describing technology candidates (and their integration) that will allow air-to-air and air-to-ground data exchange. Describe strengths and weaknesses of each. The report should include but not be limited to how the ADS-B could be made more cost effective. (Q3)

2. A report documenting infrastructure and architectural needs of these identified technology candidates. (Q4)

3. A report describing comparison of multiple alternatives and/or their integration based on costs, bandwidth, safety, reliability and security to support air-to-air and air-to-ground communications appropriate for future air traffic management operations. (Q5)

4. A report describing alternative technologies, their integration, dependencies on infrastructure and their potential use for air traffic management applications including but not limited to airborne separation and interval management. (Q7)

5. A detailed description of most promising technology alternative(s). (Q8)

The proposals were due on April 3rd, 2012. NASA Glenn Research Center led the evaluation of submitted proposals. In September 2012, three contract awards were made. They were: A Study of NAS Data Exchange Environment through 2060 (Honeywell, Columbia, MD, Alope Roy/PI); NASA Com50 (Rockwell Collins, Cedar Rapids, IA, Joel Wichgers/PI); and, Technology Candidates for Air-to-Air and Air-to-Ground Data Exchange (Agile

Defense LLC, Hopkins, MN, Brian Hayes/PI). The three studies began in October 2012 and have a 24 month duration. This paper provides a summary of approximately the first half of the second year (Q5, Q6) of effort for each study. A paper summarizing the first six months effort can be found in reference [1], and the second six months effort can be found in reference [2].

2. HONEYWELL

BACKGROUND

In the first year of the performance period, Honeywell conducted a systematic survey of the public domain literature to identify current, emerging and embryonic communication technologies, which included a wide range, starting with the existing, narrow bandwidth, low data rate, ACARS to the very futuristic optical and X-ray communications. Characterization of those technologies was done in an Excel-based workbook using a common set of key attributes and characteristics, which were derived from performance requirements defined in aviation standards. Subsequently, a Quality Function Deployment (QFD) analysis tool was used to map critical needs of key ATM applications to the capabilities of the candidate technologies to prioritize the technology candidates that can meet air-to-air and air/ground ATM application needs. A common architectural framework was established to define the data exchange environment and the context of the air-to-air and air/ground networks in that environment. Three architectures were analyzed using future cellular, next generation Ku/Ka band SATCOM and Self-Organizing Orthogonal Frequency Division Multiple Access (SO-OFDMA) technologies. Architecture options included cellular base stations located on High Altitude Platforms (HAP) and Free Space Optical (FSO) communications for cross-connects. Finally, overall system expenditure against benefits were compared for the proposed architectures to choose the right architecture for NAS environment with minimum cost outflows. The first year of study concluded that a hybrid communications architecture consisting of cellular technology for terrestrial, satellite for Oceanic, polar and remote regions and SO-OFDMA for air-to-air networking will be best suited to meet the future communication needs of the NAS.

TECHNICAL APPROACH AND ANALYSIS

The second year of study started from the architecture recommendations of the first year deliverables. The research involved two focus areas: operational and security analyses of the terrestrial and HAP-based cellular, satellite and air-to-air architectures. The operational analysis consisted of two steps: an operational view analysis and simulation modeling of the communication technologies.

The operational view analysis started with the ATM operational concepts and their communication services enablers. The required information flows for those services

were estimated by aircraft type, airspace domain and the phase of flight. The information flows were based on the Version 2 of Communications Operating Concept and Requirements for the Future Radio System (COCR) jointly developed by FAA and EUROCONTROL. The data traffic estimated in the COCR was escalated by 2.5% per year to derive the data communication demand for most of the services and aircraft classes. The 2.5% per year escalation factor was recommended in the COCR. Aircraft distribution and movement over National Air Space (NAS) was based on actual aircraft flight data reported by FAA for January 23, 2014. The aircraft data was escalated by a factor of 0.5% per year, which was used by FAA in a recent report to estimate air traffic in the year 2033. To estimate UAS distribution over NAS, it was assumed that UAS operation will be concentrated around major urban areas. Top two hundred and fifty urban areas in the NAS were selected based on their population density and the UAS platforms were distributed to those areas based on their population ranking. Aircraft movement was simulated at five minute interval over a 24-hour period using a visual tool that permitted computation and display of aircraft concentration at national and regional levels.

For the simulation, a set of priority-based queuing models were developed to estimate the throughput, latency, and dropped packets by information service flows for the communication technologies identified in the first year of this study. The queuing models were combined with the visual simulation tool to evaluate the performance of the three network architectures: cellular, satellite and SO-OFDMA air-to-air.

