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# Technology Candidates for Air-to-Air and Air-to-Ground Data Exchange

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# Technology Candidates for Air-to-Air and Air-to-Ground Data Exchange

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## 1 Executive Summary

*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. The research team, led by XCELAR, was tasked with identifying future National Airspace System (NAS) scenarios, determining requirements and functions (including gaps), investigating technical and business issues for air, ground, & air-to-ground interactions, and reporting on the results. The project was conducted under technical direction from NASA and in collaboration with XCELAR's partner, National Institute of Aerospace, and NASA technical representatives.

Parallel efforts were initiated to define the information exchange functional needs of the future NAS, and specific communication link technologies to potentially serve those needs. Those efforts converged with the mapping of each identified future NAS function to potential enabling communication solutions; those solutions were then compared with, and ranked relative to, each other on a technical basis in a structured analysis process. The technical solutions emerging from that process were then assessed from a business case perspective to determine their viability from a real-world adoption and deployment standpoint. The results of that analysis produced a proposed set of future solutions and most promising candidate technologies. Gap analyses were conducted at two points in the process, the first examining technical factors, and the second as part of the business case analysis. In each case, no gaps or unmet needs were identified in applying the solutions evaluated to the requirements identified.

The future communication solutions identified in the research comprise both specific link technologies and two enabling technologies that apply to most or all specific links. As a result, the research resulted in a new analysis approach, viewing the underlying architecture of ground-air and air-air communications as a whole, rather than as simple "link to function" paired solutions. For the business case analysis, a number of "reference architectures" were developed for both the future technologies and the current systems, based on three typical configurations of current aircraft. Current and future costs were assigned, and various comparisons made between the current and future architectures.

In general, it was assumed that if a future architecture offers lower cost than the current typical architecture, while delivering equivalent or better performance, it is likely that the future solution will gain industry acceptance. Conversely, future architectures presenting higher costs than their current counterparts must present a compelling benefit case in other areas or risk a lack of industry acceptance. The business case analysis consistently indicated lower costs for the proposed future architectures, and in most cases, significantly so. The proposed future solutions were found to offer significantly greater functionality, flexibility, and

growth potential over time, at lower cost, than current systems. This was true for overall, fleet-wide equipage for domestic and oceanic air carriers, as well as for single, General Aviation (GA) aircraft.

The overall research results indicate that all identified requirements can be met by the proposed solutions with significant capacity for future growth. Results also illustrate that the majority of the future communication needs can be met using currently allocated aviation RF spectrum, if used in more effective ways than it is today. A combination of such optimized aviation-specific links and commercial communication systems meets all identified needs for the 50-year future and beyond, with the caveat that a new, overall function will be needed to manage all information exchange, individual links, security, cost, and other factors. This function was labeled “Delivery Manager” (DM) within this research. DM employs a distributed client/server architecture, for both airborne and ground communications architectures.

Final research results included identifying the most promising candidate technologies for the future system, conclusions and recommendations, and identifying areas where further research should be considered.

## 2 Introduction

The effort to define, characterize and assess the relative merits of Technology Candidates for Air-to-Air and Air-to-Ground Data Exchange is designed to visualize and analyze the future aviation communication needs of the National Airspace System (NAS), and ultimately to recommend the optimum solutions based on the overall research results. Agile Defense, DBA XCELAR (XCELAR) performed the research summarized herein under contract to NASA, to perform a study of future air-to-air and air-to-ground datalink technologies as part of NASA's Airspace Systems Program. The study focused on identifying technologies and potential solutions to address datalink needs of the air transportation system fifty years into the future, nominally from 2013, when research began, through 2063. XCELAR's approach incorporated both technical and business considerations, and considered the needs of General Aviation and Unmanned Aerial Systems in addition to those of air carriers and other jet operators. The perspective of the aircraft operator was an integral element of the evaluation process.

A key consideration was to correctly define the underlying assumptions for the air transportation system in the year 2063, particularly in terms of regulatory considerations, system user expectations and sensitivities, and their rate of evolution over the 50-year period. One useful input to that process was to look back over a similar period, and assess the rate of change over the past 50 years in the same industry.

Examples of significant technical events approximately 50 years ago include:

- 1963 - B727 first flight
- 1963 – Cessna 336 enters service; 1965 – Cessna 337 in certification
- 1963 – Lear 23 first flight
- 1963 – First Laser Ring Gyro demonstrated
- SELCAL entered service approximately 50 years ago

More recent events help to put the timeline into better perspective: these notable events took place approximately 30 years ago:

- 1983 – First cellular telephone received FCC approval (Motorola DynaTac)
- 1983 – First PDA (Psion 1); 1993 – Apple Newton
- 1983 – GPS made available for civil use
- 1981 – First Laser Ring Gyro certified
- ACARS Entered service

This illustrates that the entire history of aviation datalink services to date is only approximately 30 years, making the 50-year future projected herein nearly 40% longer than its whole service history. Thus, it is reasonable to postulate that the next 50 years could produce a greater scope of innovation, technology introduction, performance gains, and overall progress than aviation data link has seen since its inception.

The XCELAR research team includes industry professionals whose experience spans the history of aviation data link to the present time, with an impressive track record in developing, implementing, operating, and improving all types of aviation data links, in all segments of the industry. The team believes that the research conducted, and the results presented herein, are both achievable and practical, and present a viable approach to meeting the aviation communication needs of the future.

### **3 Research Plan**

The research was conducted in accordance with a structured plan that included parallel work flows to define the future datalink requirements, and to identify and characterize technical candidates. Those two paths converged in comparison and gap analysis steps, with provisions for a “feedback loop” process to revisit previous steps as needed to fill gaps identified.

Technical analysis results were then examined from a business perspective, and another gap analysis/feedback stage planned prior to final identification and characterization of the most favorable candidates.

A regular reporting process was used, employing a combination of monthly and other scheduled reports, and periodic results reports at key stages of the research process, among the program deliverables.

