

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

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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 the final results describing the communications challenges and opportunities that have been identified as part of the study.

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## 1. INTRODUCTION

The objective of NASA's NextGen Concepts and Technology Development (CTD) Project is to integrate 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 main

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 airportal 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](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.

## GOALS

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.

#### **OUTCOMES, DELIVERABLES, AND, SCHEDULE**

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, Aloke 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 second half of the second year (Q7, Q8) of effort for each study. A paper summarizing the first six months effort can be found in reference [1], the second six months effort can be found in reference [2], and the third six months can be found in reference [3].

## **2. HONEYWELL**

### **BACKGROUND**

Honeywell, under a two-year contract, is working on NASA's NextGen Concepts and Technology Development (CTD) Project focusing communications technology research initiative. This paper summarizes Honeywell's research conducted during the second year of the study task.

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. 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.

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. This paper provided the

results of operational and security assessments of the best technology alternatives.

The results of the best alternatives assessment reinforce the conclusion of the analysis conducted in the first year that the three remaining technology and architecture candidates together provide a suitable hybrid solution. Those architectures generally meet latency and data throughput performance requirements of ATM applications in the 2060 timeframe. Subsequently, security was analyzed in terms of the susceptibilities inherent in the nature of the technologies. Potential security protections were analyzed for mitigation of the security risks presented by the threats. Security measures can be put in place to mitigate the risks but not completely eliminate the risks. A defense in depth will be a good approach to mitigate risks. Summaries of the operational and security assessments are provided below.

#### **SUMMARY OF OPERATIONAL ASSESSMENT**

The operational assessment consisted of an operational view analysis and simulation modeling analysis. In the operational view analysis, a concept of operations of communication services supporting ATM application services was developed. It identified information flows of the communication services for the following types of data traffic: critical safety services - ATS and AOC; non-critical services - AAC and SWIM; and passenger traffic - APC. The concept of operations assumed that these data traffic types, including APC, will share common links in future broadband air/ground communication systems in the 2060 timeframe. Air-to-air communication systems were assumed to be dedicated to ATS, AOC and AAC traffic only.

Communication scenarios were analyzed in context of the architectures using the best alternative technologies for air/ground and air-to-air communications. The architectures included ground-based and HAP-based 5G+ cellular architecture (architecture option 1), Ku/Ka SATCOM architecture (architecture option 2) and SO-OFDMA architecture (architecture option 3). The hybrid architecture is a combination of the three architectures and thus an analysis of the hybrid architecture was covered by the analyses of the three architectures.

The operational view analysis results included the data traffic throughputs or bandwidth predicted for the 2060 timeframe for the data traffic types (ATS, AOC, AAC, SWIM and APC) in each airspace domain and flight phase (pre-departure, arrival and taxi in APT domain; departure and arrival in TMA; operations in ENR, OPR and AOA). The data traffic was analyzed across various aircraft types, including ATR, microjets, BGA, UAS and military aircraft flying civilian routes under CAA rules. The single-aircraft

data flow results for each of these aircraft types were used for input to the simulation modeling analysis.

The next phase of the operational assessment used modeling and simulation to further assess the best alternative technologies. Starting with the latency, data bandwidth (per-aircraft data traffic estimates provided by the operational view analysis) and priority requirements of the data traffic types, the architectures were modeled and analyzed, which included computer-based modeling. Data packet loss and scalability performance were also analyzed. Aircraft traffic information was taken from FAA's ADSI data and extrapolated for the 2060 timeframe. The simulation and analysis produced performance results to assess if and how well the technologies met the requirements. The technologies were modeled and analyzed in context of the three architectures.

The modeling and simulation part of the operational assessment utilized a combination of modeling of the single-system architectures, which included computer-based modeling of the systems, and a traffic and network simulation covering the CONUS. The traffic and network simulation, the Air Traffic Simulation Model Tool, applied the models of the three best alternative architectures to a planned CONUS-wide network for air/ground and air-to-air communications. The Microsoft Windows® based tool is a NAS network simulation and visualization tool to generate performance statistics for analysis and evaluation. It is a highly configurable tool and provides a GUI for setup, operation and report generation.

A summary of the modeling and simulation results are provided below.