The operational analysis concluded that the cellular architectures could support up to 400 aircraft in a cell without any significant degradation of the desired services. On the other hand, satellite architecture experienced significant loss of passenger data traffic even with five aircraft per spot beam and had loss of SWIM services when the number of aircraft exceeded fifty per spot beam. In addition, satellite networks had much higher latency compared to cellular networks due to higher propagation delays. The SO-OFDMA air-to-air network using VHF media could support basic surveillance, air traffic and airline operational services but did not have adequate capacity to support SWIM or passenger data.

For the security analysis, a security perimeter was defined between the regulated aeronautical network and the unregulated public network. All classes of devices on the perimeter that would be exposed to the public domain were identified at the first step of the analysis. Subsequently, high-level threat vectors for these classes of devices were identified. The safety objectives and the hazard severity categories for datalink services from the COCR were analyzed in the second step and mapped against the threat vectors to develop a hazard score for each of the threats identified in the first step. In the third step of the security analysis, vulnerability of the three recommended architectures were assessed against the probability of

attaining certain hazard score for a given datalink service. If the assessed safety hazard probability of a threat was below the required safety objective for the datalink service, then that particular threat was classified to have no impact on the communication architecture to offer the datalink service. Conversely, if the hazard probability of a threat was higher than the safety objective, that threat was deemed have security impact on the recommended architecture. At the final step of the security analysis, some high level mitigation strategies were recommended for the threats having security impact on the proposed architectures. In summary, RF jamming and man-in-the-middle attacks are major concerns for cellular architectures whereas jamming of the feeder links from a UAS would have serious impact on satellite communications. Lack of link and media access control security in the SO-OFDMA air-to-air network makes it very vulnerable to many security threats. The dynamic nature of the broadcast mode SO-OFDMA makes it difficult to implement cost-effective security measures for this architecture.

CONCLUSIONS

This study concludes that all three technology elements, cellular, satellite and SO-OFDMA air-to-air would have a role in the future communications supporting air traffic management beyond NextGen. To mitigate some of the security risks associated with a technology architecture and to provide added capacity, flexibility, reliability and quality of service for future ATM, a hybrid communication architecture utilizing cellular, satellite and air-to-air networking is recommended. In addition, technology elements to seamlessly and simultaneously utilize all available air/ground connectivity options should be employed.

History of technology evolution over the last fifty years is indicative of the challenges to predict the communication technologies and ATM environment fifty years in the future. This Honeywell study captures a high-level view of the future based on current knowledge. It is possible that some game changing technology such as the personal computers, the Internet and the cell phones will materialize within the near future. Therefore, it is strongly recommended that this study be updated at a periodic interval to include future research and developments.

Free Space Optics (FSO), one of the technologies identified in this study, has the potential to become a game changer for future ATM communications. One of the key challenges for applying FSO to aeronautical communications is the acquisition and tracking of aircraft moving at very high relative speeds. Although this study included a preliminary assessment of the FSO technology, it is recommended that a future study should develop technical approach and system design for aircraft acquisition and tracking to support FSO communications.

Similar to FSO, operation of UAS in the NAS is in the infancy today. However, UASs may have a far-reaching

impact on future ATM. Therefore, it is recommended that a detailed study be initiated as soon as possible to assess the impact of low-altitude UAS on future NAS communications. That study should also address harmonization strategies for UAS command and control links with traditional ATC communications as well as general integration of UAS information for situational awareness of the pilots and controllers.

ADDITIONAL STUDY RECOMMENDATIONS

In addition to the studies recommended above, Honeywell suggests the following items for future work:

- Develop high fidelity simulation models of the proposed architectures to perform tradeoff analyses and operational scenario-based simulations. By integrating these simulation models with other pre-existing NASA models, higher fidelity system models can be developed to aid future system design.
- Security analysis presented in this paper provides a high level assessment of the security threats, risks and their potential mitigation approaches. A future study should specifically expand this analysis to fully address the security vulnerabilities of the proposed architectures and develop mitigation approaches.
- RF spectrum is a very limited resource and its demand is increasing exponentially with time. Therefore, a future study should analyze the availability of effective spectrum for aeronautical communications and develop a technical approach for reuse and dynamic, on demand, allocation of spectrum.
- The aviation network of the future needs to be very dynamic with multiple air/ground connectivity options supporting simultaneous traffic flows with varied quality of service requirements and ad-hoc, self-configuring air-to-air networks. To maintain robust data flows and to assure low latency and jitter, future aeronautical networks must support sophisticated routing algorithms that can converge very quickly and impose very little system overhead. It is essential to research and design this routing algorithm soon such that it would be ready for standardization within the next ten years. This research should include management of multiple links for seamless inter-technology handovers and leverage currently evolving IP mobility standards.
- Similar to the routing challenges, aircraft architecture may also need to be investigated to facilitate such a dynamic network operation while ensuring security of the flight critical services and safety of flight.