#### **3.1 Research Process**

The anticipated functions and requirements of the NAS of the future were defined using input from NASA, industry, academia, and the study team, using a structure based on phase of flight and vehicle/operator types. These scenarios were then used to derive the associated information flow and data communication requirements. In parallel, initial analysis of candidate link technologies was initiated, starting with projected capabilities, loading, and improvements of currently available technologies through the study period.

An initial analysis of currently known link technologies was conducted to assess their current and probable future capabilities compared to projected loads and other factors. This “look forward” analysis provided a starting point in the identification and analysis of future solutions. It quantified potential unmet needs in current systems, and thus identified that may require new solutions. An example is the current use of 1030/1090 MHz for ATRBS, ADS-B, TCAS, and other proposed functions such as air-to-air linking of wake turbulence data. The research team’s analysis indicates that the current system will reach its capacity limit well before the 50-year future point, and alternate solutions must be considered as part of the study.

The research then considered various candidate technologies for alternative future links, characterizing those that showed the most promise from a technical standpoint, and incrementally maturing the most viable ones. Architectural and infrastructure issues were considered, along with compatibility with other current and future systems. Performance modeling was conducted to allow technical comparisons between candidates, and a structured candidate comparison was developed between the twelve most viable candidates from a technical perspective.

Finally, those candidate solutions that were deemed technically viable were subjected to business case analysis, which examined the costs of proposed future solutions relative to current industry practice. The ultimate goal of the research was to identify a group of most promising technologies for the aviation datalink 50 years in the future.

Fig. 1 depicts the overall flow of the research from beginning to end, with reports at various key points in the process. The parallel paths of defining future NAS functions and derived communication requirements, and of identifying potential candidate link technologies, are shown in the upper left area. Those two efforts converge with the evaluation of candidates against technical requirements, with those deemed to be worthy of further research documented in the *Technology Candidate Descriptions* report. An analysis of various system considerations was then initiated, with the results documented in the *Infrastructure and Architectural Needs* report.

At this point in the research, any identified gaps or unmet needs would have initiated a parallel effort to identify additional or alternative candidates to potentially fill the gap. This part of the process is depicted in the upper right portion of the flow chart. Remaining candidates were subjected to a structured comparison process to quantify the relative merits of all viable candidates for each identified function, from a technical perspective. Results were documented in the *Candidate Comparison* report. One of the conclusions of the research to that point was that there were in fact no gaps or unmet needs, and a group of nine candidate link technologies, and two underlying or enabling technologies, became the focus of the business case analysis.

The business case analysis, shown near the bottom center of the flow chart, examined the potential costs of the 50-year future solution proposed as a result of the technical research, relative to current industry solutions and their costs. Another gap analysis was performed based on the totality of the research and its results, with another potential “feedback loop” to examine potential ways to fill identified gaps. Again, no gaps were identified, and the research proceeded to the final planned step, identifying the most promising candidate solutions. Both the business case analysis and the most promising solutions were documented in the *Most Promising Technology Alternatives* report. The research was divided into two segments, designated the Base Year and Option Year one. Base Year activities were initiated in October 2012, and Option Year 1 concluded in January 2015.