#### **Ground-based Cellular Network Results**

Latency requirements of ATS, AOC, AAC, SWIM and APC data types were met for high-density aircraft traffic (up to 400 aircraft per 2 degree by 2 degree cell). However, APC, having the lowest priority for transmission and much greater traffic volume, experienced significantly more latency at 400 aircraft per cell and significant packet loss starting at 50 aircraft per cell. There was no packet loss experienced by ATS, AOC, AAC and SWIM up to 400 aircraft per cell. To cover the CONUS, 360 cells (ground base stations) were needed.

#### **HAP-based Cellular Network Results**

Results were similar to the results of the ground-based cellular network. A single HAP cell is able to support a greater number of aircraft and thus fewer HAP cells are needed to cover the CONUS in comparison to the coverage of ground-based cells. However, a higher link capacity is required for the aircraft-to-HAP link to support the greater number of aircraft in the cell (4 degree by 4

degree cell). This link represents a potential bottleneck in traffic flow. To cover the CONUS, 100 cells (HAP base stations) were needed.

#### Satellite Network Results

Latency was significantly higher due to the inherent propagation delays in satellite communications. SATCOM is not suitable for latency critical real-time applications. SATCOM supported ATS, AOC and AAC with up to 300 aircraft per spot beam (4 degree by 4 degree spot beam). Packet loss was experienced by SWIM and APC starting at 5 aircraft per spot beam. The potential bottleneck in the SATCOM system is the satellite-to-ground gateway link. To cover the CONUS, 100 spot beams from a satellite were needed.

#### Aircraft-to-Aircraft Communications Network Results

The simulation results showed generally good air-to-air and air/ground coverage across the CONUS, based on the aircraft flight schedules, routes and aircraft density represented by the FAA's ASDI data used in the simulation. There were instances of disconnected aircraft (from the ground) during times when the aircraft did not have a complete path to a ground station. This occurs in sections of lightly traveled routes such as routes between the east and the northwest over areas such as Montana. A disconnected occurrence was also indicated as such when the number of hops between an aircraft to a ground station exceeded a maximum number of hops, which was configurable in the simulation. An aircraft RF range of 120 nm was represented as a mobile node with a range circle with 2 degree radius. The ground stations were placed at major airports and 21 selected airports provided the coverage for the CONUS.

#### **SUMMARY OF SECURITY ASSESSMENT**

The security assessment considered security in context of the architectures and defined a security perimeter boundary to properly set the context of the security analysis of the technologies. The security perimeter included the physical and link layers and the access network layer. However, potential hackers (black hat hackers) operating on the ground-based networks further back from the aircraft/ground network in the overall end-to-end network topology were also considered as potential threats in the analysis. The following threats were identified and analyzed: jamming, scrambling, aircraft impersonation, rogue (fake) base station, key management breaches, attacks from man-in-the-middle hackers and attacks from black hat hackers. These threats were numerically analyzed on the extent of impact they would have on data integrity and loss of communications (percentage of system degraded or disrupted by the attack) and the required capabilities to effect the attacks (percentage estimate of

likelihood the attack can be done given cost and complexity to do it). The product of the impact and likelihood of each threat to data integrity and communications was assigned a hazard level classification. The hazard level of each threat was compared against the safety objective of each ATM service to determine the level of security risk. A hazard level that is greater than the safety objective indicates a security risk. The safety objectives of the ATM application services were defined using the same set of classifications and were based on COCR requirements. Technical mitigations of the security risks were identified and analyzed.

A summary of the security assessment results are provided below.

#### Cellular Network Results

The assessment of cellular networks showed that all data communication services can be supported without major security issues with the exception of very safety critical, future services such as the Autoexec service, which will require more robust security to protect it against threats. A service such as Autoexec is susceptible to jamming, scrambling and rogue base station threats.

#### Satellite Network Results

Feeder links (satellite-to-ground station) were found to be susceptible to attack. Emerging technologies were identified that can be used effectively to jam the feeder link. To mitigate this risk, the feeder link could be eliminated in lieu of user links between satellite and user terminals on the premises of ground-based users.

#### Aircraft-to-Aircraft Communication Network Results

The self-organized aircraft-to-aircraft network, which is in the conceptual phase of development, was recognized as lacking security mechanisms at this point in its development. Without security mechanisms, it is susceptible to attacks such as jamming and impersonation. An aircraft-to-aircraft network uses non-centralized control as an ad hoc network, which provides some immunity to single point failures that can be experienced by centrally controlled networks.