3. ROCKWELL COLLINS

BACKGROUND

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 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, and decision support systems.

Wireless communications including both Aircraft-to-Aircraft (A-A) and Aircraft-to-Ground (A-G) is an essential infrastructure element necessary to realize the future NAS vision such that the appropriate information is available at the required quality of service to enable the Air Traffic Management (ATM) systems to better utilize the airspace through enhanced operational procedures and applications.

NAS COMMUNICATIONS

NAS communications are anticipated to evolve from today's primarily voice communications to a future with much more highly capable voice and data communications that will enable a broad range of enhanced operations.

Today's Communications

Today's NAS air-to-air and air-to-ground ATM-relevant communications are rather limited and consist primarily of VHF, HF, and SATCOM which 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. Emerging or soon to emerge is the use of VHF data link (VDL) to support data communications between air traffic controllers and aircraft as well as the use of VHF Data Broadcast (VDB) to support GPS/Local Area Augmentation System (LAAS) Category I precision approaches.

Future NAS Comm. Candidates Overview

Future concepts of operation for the long term national air transportation system within the study's 50 year time horizon include incorporating new types of aircraft (e.g., UAVs) as well as advanced operating procedures and applications that will drive the need for more and better A-A and A-G data communications. Note that in the context

of this study, A-G communications also implies the reciprocal ground-to-aircraft (G-A) communications.

Twelve A-A and nineteen A-G communications candidates have been identified as given in Table R-1 and Table R-2, respectively. The A-A candidates include 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 may 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 include LOS candidates from VHF to optical, as well as beyond line-of-sight (BLOS) candidates that include 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 alternatives are not at this time expected to be 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 in the future significant aircraft cost and weight savings by removing the need for HF communications equipment.

Analyses of Communications Candidates

As part of the study, initial analyses to characterize and evaluate the identified A-A and A-G candidates was completed. The analyses included:

- Quantifying the characteristics and attributes of each candidate including the communication bandwidth, latency, communications range, expected user data rates, link spectral efficiency, capacity, availability, coverage, advantages and disadvantages, and technology readiness level (TRL);
- Identifying future NAS Air Traffic Management uses / applications and straw-man initial Required Communications Performance (RCP) to support them;
- Mapping the candidates to the ATM uses / applications based upon their ability to support the RCP;
- Identifying the infrastructure and architecture needed to implement each of the candidates;
- Performing an initial security assessment of the candidates by identifying threats, vulnerabilities, and risk mitigation strategies relevant to the A-A and A-G data exchanges;
- Characterizing the relative costs associated with each candidate;
- Identifying and prioritizing a representative set of Air Traffic Management applications that are enabled by the A-A and/or A-G communications and are expected to be utilized in the future NAS.

- Performing use case analyses for a subset of potential future airspace ATM applications including Delegated Interval (DI) / Interval Management (IM), Delegated Separation (DS), and Airborne Self-separation (AS).
- Prioritizing the A-A and A-G communications candidates from most promising to least promising based upon a broad set of evaluation criteria that span the categories of technical performance, cost, and risk.

While the presentation of the results from all of the analyses that have been completed to date is beyond the scope of this paper, a high level overview of the cost analysis is provided below.

INITIAL COST ASSESSMENT OF FUTURE NAS COMMUNICATIONS CANDIDATES

This section provides a summary of an initial cost assessment that has been completed for the A-A and A-G candidates that have been identified. The subsections below describe at a high level the cost assessment methodology, the cost model, the cost assessment results, and the interim study findings from the cost assessment.

Initial Cost Assessment Methodology

A cost estimation methodology was developed to enable comparative assessments between the various A-A and A-G communication candidates. There are four analytical cost estimation methods commonly used to develop cost estimates for large acquisition programs. These four methods include: 1) Analogy; 2) Parametric (or Statistical); 3) Engineering (or Bottoms Up); and 4) Extrapolation of Actual Costs methods. Ultimately, a parametric cost methodology was selected for the purposes of the initial cost assessment because of its advantages over the other methods for estimating costs at this very early stage of the future communication systems acquisition life-cycle.