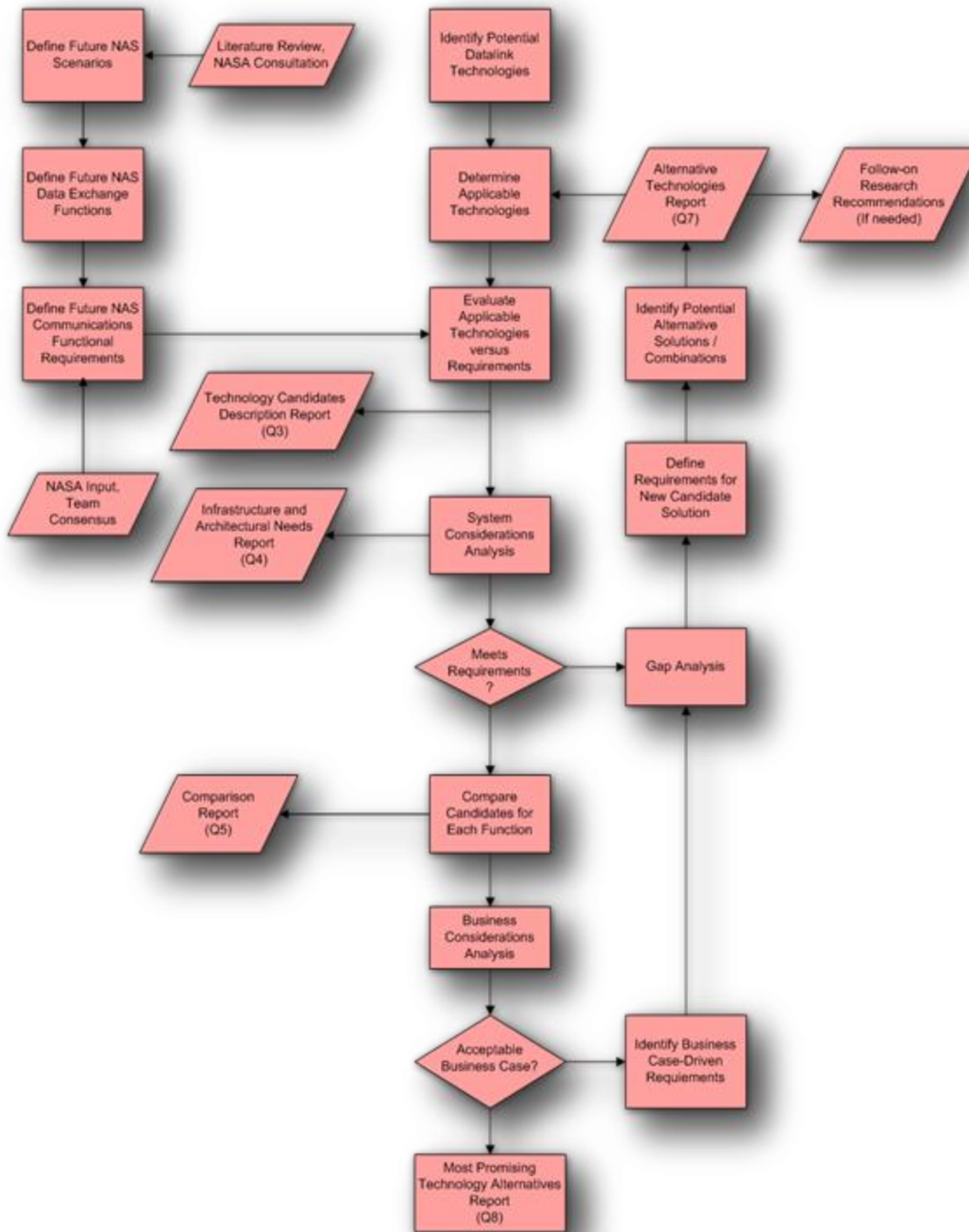


Figure 3-1 Research Flow Chart

### **3.2 Work Breakdown**

The research was conducted in accordance with a structured Work Plan, submitted as the first Deliverable. Major tasks included the following, structured in accordance with the research process shown in Fig. 1.

- KOM and Work Plan
  - Work Plan document
- Literature Review
- Define Future NAS Scenarios
  - Host and Organize a NAS Communications Workshop
  - “Summary of Results of the Future NAS Communications Workshop” report
  - “Future NAS Scenarios” report
- Define Data Exchange Functions
- Define Data Communications Functional Requirements for Each Scenario
  - Identify Candidate Link Technologies
  - Derive Functional Requirements
  - Evaluate the Suitability of the Various Candidate Link Technologies
  - Prepare a Functional Requirements Matrix
  - Include value-weightings (must-have, very desirable, nice-to-have)
- Define Potential Datalink Technologies
  - Evaluate the suitability of the identified datalink technologies
  - Identify existing, updated and new datalink systems
  - “Technology Candidate Descriptions” report
- Infrastructure and Architecture Needs
  - Analyze the System Level considerations of each Candidate datalink technology
  - Interoperability with other systems
  - Applicability across multiple user groups, scalability over time and changing industry needs



- Failure modes, effects, and backups needed to achieve the functional requirements
- “Infrastructure and Architectural Needs” report
- Conference Presentation
  - ICNS 2013
- Base Year Report
- Characterize and Compare Candidates
  - Comparison matrix correlating functional requirements against both existing and emerging candidate systems
  - Comparing candidates for the same functions with each other
  - Identify functional or operational gaps for each candidate system
  - “Candidate Comparison” report
  - Prepare a business case for each candidate technology
  - Consider current conditions, projection of future influences like advances in component design and increased production volumes
  - “Most Promising Technology Alternatives” report
- Gap Analysis and Alternative Technologies
  - “Alternative Technologies” report
- Conference Presentation
  - ICNS 2014
- Final Review Presentation and Final Comprehensive Report
  - “Final Comprehensive Report”

### **3.3 Research Team**

The research team was conducted by prime contractor XCELAR and its subcontractor, National Institute of Aerospace (NIA). Organizational roles and responsibilities are summarized in Table 1, and Table 2 provides information about key personnel contributing to the research.

**Table 3-1: Organizational Roles and Responsibilities**

Organization	Roles and Responsibility
AGILE DEFENSE / XCELAR	Principal Investigator Science CO-I CO-I Program Management
National Institute of Aerospace (NIA)	SME / Academic Coordination Project Management

**Table 3-2: Key Personnel**

<b>Brian Haynes / XCELAR</b>	<ul style="list-style-type: none"> <li>• Overall program leadership</li> <li>• Manage conduct of research, and overall technical direction</li> <li>• Subject Matter Expert (SME) – multiple areas, including: airline and General Aviation (GA) operations; ground-air communication systems; weather data systems; aircraft integration; business case analysis; avionics; small UAS design &amp; avionics considerations</li> <li>• Schedule, logistics, progress reports, budgetary management</li> <li>• Contact PI</li> </ul>
<b>Captain Robert “Rocky” Stone</b>	<ul style="list-style-type: none"> <li>• Scientific direction of work</li> <li>• SME – multiple areas, including: airline operations; flight deck systems; ADS-B; air traffic management; turbulence mitigation; flight deck weather applications; NextGen; business case analysis; system engineering</li> </ul>

	<ul style="list-style-type: none"> <li>• Requirements definition &amp; suitability analysis</li> <li>• Airline industry outreach / input solicitation</li> </ul>
<b>Richard Haendel / XCELAR</b>	<ul style="list-style-type: none"> <li>• Communication Systems Analysis</li> <li>• SME – multiple areas, including: avionics components, systems and design; avionics manufacturing, certification, and cost projection; RF propagation and performance analysis; antenna design and integration; satellite communication systems and technologies; ground-air &amp; air-air communications; network design, analysis, and fault tolerance assessment; Airline, Business, GA, large UAS, and military avionics systems</li> <li>• Requirements definition &amp; suitability analysis</li> <li>• Avionics industry outreach / input solicitation</li> </ul>
<b>Dan Johnson / XCELAR</b>	<ul style="list-style-type: none"> <li>• Market Impact Analysis</li> <li>• SME – multiple areas, including: GA manufacturing, cost projection, market analysis, and operations; aircraft sensors and air data systems; GA datalink and weather systems; small UAS applications &amp; market analysis</li> <li>• Program logistic and administrative support</li> <li>• GA industry outreach and input solicitation</li> </ul>
<b>Fred Brooks / NIA</b>	<ul style="list-style-type: none"> <li>• Academic community coordination</li> <li>• GA and VLJ systems analysis</li> <li>• SME – multiple areas, including: GA ADS-B systems and applications; VLJ design, market analysis, and operations; NextGen; FAA, NASA, and academic research in aeronautics</li> <li>• Program logistics support</li> <li>• NASA outreach and input solicitation</li> <li>• Academic community outreach and input solicitation</li> </ul>