Application of the self-organized cell concept and the concept of the decentralized network with appropriate security measures and key management were proposed to mitigate risks. Other mitigation strategies include jammer localization and hacker monitoring, which is based on the observation that jammers and hackers are typically localized. By localizing the jammer and hackers through monitoring preventive measures can be implemented effectively.

#### **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, 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 data communications.

## **FUTURE COMMUNICATIONS CANDIDATES**

Initial research to identify and evaluate communication technology candidates to fill the NAS long-term communications needs gaps has been completed. Twelve Aircraft-to-Aircraft (A-A) and nineteen Aircraft-to-Ground (A-G) communications candidates have been identified. 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.

As part of the initial research, analyses to characterize and evaluate the identified A-A and A-G candidates were completed. The analyses completed were as identified in the introduction section of this paper.

### **Most Promising 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 these flight domains.

### **Evaluation Methodology**

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 have been grouped into three categories that include technical performance, cost, and risk shown in Table RC-1.

A rating scale (from 1 to 5) was defined for each of the evaluation criteria (also shown in Table RC-1) 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, an additional rating of "showstopper" (SS) was defined. Such a rating was defined to indicate 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 was given for a particular communication candidate, further assessment of that candidate was stopped for the flight domain(s) under investigation since the candidate's rating for the criterion was determined to be completely unacceptable (i.e., a "showstopper" to selection as a viable candidate).

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 characterized 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 was used to rank the candidates, whereby a higher weighted "total score" for a given candidate represented a higher priority candidate. The weighting factors used in this assessment are provided in the second column of Table RC-1.

### **Evaluations**

The A-A and A-G communication candidates were all evaluated (using the evaluation criteria and rating scale as given in Table RC-1) for their ability to support the ATM communication needs. The evaluations were completed across a range of various flight domains, including airport surface (APT), terminal area (TMA), enroute (ENR), oceanic/remote, and polar (ORP). The assessments were done for each of these individual flight domains as well as for several combinations of flight domains.

An example evaluation matrix is shown in Figure RC-1, 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 assessed.

### **Prioritization Results**

Tables RC-2 and RC-3 summarize the results of the prioritized rankings of the A-A and A-G (respectively) communications candidates by flight domain.

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 commensurate with meeting the Required Communications Performance (RCP) for most of the long-term NAS ATM

applications that have been identified 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 long-term ATM applications.

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 quality of service 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.

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 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.

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.

Additional R&D is recommended to more comprehensively identify and evaluate communication candidate Figure RC-1: Evaluation Criteria, Rating Scale, and Weighting Factors Used to Evaluate and Prioritize the Communications Candidates.

Figure RC-1: A-A Communication Candidates Evaluations in Airport Surface Flight Domain

Airport Surface 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
Technical Performance			VHF	UHF	L-Band	S-Band	C-Band	X-Band	Optical	Hybrid RF/Optical	LEO SATCOM	GEO SATCOM	MEO SATCOM	GEO + HEO SATCOM
	1	6	Coverage Volume / Comm. Range	4	4	4	3	3	2	2	5	4	5	4
	2	5	Data Rate	2	2	3	4	4	4	5	4	4	4	4
	3	3	Spectral Efficiency	3	3	3	3	4	5	5	4	4	4	4
	4	5	Capacity	2	2	3	4	4	5	5	4	4	4	4
	5	3	Number of Users	2	2	3	4	4	3	3	4	4	4	4
	6	3	Availability & Continuity	5	5	5	5	3	1	2	5	4	5	4
	7	3	Integrity	5	5	5	5	4	5	5	4	4	4	4
	8	3	Latency	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	4	4	3	4
	10	3	Security / Vulnerabilities	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
	12	3	Installable on Range of Air Vehicles	4	5	5	4	4	3	2	2	2	1	2
	13	5	Ability to Support Broadcast Comms.	5	5	5	5	4	4	1	2	2	4	2
Cost	14	8	Satisfy Rqmts. for Safety Services (QoS)	5	5	5	5	5	3	1	2	3	1	1
	15	8	Satisfy Rqmts. for Advisory Services (QoS)	5	5	5	5	5	4	3	3	2	3	2
	16	9	Airborne Infrastructure Cost	5	5	4	3	4	3	1	1	3	2	2
Risk	17	4	Ground / Satellite Infrastructure Cost	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
	19	9	Spectrum Availability & Compatibility	5	1	5	3	5	2	2	5	3	4	3
	20	1	Technical Maturity / Readiness Level (TRL)	5	5	5	4	5	2	1	1	4	4	4
	21	1	Standization Status	4	3	3	3	4	1	1	1	4	3	2
	22	3	Global Harmonization Risk	5	2	5	3	5	3	2	2	5	4	4
	23	3	Certification Complexity	5	5	5	4	5	3	2	1	5	4	4
	24	3	Susceptible to Wide Outage / Long MTTR	4	4	4	4	4	3	1	2	2	1	2
	25	3	Ease of Transition	5	3	5	3	5	3	3	3	3	3	3
	-----		Candidate Non-weighted Total Score	105	94	107	97	107	80	65	69	93	78	81
	100		Candidate Weighted Total Score	429	378	435	394	434	327	257	276	371	291	315
			Candidate Priority in this Assessment	3	5	1	4	2	7	12	11	6	9	8