A parametric cost model was developed that uses statistical relationships between historical costs associated with a number of relevant benchmark CNS systems that are in use today and other cost adjustment factors to estimate the costs for the candidate systems. The model applies cost adjustment 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 Model

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 prior to fielding the system.

Nevertheless, a total system cost model was developed for the purposes of relative cost comparisons of the various future communications candidates based upon estimating

the costs associated with four system cost elements including: 1) Technology Maturation and Standards Costs, 2) Equipment Costs, 3) Deployment Costs, and 4) Operation and Maintenance Costs, as is depicted in Figure R-1.

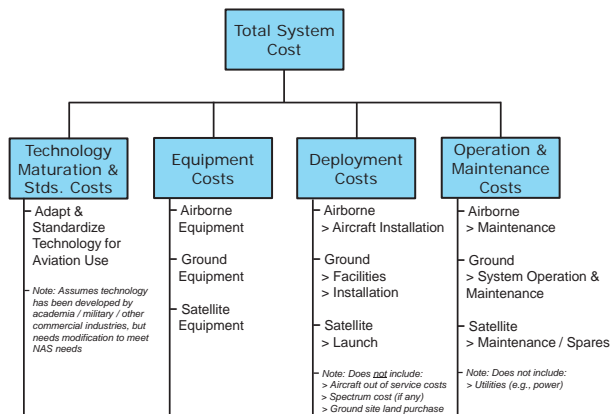


Figure R-1: Total System Cost Model

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. Thus, the cost model has only burdened a currently immature technology candidate with the incremental costs that would be incurred by the NAS stakeholders to incorporate a technology that has been sufficiently matured to support other commercial industries.

Equipment costs include all the costs associated with designing, developing, and 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. For the airborne equipment costs associated with NAS communication candidates, it includes the cost of “certified” communications avionics equipment and antennas. It does not include the costs for modifying downstream equipment (e.g., FMS, displays/human machine interfaces, decision support equipment) for utilizing or displaying the information communicated to support a wide variety of intended applications. For ground equipment costs, it includes the cost of ground communication equipment. For satellite costs, it includes the cost of the satellites.

Deployment costs include the cost of taking the equipment and installing it in a deployed state. For

airborne deployment costs, the cost estimates include the installation cost 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. It is recognized that taking an aircraft out of service to upgrade the communication system, especially on aircraft that perform commercial operations like those for the airlines, could result in substantial lost revenue costs. However, if scheduled appropriately where the aircraft is already out of service during a periodic maintenance checks (e.g., 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 could be negligible. For the purposes of the cost model results presented herein, lost revenue or lost opportunity costs have not been estimated.

For ground system deployment costs, the cost estimates include the cost of building the facilities and installing the equipment on site. It does not 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 not included an estimate of any potential costs for acquiring the spectrum allocation associated with a particular candidate, which could potentially be a very significant cost.

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).

Numerous assumptions have been made in the development of the cost model that are too numerous to fully articulate in this short paper. A few of the high-level assumptions include:

- The costs have been normalized to 2013 costs, even though some communications candidates may not be technically realizable for many years in the future.
- It has been assumed that the total cost of maturing currently immature candidates will not be solely burdened on the air transportation system stakeholders (i.e., other entities will also mature currently immature candidate technologies).
- For the purposes of cost comparison, a 25 year lifecycle cost was estimated, whereby the life of the airborne systems, ground stations, and satellite systems were assumed as follows:
 - a) Airborne Systems: 25 year life.

- b) Ground Stations: 25 year life.
- c) Satellite Systems: The service life of the various satellite systems was assumed as follows – LEO (assumed 6.25 year useful life and would thus need to be built and deployed 4 times during the 25 year system cost lifecycle), MEO (assumed 8.33 year useful life, built and deployed 3 times during 25 year system cost lifecycle), and GEO as well as GEO + HEO (assumed 12.5 year useful life, built and deployed twice during 25 year system cost lifecycle, plus for the GEO + HEO additional HEO spare satellites and additional intermediate launches of HEO satellites).

- For the purposes of the relative cost comparisons, the cost of inflation has been assumed to be equivalent to the time value of money. This assumption simplifies the cost model and does not obscure the predicted costs with the compounding effects of inflation over multiple decades.
- For the purposes of relative cost comparisons between the candidate technologies, it has been assumed that all aircraft in the aircraft fleet are equipped with the particular communications candidate and thus the cost estimates are not truly total systems costs, but rather are cost scores that are useful for relative comparison among the candidates. If this assumption was not made, then those candidates communication technologies 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 cost comparison between technologies very hard to interpret.
- For the purpose of airborne cost modeling results provided in this paper, aircraft were grouped into eight categories with an assumed aircraft fleet model in the United States changing over the 25 years as given in Table R-1 (referred to as Aircraft Fleet Model #1).