<b>Hank Jarrett</b>	<ul style="list-style-type: none"><li>• Literature Review Lead</li><li>• SME – multiple areas, including: systems engineering; satellite communication systems design; safety engineering; GA ADS-B applications; NASA AGATE and SATS programs, and subsequent related research and literature; business case analysis</li><li>• Coordination and harmonization of NAS scenarios with other related research</li><li>• NASA outreach and input solicitation</li></ul>
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## 4 Literature Review

A Literature Review was conducted as an initial step to familiarize the team with previous efforts that might affect the conduct of the research, such as avoiding duplication of efforts, or suggesting areas where additional or targeted study is needed. The scope of the review included future NAS operations concepts, future datalink technologies, and future information exchange needs. A detailed summary of literature reviewed can be found in Appendix 2.

The goal of the literature review was to identify and document past or existing efforts and documentation regarding the datalink needs of the future National Airspace System (NAS) Air Transportation Systems for the 2013-2063 time period. Objectives were to identify relevant analysis, studies, and methodology during the literature review, to help bring the current state of knowledge in synch with the team's hypotheses, including the potential identification of:

- Applicable "Future NAS Scenario" inputs
- Other research that has investigated closely related issues
- Extant models applied to similar problems, and their assumptions
- Alternate analysis methods that could apply to this project
- Existing questions that can be applied to this work effort
- Harmonize study elements with other related efforts (example: harmonize Future NAS Scenarios with other Future NAS studies and outputs)
- A roadmap of future research to be conducted in the remainder of the effort in this contract.

Each Lead Reviewer, and other contributors as needed, captured notes from each document that were deemed to have possible relevance to the conduct of this research. These notes were then reviewed and evaluated by the overall team, and used to produce the following findings:

- There has been very limited applicable study work in the past 10 – 15 years
- The majority of previous work pertains to already-identified link technologies and/or NAS concepts, not future concepts
- There is a tendency to focus on specific link technologies and their capabilities rather than future functions/unmet needs
- There is very limited consideration of link-independent, result-based data delivery concepts rather than specific links for each purpose
- The current research effort's planned approach of defining the future NAS, then functions/unmet needs, then delivery solutions continues to look like the correct methodology
- "Form follows function" thinking is needed, rather than the reverse

## 5 Future Data Exchange Requirements

A workshop was held to develop the underlying assumptions to be used in defining future information exchange needs, and to develop consensus on the working definition of the “50-year Future”, and related scope issues, for NAS scenario development and for the remainder of the study. The research team considered the overall question of expected characteristics of the future NAS, along with more in-depth discussions of specific NAS capabilities, vehicle capabilities, and potential “mid-point” scenarios to understand how transitions from current to future states might be accomplished. Due to limitations of workshop time, efforts were focused primarily on air transport users; in some cases additional sub-scenarios were developed later in the research where the defining NAS characteristics were expected to differ for other user groups (i.e., General Aviation, charter, Business Aviation). In some cases more detail was added to the future NAS concepts as the analysis of various link candidates raised additional requirements questions. The results of the workshop and future NAS definitions were documented in the *Future NAS Scenarios* report. The following sections summarize the future NAS scenarios, derived information exchange needs, and future communication functions.

Scenarios were developed based on the needs of the future NAS for safety, efficiency, and capacity. Scenarios were structured by phase of flight, and included departure, enroute, arrival, and ground operations. Four baseline scenarios were developed during the workshop to illustrate the considerations to be used throughout the research effort.

### 5.1 Future NAS Scenarios

The underlying concept for future National Airspace System (NAS) operations was based on a network-based Air Traffic Management (ATM) approach, in which the aerial vehicle (including commercial aircraft, corporate and private jets, General Aviation (GA), and a wide range of Unmanned Aerial Systems (UAS)) has a high degree of autonomy. Universal ADS-B deployment for all IFR operations, and most VFR operations, was assumed. Overall traffic flow would be optimized across the system based on four types of interactions between the aircraft and the system:

- Establish/negotiate expected flight conduct;
- Monitor compliance; annunciate actual/expected deviations;
- Adapt network to deviations;
- Negotiate / establish new expectations as needed.

This can either be centrally managed (i.e., a ground function) or distributed. The basic communication elements are essentially the same in either case under the study concept, but the distribution of traffic changes. For example, in a centrally-managed model more of the conduct-of-flight communications would involve ground-air-ground communications, whereas in a distributed model more air-air communications would be required. For initial Phase 1 evaluation a ground-based ATM function was assumed for operations over land masses; oceanic operations were assumed to involve a greater degree of distributed management and separation, facilitated by ground ATM via space-based ADS-B. The study was structured to accommodate straightforward adaptation to varying levels of distributed ATM in future iterations.

The future NAS scenarios defined in the workshop and subsequent updates are summarized below. Four basic scenarios were developed, to characterize information exchange needs during four phases of flight: Departures, Enroute/Cruise, Arrivals, and Ground Operations.