Table RC-1: Evaluation Criteria, Rating Scale, and Weighting Factors to Prioritize the Communications Candidates

				Ratings Scale Summary						
	#	Criteria Weight (%)	Evaluation Criteria	Brief Description	5	4	3	2	1	SS
					Very Good	Good	Medium	Fair	Poor	Showstopper 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	Easily 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	Easily Meets	Meets	Meets most	Meets many	Meets some	Does not meet QoS for Advisory Services
Cost	16	9	Airborne Infrastructure Cost	Relative airborne cost	Very Low	Low	Average	High	Very High	Cost Showstopper
	17	4	Ground / Satellite Infrastructure Cost	Relative cost of ground/satellite infrastructure to civil aviation	Very Low	Low	Average	High	Very High	Cost Showstopper
	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 susceptibility 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	---



**Table RC-2: Prioritization of A-A Candidates**

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

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

**Table RC-3: Prioritization of A-G 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

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

## 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:

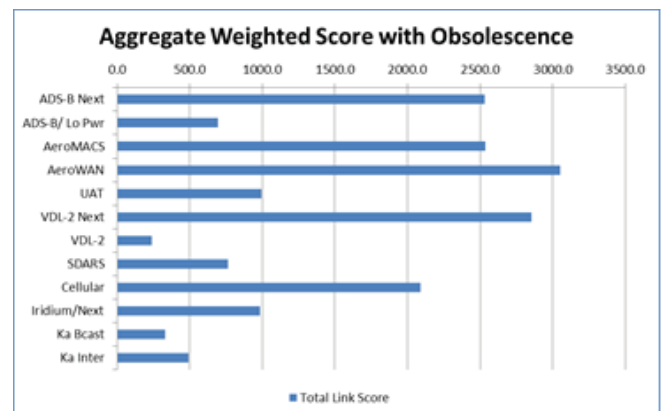
- Airborne Aircraft, Inbound Communications;

- 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 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 in Figure X-1 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.



**Figure X-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.

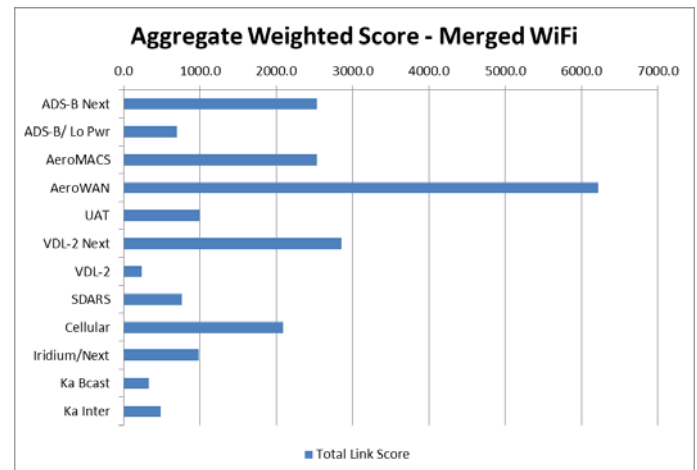
An additional analysis step examined the effect on rankings of merging two technically similar systems, AeroMACS and AeroWAN. Both are based on the same underlying mobile wireless networking technology, but as proposed in the study to date, serve different operating environments using different RF spectrum. AeroMACS is designed to serve aircraft on the ground, within the immediate airport environment, and is based on use of spectrum previously allocated to Microwave Landing Systems (MLS) from 5091 - 5150 MHz. AeroWAN is intended to serve aircraft in flight, and was originally envisioned to operate in re-purposed spectrum in the current DME band from 978 - 1213 MHz. However, if these two systems could be technically merged, a number of advantages could be realized. First, the same avionics and ground station equipment could serve both functions, reducing aircraft equipment cost, weight and complexity, and allowing commonality of ground station equipment, development, and production. AeroMACS ground stations established at airports could also be used to serve AeroWAN ground-air operations, reducing the number of AeroWAN-specific ground stations required. Seamless transitions from airborne to ground-based networking would become inherent to the system. From a merit score perspective, this unified system would serve a much wider range of future NAS functions than in the previous scoring.