Cost Assessment Results

The cost assessment results summary is provided as “cost scores” for relative comparison of the costs associated with using each candidate technology for A-A or A-G communications. 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 aircraft fleet that

equips, the communications quality of service that needs to be met, and the communication coverage volume required to support the intended applications.

Tables R-2 and R-3 provide the results from estimating the total relative cost scores associated with each of the twelve A-A and nineteen A-G communications candidates, respectively, over a 25-year communication system life cycle for Aircraft Fleet Model #1 as given in Table R-1. Figures R-2 and R-3 contain plots of the relative cost scores for the A-A and A-G candidates from Tables R-2 and R-3, respectively. Note that the total cost scores were estimated using a number of other aircraft fleet models which have resulted in similar relative total cost relationships among the communications candidates.

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 the individual communication candidates, the cost model has also been exercised to estimate the relative costs when implementing an integrated communication system that utilizes a number of the communication candidates to meet the needs of the NAS 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. The results from the assessment of various integrated communications alternatives have not been provided in this short paper, but are expected to be released in a future NASA contractor technical report.

Table R-1: Aircraft Fleet Model #1 (2013 to 2038, 25 Year Duration)

Aircraft Category	Fleet Number of Aircraft at Start	Yearly Growth Rate	Entry into Service Rate	Aircraft (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_Medium	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

Table R-2: Cost Scores for Aircraft-to-Aircraft Communication Candidates

#	Candidate Technology	Cost Score (\$B)				
		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

Table R-3: Cost Scores for Aircraft-to-Ground Communication Candidates

#	Candidate Technology	Cost Score (\$B)				
		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

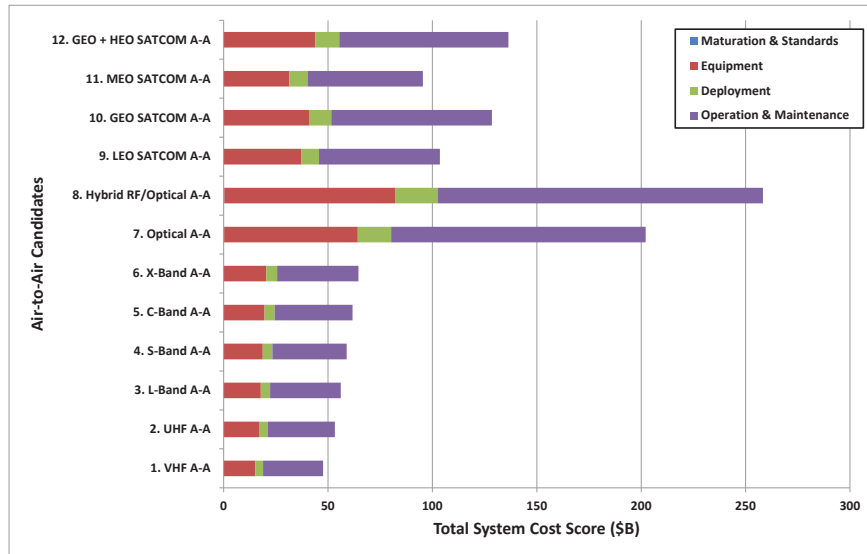


Figure R-2: Plot of Cost Scores for Aircraft-to-Aircraft Communication Candidates