#### **5.1.1 Scenario 1: Terminal Operations - Departures**

- User Group – Air Transport
- Top-Level Goals:
- Increased Capacity over Current Levels
  - Maintain Capacity Over Wide Range of Operating Conditions
- Maximize Efficiency for All Operations
- Primary Measure: Aggregate Cost
- Includes fuel, crew cost/time, asset utilization
- Equivalent or Greater Level of Safety

#### **5.1.2 Expected Capabilities & Needs**

- Departure throughput is limited by runway occupancy and wake vortex avoidance criteria
  - Departure throughput requires ground operations to deliver aircraft to the runway with minimum queueing and delay
- Optimum routing on departure with collision avoidance
  - Eliminate the climb corridor; begin wind-optimized Great Circle Route as soon as possible after lift-off
  - Minimized tunneling or standard departure routing, allow for User Preferred Routing (UPR) shortly after take-off with real time de-confliction as necessary from arrivals, en-route traffic
- Optimum profile climb on departure
  - Uninterrupted climb / high-speed
  - Prioritized over the Optimum Profile Descent

- Wake Vortex avoidance
- Hazardous weather avoidance
  - Convection, icing, turbulence
- Terrain clearance

### 5.1.3 Scenario 2: Enroute Operations

- Defined Enroute to begin at Top of Climb (TOC) and end at Pre-Arrival Sequencing point)
- Primary User Group – Air Transport
- Top-Level Goals:
  - Increased Capacity over Current Levels enabled by new separation standards and better surveillance tools
  - Two separation standards, tailored to avoid the specific hazard
    - Collision avoidance separation standard
    - Wake vortex avoidance separation standard
  - Maximize Efficiency for All Operations
  - Primary Measure: Aggregate Cost
    - Includes fuel, crew cost/time, asset utilization
  - Equivalent or Greater Level of Safety
  - Maintain Capacity Over Wide Range of Operating Conditions

#### 5.1.3.1 Expected Capabilities & Needs

- Flow control / pre-arrival conditioning (course granularity)
  - Pre-arrival sequencing nominally begins at 150-500 miles
- Increased traffic density / decreased spacing
- Higher cruise altitudes
- Some sub-orbital operations
- Collision avoidance
  - Optimized conflict detection and resolution
- Pair-wise Trajectory Management (PTM)
  - Deviations from the optimum only to resolve actual conflicts
  - Multiple layers of conflict detection and collision avoidance
  - Predictive behavior of adjacent aircraft
- Altitude optimization for wind and aircraft performance or ride quality
  - Flights not required to be at cardinal cruise altitude, all aircraft performing constant cruise/climb
- Route optimization for fuel burn and time
- Hazardous weather avoidance



- Convection, turbulence, volcanic ash
- Wake vortex avoidance

#### **5.1.4 Scenario 3: Terminal Operations - Arrivals**

- User Group – Air Transport
- Top-Level Goals:
  - Increased Capacity over Current Levels
  - Maximize Efficiency for All Operations
  - Primary Measure: Aggregate Cost
  - Includes fuel, crew cost/time, asset utilization
  - Equivalent or Greater Level of Safety
  - Maintain Capacity Over Wide Range of Operating Conditions

##### **5.1.4.1 Expected Capabilities & Needs**

- Traffic sequencing to minimize arrival constraints
  - Assumed that runway utilization is the limiting factor for increasing arrival throughput
- Any delays for sequencing and runway availability absorbed while the aircraft is more efficiently operating at cruise altitude
  - I.e., rather than in an “trombone downwind”
  - Process (communications) begins: 150-500 nm “upstream”
- Optimum User Preferred Routing (UPR) from the en route environment to the runway
- Optimum Profile Descent (OPD) along optimum route
- Collision avoidance throughout arrival
- Terrain clearance assured throughout arrival
- Wake vortex avoidance throughout the arrival
  - Wake vortex efforts are significant (now) and we assume that the phenomenon will be much less of an impact to the NAS – thus, the “Communication” needs of the NAS will be impacted by an increase in airspace density (congested terminal area)
- Assumption: closer spacing than current (<1 mile) – for “worst Case” datalink modeling
- Assumption: wake alleviation technologies
- Hazardous weather avoided throughout arrival
- Convection, Icing, Turbulence
- Stabilized approach

- Glide path, final approach speed, and landing configuration by 3 miles on final approach

### **5.1.5 Scenario 4: Ground Operations**

- User Group – Air Transport
- Assumed no significant increase in surface landing facilities (Concrete)
- Top-Level Goals:
  - Increased Capacity over Current Levels
  - Maximize Efficiency for All Operations
  - Primary Measure: Aggregate Cost
  - Includes fuel, crew cost/time, asset utilization
  - Equivalent or Greater Level of Safety
  - Maintain Capacity Over Wide Range of Operating Conditions

#### **5.1.5.1 Expected Capabilities & Needs**

- Gate departure metering & arrival scheduling to achieve minimized queuing at the runways, taxiways, and gates
  - Accurate communication of “anticipated” departure time to ATM
  - Coordinated pushback/flow management/departure clearance timing
- Autonomous Taxiing
  - Guided taxiing
  - Now: green lights depict “your” path to the gate from your runway exit
  - Cockpit will receive optimized ground routing, speed, etc. to and from runway
  - Includes: Runway incursion protection, metering, collision avoidance, optimized routing
- Low visibility flow management & collision avoidance; synthetic vision navigation, ground collision avoidance system
- Deice routing/queue management; weather/holdover time monitoring
  - Pass-through de-icing
  - Aircraft takes care of de-icing / anti-icing themselves
- Safety separation for small aircraft behind large aircraft / jet blast
- Security / Police / SWAT / Secret Service / TSA
- Fire / Emergency Ops / Medical
- Customs / Immigration
- Weather information for all ground operations

## **5.2 Information Exchange Breakdown**

Using the scenarios as a guide, a breakdown of overall information exchange needs was developed. Information exchange needs were categorized into general groups that were not limited to a particular type or class of aircraft. As a reminder both to the research team and future reader that information exchange needs apply to all types of airspace users, the term “air vehicle” was used, to include not only traditional aircraft, but other types of current and future vehicles including lighter than air craft, space vehicles, UAS, hypersonic vehicles, and others. Information exchange needs were organized by the destination and direction of exchange:

- Information from the air vehicle
- Information to the air vehicle
- Information from ground-based Air Traffic Management (ATM)
- Information to ATM
- Information from ground-based non-ATM (i.e., dispatch, flight following)
- Information to ground-based non-ATM

Functional categories of information exchange were defined for each group, as the basis for developing more detailed functional requirements. The following section summarizes the top level information exchange needs identified in conjunction with the NAS scenarios.