From a technology investment standpoint, one area of interest was the potential identification of one or more particularly compelling solutions, whose broad applicability and potential benefits could yield significant benefits from a single development effort. The merging of AeroMACS and AeroWAN can be seen to offer just such an opportunity, and shown in Fig. 2 where the previous scoring (Fig. 1) is revised to reflect the relative merits of the "Merged WiFi" system compared to the same group of other solutions as previously scored. It can be seen that the Merged WiFi now ranks significantly higher than its nearest competitors – more than double in fact.

There are three basic technical approaches which could be used to merge the two systems. Either system could be modified to operate in the proposed spectrum of the other, or it is possible that over the 50-year period adequate technical advancements will have been made to permit a single SDR to operate successfully across the

very wide range of frequencies needed to operate in both bands simultaneously. Additional research is needed to assess the relative merits of these approaches and formulate recommendations.

The final phase of planned research is focused primarily on business case analysis, and is currently in progress. The top scoring candidates have been analyzed in terms of current conditions, projected future influences over the 50-year research period, and production volumes. A reference architecture has been developed for each candidate for each applicable market segment, establishing the number of redundant units of each type needed and other factors. Projected costs have been estimated for each applicable system, and estimates of related costs such as spares and maintenance are currently being finalized. The final business case analysis will be completed in October 2014. Based on analysis to date it is not anticipated that any gaps, from a business case standpoint, will be identified in fulfilling all identified future NAS functions using the candidates analyzed. The program is currently scheduled to conclude in late 2014.



**Figure X-2:** Aggregate Weighted Scores with Merged WiFi

## 5. CONCLUSIONS

The Next Generation 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 reduction and capacity increases to airlines, service providers and airspace users in general.

This paper described status and advances made in the Future Communications Concepts and Analysis NRA study performed by Honeywell Corp., Rockwell Collins Corp., and XCELAR LLC. The two-year effort investigates communications technologies, architectures,

cost, security, spectrum, evaluates technology maturity, viability and assesses of a range of applications that would be transported in the future. The findings to date indicate no one technology will provide services across different flight domains. Moreover, the solution space will include using different communication technologies working together to optimize performance at different stages of flight. A key enabler to achieving modernization is 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 and ground components. Cost analysis and benefit investigation reveals the need to take advantage of commercial communication networks rather than implementing custom aviation communications solutions. Additionally, this study has identified that modernization of communications infrastructure will require coordinated synchronization of operational improvements with technology deployments to maximize benefits.

This paper presented progress made in the three studies and described the communications challenges and opportunities that have been identified as part of the study.

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## 8. BIOGRAPHIES



**Ms. 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.



**Mr. Rafael Apaza** is a senior 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.



**Mr. 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 including: a B.S. in Electrical Engineering from the Milwaukee School of Engineering in 1987; an M.S. in Electrical Engineering from Washington University in 1991; and, an M.S. in Electrical and Computer Engineering from Iowa State University in 1995. Joel has completed research and



development in communications, navigation, and surveillance (CNS) systems; avionics flight decks; aircraft flight control and flight management systems; enhanced and synthetic vision systems; and air traffic management (ATM) technologies and systems in support of next generation (NextGen) airspace operations. Joel has 16 issued patents and has received numerous recognition awards during his career, including six citations from RTCA for his leadership and outstanding contributions to the development of aviation standards.



**Mr. 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

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**Mr. Aloke 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 managing several major telecommunications OEM accounts. In this role, Mr. Roy was responsible for business development, outsourcing, and globalization of hardware design activities supporting large volume contract electronic manufacturing. His prior experiences include various positions at Bell Laboratories and ARINC Aviation Systems Division. Currently, he chairs ICAO ACP Working Group 'S' and RTCA Special Committee 223, which are developing the Aeronautical Mobile Airport Communication System requirements and operational performance standards. Mr. Roy holds an MBA degree from University of Maryland-College Park and an MSEE degree from Louisiana State University.