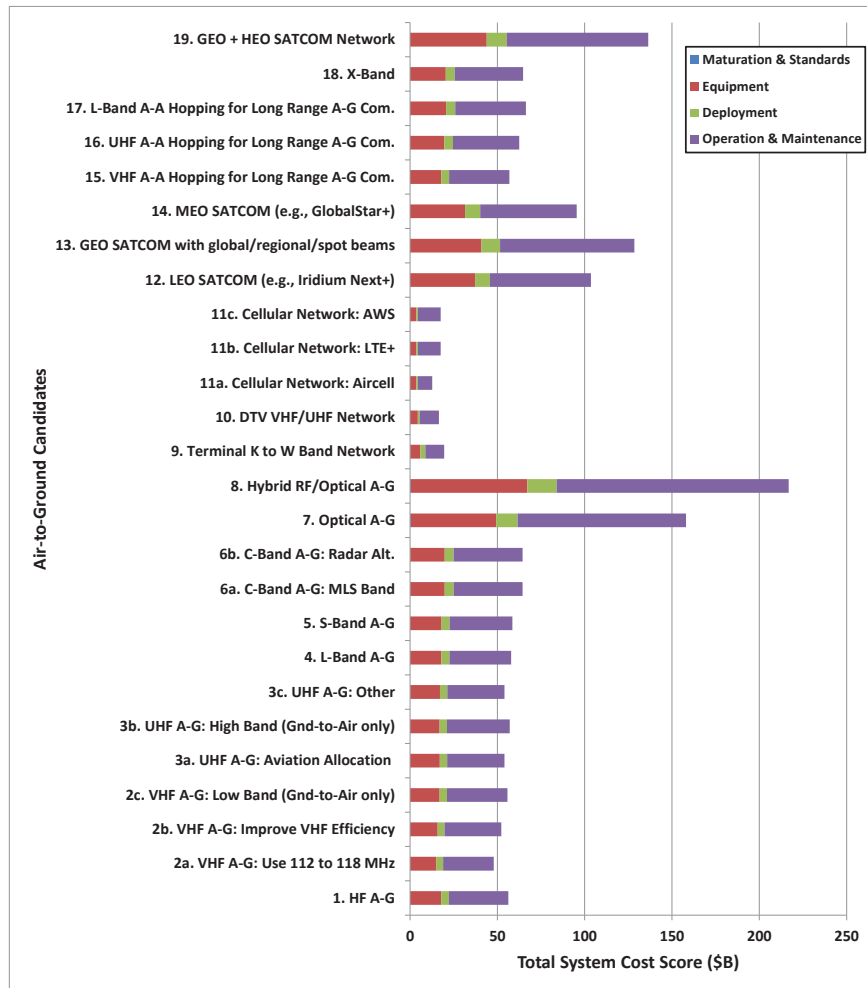


Figure R-3: Plot of Cost Scores for Aircraft-to-Ground Communication Candidates

Interim Study Findings Resulting from Cost Assessment

Initial investigations into the relative costs associated with the communications candidates identified for potential future NAS ATM applications has resulted in the following interim study findings:

- 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), rather than building custom aviation-only communications networks, presuming that they would be able to meet the quality of service / safety / security requirements.
- 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 that would need to be borne by the aviation stakeholders, especially 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.
 - 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).

Additional R&D is planned to more comprehensively identify and evaluate air-to-air and air-to-ground communication candidates for meeting the long-term needs of the NAS in a cost effective manner.

4. XCELAR

BACKGROUND

Technology Candidates for Air-to-Air and Air-to-Ground Data Exchange is a two-year research effort to visualize the U. S. aviation industry at a point 50 years in the future, and to define potential communication solutions to meet those future data exchange needs. Parallel efforts to date have defined and characterized the information exchange functional needs of the future NAS, and specific communication link technologies to potentially serve those needs. Those two efforts have now converged, with each function being matched to potential enabling communication solutions, and those solutions compared with, and ranked relative to, each other. Infrastructure and architecture aspects have also been considered, and a gap analysis performed from a technical standpoint.

The XCELAR Team has considered a wide range of communication solutions, and has identified candidate technologies that fall into (3) three categories: (1) extensions and enhancements to current, (2) existing aviation links; re-architecture of current aviation systems, and/or RF spectrum; and (3) the application of new, primarily commercial link technologies not currently associated with aviation applications, and not located in aviation protected RF spectrum. The first two categories are defined herein as “Aviation-Specific Candidates” due to their operation in aviation (reserved/protected) specific RF spectrum. An iterative comparison process was used, in which a pre-screening step identified the most viable candidates for each link. Only the three to five most viable candidates were included in the final comparison process. A total of twelve candidates were used in the final comparison step, including current systems, enhancements to current systems, and new or future solutions. In all cases, each function had at least two viable candidate solutions with no significant gaps or unmet needs identified.

Two key supporting technologies, which are not link technologies, per se, but play important roles in making the identified link technologies practical and implementable, are also described. The team is considering a combination of aviation-specific communication options and commercial link technology candidates to provide the broadest overall capabilities and lowest overall cost, while always assuring the availability of aviation-protected spectrum operations for critical functions.

Aviation-specific candidate technologies include:

- VDL Mode 2 (VDL-2) and a proposed aggregated / restructured VDL-2, herein referred to as VDL-Next;
- ADS-B based on the current 1090 MHz architecture with a new low power option (1 watt or less transmit power for ground operations);

- A restructured link system re-using 1030 MHz spectrum, referred to herein as “ADS-B Next”;
- Space-based ADS-B;
- AeroMACS; and
- AeroWAN, a new wireless Aeronautical Wide-Area Network, re-using portions of the current DME/TACAN frequency band.