### **Information from air vehicle**

- Vehicle status
  - Health
  - System status
  - Departure from normal conditions
  - Location
  - State Vector / Aerodynamic information about vehicle
  - Intentions
- Local environment atmospheric
- Acknowledgement of select input data
- Special requests
- Stream of data from occupants / cargo on board

### **Information to air vehicle**

- Other proximate vehicle status / information
  - Location
  - State Vector / Aerodynamic information about vehicle
  - Intentions
  - Atmospheric

- Airspace system information
  - Enroute
  - Destination
  - Atmospheric
- ATM Guidance & relevant information
- Acknowledgement of select output data
  - e.g. Conflict resolution negotiation
- Replies to special requests
- Stream of data to occupants / cargo on board

#### **Information from ground-based ATM**

- Airspace system information
  - ATM Guidance & relevant information
  - Processed Atmospheric
- Replies to special requests
- Non-cooperative airborne objects (aircraft, birds, balloons, etc.)
  - Location / State Vector / Aerodynamic information about objects

#### **Information to ground-based ATM**

- All vehicle status / information
  - Location
  - Health / departure from normal
  - State Vector / Aerodynamic information about vehicle
  - Intentions
- Atmospheric
- Inputs from/about non-cooperating vehicles
- Acknowledgements & Replies to special requests
- Monitoring of conflict resolution, routing changes

#### **Information from ground-based non-ATM**

- “Company” communication
  - AOC, AAC
  - Mission pertinent
- “Personal” communication (to passengers)
  - Voice, data
- Security
- Command & Control for autonomous operations
- Atmospheric

### **Information to ground-based non-ATM**

- “Company” communication
  - AOC, AAC
  - Mission pertinent
- “Personal” communication
  - Voice, data
  - Telemetry [Data]
- Video / Graphics
- Security
  - e.g. FAMS air-to-ground, cabin surveillance, emergency control of air vehicle (dialog with ground-based emergency control)
- Command & Control acknowledgements to ground
- Atmospheric information

These functional information exchange needs formed the basis for deriving specific data communication functions and associated requirements to be used to assess various candidate solution technologies. Candidate link technologies were then vetted against those requirements to measure how effectively the various candidates fulfilled the relevant requirements and their associated functional objectives, as summarized in the following sections.

### ***5.3 Data Communication Functions***

This section summarizes the user functions defined for use within the research effort. 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.

Each function was given a Function Code for ease and consistency of reference, categorized by the general type of operation involved. Four types of functions and codes were used:

- AAI-x refers to Airborne Aircraft, Inbound Communications;
- AAO-x refers to Airborne Aircraft, Outbound Communications;
- AGI-x refers to Aircraft on the Ground, Inbound Communications; and

- AGO-x refers to Aircraft on the Ground, Outbound Communications

For example, AAI-1 denotes the first function defined under Airborne Aircraft, Inbound Communication, AAI-2 the next, and so on. Function codes for each function can be found in the leftmost column of the tables in Appendix 1.

### 5.3.1 Airborne Aircraft, Inbound Communications (See also Appendix 1A)

This category includes communications received by aircraft in flight, both from airborne and ground sources. Appendix 1A provides more detail on aircraft types: Unmanned Aircraft (“U”), General Aviation (“G”), Air Transport (“A”), or Hypersonic (“H”), defined for this study as a maximum if Mach 8.

- **AAI-1** Information from other proximate aircraft used by own ship for flight path de-confliction, collision avoidance, and wake vortex avoidance. Own ship must be able to see aircraft far enough away to allow for all three applications. 80 mile range suggested from RTCA DO-289, Minimum Aviation System Performance Standards (MASPS) for Aircraft Surveillance Applications (ASA).
- **AAI-2** Other information used by own ship for general situational awareness about proximate traffic.
- **AAI-3** Other information used by own ship for the prediction of a “wake free” flight path. From RTCA DO-339.
- **AAI-4** Digital information used by own ship systems for the avoidance of significant hazardous weather or the mitigation of significant hazardous weather encounters. Information used for pilot situational awareness. From RTCA DO-340.
- **AAI-5** Digital information used by own ship systems for the avoidance of hazardous weather or the mitigation of hazardous weather encounters. Information used for pilot situational awareness. From RTCA DO-340.
- **AAI-6** Digital information used by own ship for the avoidance of immediately hazardous weather, as defined by RTCA DO-308.
- **AAI-7** Information to allow for the efficient management of own ship with regard to Time Based Flow Management (TBFM) constraints.
- **AAI-8** Additional general pertinent information required for arrival at an airport.
- **AAI-9** Graphical depictions of weather information used by general aviation flight crews for the avoidance of hazardous weather or the mitigation of hazardous weather encounters. Information used for pilot situational awareness. From RTCA DO-340.
- **AAI-10** Graphical depictions of weather information used by air transport flight crews for the avoidance of hazardous weather or the mitigation of hazardous

weather encounters. Information used for pilot situational awareness. From RTCA DO-340.

- **AAI-11** Textual weather information used by air transport flight crews for the avoidance of hazardous weather or the mitigation of hazardous weather encounters. Information used for pilot situational awareness. From RTCA DO-340.
- **AAI-12** Textual weather information used by general aviation flight crews for the avoidance of hazardous weather or the mitigation of hazardous weather encounters. Information used for pilot situational awareness. From RTCA DO-340.
- **AAI-13** Numerical weather information used by UAV operators or UAV onboard systems for the avoidance of hazardous weather or the mitigation of hazardous weather encounters. Information used for pilot situational awareness.
- **AAI-14** Miscellaneous Air Traffic Management information primarily used for long term planning.
- **AAI-15** Airline Operational Control (AOC) messages.
- **AAI-16** Airline messages for passenger convenience.

### ***5.3.2 Airborne Aircraft, Outbound Communications (See also Appendix 1B)***

This category includes communications transmitted from aircraft in flight, both to other aircraft and to ground destinations.