The two supporting technologies that provide important enabling capabilities to the overall future solution set are referred to in the research effort as the Delivery Manager (DM) and Software-Defined Radio (SDR) technologies. The Delivery Manager enables multiple individual links or link technologies to be harnessed as a group, routing information dynamically across the most favorable link at any given time based on required availability, integrity, capacity, cost and other criteria. This may allow for the use of non-aviation protected spectrum for certain functions, while still utilizing aviation protected spectrum where criteria require it. The rapidly maturing SDR technology allows broadband reception and processing of various disparate signals and modulation/encoding techniques in proximate bands using an SDR architecture that allows a single receiver to receive and process multiple link technologies for different purposes, significantly increasing the flexibility of individual communication devices and the system as a whole. Each receiver is paired with a small number of similarly programmable transmit modules and associated filtering, and together reduce overall cost and complexity, and also become an important enabling factor in the migration from current to future technologies.

Commercial, non-aviation candidate technologies include:

- Cellular technologies such as 4G/LTE and future generations;
- Iridium and Iridium-Next Low Earth Orbit (LEO) Satellite;
- Ku- and Ka-Band satellite systems;
- SDARS, Satellite Digital Audio Radio Service.

Future NAS participating aircraft considered in identifying user functions included Air Transport, General Aviation, UAS, and Hypersonic aircraft. Operations ranged from commercial airlines, to corporate jets, to private pilots, to large and small UASs, to space operations. Hypersonic and space operations analysis was limited to Mach 8 and below, and specialized communication considerations such as space vehicle reentry ionization blackouts were not considered to be within the study scope. Four basic types of functions, broken out into forty-six specific functions, were considered:

- Airborne Aircraft, Inbound Communications;
- Airborne Aircraft, Outbound Communications;
- Aircraft on the Ground, Inbound Communications; and

- Aircraft on the Ground, Outbound Communications

Each function was assigned a priority based on its relative importance to the safe and efficient conduct of flight. Each candidate link was ranked according to its suitability for each function and the priority of each function. The susceptibility of each technology to becoming obsolete over time was also assessed, and each candidate assigned an obsolescence rating, using a scale of 1 (most susceptible) to 5 (least susceptible), including:

- Adaptability to Evolving Technology
- Adaptability to Future Functions
- Bandwidth Expansion Capability
- Acquisition and Operation Cost Trends
- Potential Trends in Underlying Business Model (commercial candidates)
- Uncertainty of Long-Term Stability (technical or business model)

The overall result of these link analyses may provide the clearest “investment case” perspective of which candidates merit the most investment in research and development to realize the maximum future benefit. Results are depicted graphically below. It can be seen that the highest ranking candidates are AeroWAN, VDL-2 Next, and ADS-B Next. ADS-B Next and AeroMACS have nearly identical rankings; AeroMACS is already the subject of significant research, the merit of which is reinforced by this analysis. It should also be noted that cellular technologies also score well, due in part to their particularly strong scores in general aviation applications, and facilitated by the Delivery Manager as a path to approval for use across a broader range of functions.

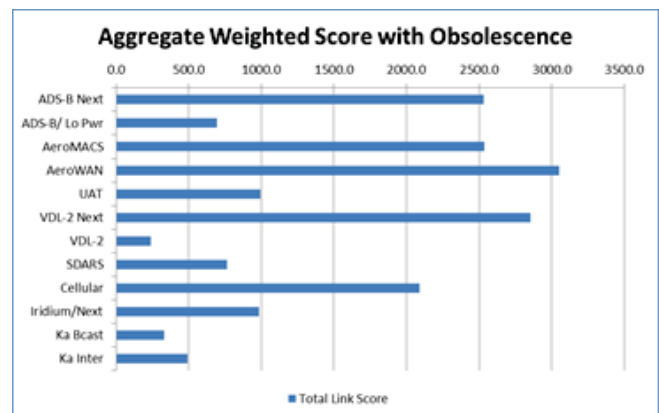


Fig. 1 - Aggregate Weighted Score with Obsolescence

The Gap Analysis input down-select step identified the top three or more candidates for each function; in each case there were at least 2 candidates with scores of 7 or higher, indicating that suitable performance can be obtained for each function from two or more candidates. The analysis indicates that in the context of current technologies only, there are functions that are expected to be required in the

2063 aviation industry that may not be adequately served by today's technology without enhancements. Analysis of the comparison data also indicates that through the application of future link technologies identified in the study to date, all identified future functions could be enabled successfully.

The remaining steps to be completed in the planned research effort focus primarily on business case analysis, in which the technical solutions now identified and characterized are assessed in terms of equipment decision drivers for the various industry segments, initial and life cycle cost, and cost / benefit. The program is currently scheduled to conclude in late 2014.

5. CONCLUSIONS

A NASA Research Announcement (NRA) study to investigate potential future aeronautical communication technologies that could serve aviation in the 2060 time frame was awarded in 2012. This NRA study is a one-year effort with an option for an additional year extension. The objective of this study is to investigate future air-ground communications technologies, evaluate possible architectures, assess future communication needs and identify challenges that will need to be addressed in the development and implementation of such potential systems. An important element of the study is to consider technological and Air Traffic Management advances planned for implementation by the NextGen and SESAR programs. NASA awarded the study to Rockwell Collins Corporation, Honeywell Corporation and Xcelar Corporation to independently conduct the study. This paper provides results obtained to date by each company.

Preliminary findings indicate that spectrum and technology certification will continue to pose a challenge, especially in areas where software is increasingly used to perform hardware functions. It is anticipated that although some spectrum will become available as a result of the decommissioning of technologies i.e. VOR, the demand for spectrum will increase and future technologies will need to provide the ability to maximize the use of finite spectrum resources. Advances in electronics and communications technology will enable the integration of services and applications and thus reducing the number of system deployed to the aircraft. Finally, the future aviation radio technology will depend on numerous factors including: air traffic management procedures, airline operations business models and the configuration of the airspace, which is anticipated to include Unmanned Aircraft Systems, hypersonic flights and manned aircraft.

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BIOGRAPHIES



Denise S. Ponchak is the Branch Chief of the Communications Networks and Architectures Branch at the National Aeronautics and Space Administration's (NASA) Glenn Research Center at Lewis Field in Cleveland, Ohio. The Branch is responsible for designing advanced networking concepts, architectures, and technologies for aeronautics and space applications. Prior to becoming Branch Chief, Ms. Ponchak was an Aeronautical Communications Project Manager focusing on increasing the National Airspace System's telecommunications capability, and a communications research engineer supporting future satellite-based communications. She holds a Bachelor's of Electrical Engineering and a Master's of Science in Electrical Engineering from Cleveland State University in 1983 and 1988 respectively.



Rafael Apaza is a Communications Research Engineer at NASA Glenn Research Center. Prior to working for NASA, Rafael was the Communications Navigation and Surveillance (CNS) lead for the FAA Aviation Research and Development Office. In addition, Rafael supported the FAA's SWIM project, participating in both the SWIM Architecture Development and SWIM Transition projects. From 1999-2002 he was the FAA Great Lakes NAS Planning Program Manager for Michigan and Wisconsin. From 1987-1999, he worked as a systems engineer for FAA Airway Facilities, specializing in Communications and Surveillance. He holds a BSEE (1985), a MSEE (1995) from Wayne State University, and a MCIS (2001) from the University of Michigan.



Joel Wichgers is a Principal Systems Engineer working for Rockwell Collins in their Advanced Technology Center located in Cedar Rapids, Iowa. He has over 27 years of experience in aerospace engineering, at Rockwell Collins and McDonnell Douglas Aircraft Company (now Boeing). Joel has earned three college degrees

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Brian D. Haynes - Mr. Haynes has served as a PI for NASA, DHS, DoD, and FAA in aviation research, development, policy-making, and technology assessment programs over the last three decades. Mr. Haynes's work has related to National Airspace

System architecture / operations, aircraft sensor systems, airport moving maps and runway incursion prevention, Electronic Flight Bag human factors, RF interference with aircraft navigation and communication systems, NGATS, and other areas requiring the melding of multi-disciplinary aviation expertise into innovative, relevant research results.

Mr. Haynes has been involved in aerospace technology

and research for over 30 years. In addition to his experience with the above-mentioned programs, he has been an industry leader in avionics, weather, datalink, and missile defense technologies. As head of Flight Operations Technology at United Airlines, he led many related initiatives including NAS capacity enhancement, wake sensing technologies, fleet avionics equipage strategy, and business case development for flight operations technology programs.



Mr. Alope Roy is a Senior Program Manager with Honeywell Advanced Technology organization; he currently manages data communication, information security and radio technology development programs supporting aerospace industries. Previously, Mr. Roy was Director of Programs at Flextronics Corporation

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