- **AAO-1** Information for ATM and other proximate aircraft to be used for flight path de-confliction, collision avoidance, and wake vortex avoidance. Own ship must be able to see aircraft far enough away to allow for all three applications. 80 mile range suggested from RTCA DO-289, Minimum Aviation System Performance Standards (MASPS) for Aircraft Surveillance Applications (ASA).
- **AAO-2** Other information used by ATM and proximate aircraft for general situational awareness about transmitting traffic.
- **AAO-3** Other information used by ATM and proximate aircraft for the prediction of a “wake free” flight path. From RTCA DO-339.
- **AAO-4** Special category of transmission of location and state information primarily from small UAVs for the use of ATM and proximate aircraft.
- **AAO-5** Vehicle health information from manned vehicles.
- **AAO-6** Vehicle health information from UAVs.

- **AAO-7** General atmospheric information used to initiate and validate numerical weather models.
- **AAO-8** General atmospheric information used to initiate and validate numerical weather models, at higher data collection rates for better resolution in the terminal area.
- **AAO-9** Special requests from aircraft.

### 5.3.3 *Aircraft on Ground, Inbound Communications (See also Appendix 1C)*

Communication with aircraft that are not in flight was considered separately, due both to the availability of different link options and to the potential inefficiency of using ground-air or air-air link for ground-ground communications. This section summarizes communication functions inbound to the aircraft while it is on the ground.

- **AGI-1** Non-instructional situational awareness information such as ATIS, NOTAMS, Traffic Flow Management restrictions, active runways, etc.
- **AGI-2** Graphical weather products for general situational awareness.
- **AGI-3** Graphical weather products for specific hazards, such as Terminal Doppler Weather Radar (TDWR) for convection, gust fronts, etc., WSDM for icing information, etc.
- **AGI-4** Textual weather products for air transport pilot situational awareness.
- **AGI-5** Textual weather products for general aviation pilot situational awareness.
- **AGI-6** Numerical weather products necessary for UAV flight operations.
- **AGI-7** Taxi out instructions from ramp and ATC.
- **AGI-8** Departure clearance, and any other ATC instructions.
- **AGI-9** Airline operational control messages such as destination gate assignment, maintenance information, weight and balance information.
- **AGI-10** Airline administrative information, such as passenger connecting gate information.
- **AGI-11** Information from proximate vehicles on their location and intentions.
- **AGI-12** Information about proximate vehicle characteristics.
- **AGI-13** Information from proximate vehicles needed to determine any wake vortex constraints on departure.
- **AGI-14** Hazardous weather reports from other proximate aircraft in the terminal area.



#### 5.3.4 *Aircraft on Ground, Outbound Communications (See also Appendix 1D)*

These functions are similar to AGI, but focus on communications outbound from the aircraft and are accordingly designated as “AGO-x”.

- **AGO-1** Vehicle position and velocity information, including an indication that the vehicle is “on the ground”.
- **AGO-2** Vehicle position and velocity information from a UAV, including an indication that the vehicle is “on the ground”.
- **AGO-3** Vehicle status and health information.
- **AGO-4** Vehicle status and health information from a UAV.
- **AGO-5** Transmission of the value of the initial circulation strength of the wake vortex of the aircraft once it becomes airborne. This information can be used to plan departure queues and for wake vortex mitigation upon departure.
- **AGO-6** Local weather observations. Not all information may be available until the aircraft is in the air.
- **AGO-7** Special Requests. A general category to include various specialized needs such as gate assignment, passenger connection information, and medical information for passenger emergencies.

## 6 Candidate Technologies

This section summarizes the candidate technologies that were included in the candidate comparison process, including both specific links and the two enabling technologies that are associated with most or all of the proposed link implementations. Each candidate technology is summarized from a technical perspective, including its associated architecture considerations such as interoperability, applicability to multiple user groups, scalability over time and changing industry needs, and the potential impacts of failures on the overall system. Architectures are described functionally, in keeping with the conceptual nature of the study at the current stage. The candidate technologies described are:

- Broad-Band Software-Defined Radio (SDR)
- Delivery Manager / Overall System Architecture
- VHF Datalink, including VDL Mode 2 (VDL-2)
- ADS-B and ADS-B Next
- AeroMACS
- AeroWAN
- SDARS
- Commercial Cellular Links and “Cloud Communications”
- Ku-/Ka-Band satellite
- Iridium/Next and similar L-Band LEO links

### 6.1 Enabling Technologies

As previously discussed, the research team identified two enabling technologies considered to be important to the successful implementation of various link-specific technologies in the future architecture: Broad Band software Defined Radio (BBSDR) technology, and the Delivery Manager (DM) function. These two technologies serve as a platform on which various link-specific solutions are integrated in a system-based approach. As such, while neither functions directly as a communication link, they are common to the overall success of all.

#### 6.1.1 Broadband Software-Defined Radio (BBSDR) Technology

BBSDR technology allows a single radio device to operate across an entire frequency band simultaneously, operating multiple links of various types using Digital Signal Processing (DSP) techniques. The BBSDR Architecture is shown in Fig. 2. The Software Defined Radio (SDR)

component allows the device to adapt to new types of modulation and other link characteristics by changing its software, rather than altering or replacing its hardware as in conventional radio systems. By 2063 this technology will enable a single receiver to monitor the entire L-Band, or VHF Band, large segments of the cellular communications spectrum, or even large portions of the Ku- or Ka-Band, demodulating and outputting link content to the DM from multiple links over a single high-speed interface. It will also provide the DM with detailed information on link quality and other characteristics for the DM to use in managing overall communication effectively. The same is true for transmission, with slightly different architecture.

This technology allows the operation of many links in parallel, using a small number of Line Replaceable Units (LRUs) for maximum capability at minimum cost and complexity. Redundancy is greatly simplified; for example, all L-Band links could be made fully redundant using two identical L-Band BBSDR units.

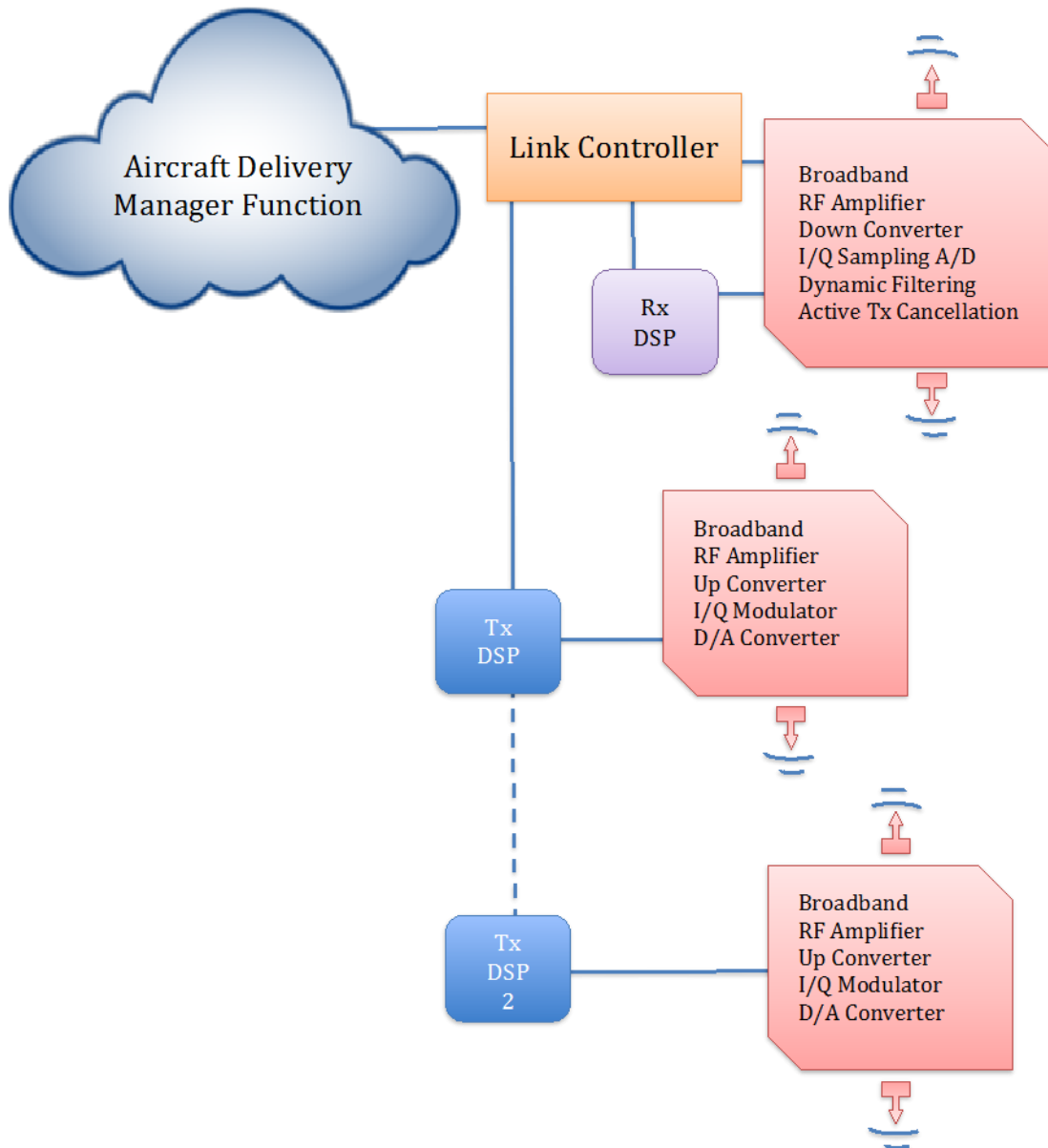
A BBSDR-based architecture can enable substantially increased longevity for avionics, and reduced susceptibility to obsolescence, through its ability to use software-only updates to many formerly hardware-based link characteristics. Modulation and demodulation, data encoding and decoding, tuning and filtering, bandwidth and channelization, error correction, and data rates are all examples of link characteristics that can be changed in a wide variety of ways via software load, or in many cases, even simpler field configuration data updates on an SDR-based device. This allows a single avionics unit to be upgraded and adapted to evolving system capabilities, spectrum availability, and other technologies to a much greater degree than current equipment.

#### **6.1.1.1 BBSDR Architecture**

A single BBSDR would be able to access all links in a given frequency band. Two or more identical units would be used to provide redundant backup where required. Initially this would include one BBSDR unit (plus backups) each for the VHF aviation band and the entire L-Band. L-Band links could include the current DME, TACAN, ADS-B, TCAS, UAT, GNSS, and Iridium communication systems, along with the proposed 1030 MHz ADS-B Next, and other services. Each BBSDR will be managed by the DM.

Receive (RX) and Transmit (TX) functions for each BBSDR have somewhat different architectures. TX and RX antennas should be physically separated to minimize TX interference with RX operations. A single BBSDR may also have more than one TX subsystem depending on performance requirements for simultaneous transmissions at high power on different links. A single TX subsystem can be configured to support multiple modulation and data formats but cannot simultaneously support multiple simultaneous transmissions. Configuration of adaptive filtering and other mitigation methods will be coordinated dynamically between the

TX and RX functions to further minimize interference between simultaneous TX and RX operations. In general this will apply more to commercial and/or larger aircraft; in GA applications it is more likely that transmissions at different frequencies and/or modulations can be temporarily interleaved to allow use of a single modulation, power amplification, and dynamic filtering resource to be used to multiple purposes at the same time. A conceptual SDR architecture is shown in Appendix 7 for reference.



**Figure 6-1: BBSDR Architecture**

#### ***6.1.1.2 BBSDR Interoperability and Applicability***

The proposed BBSDR technology is fully interoperable with current proposed future systems. The SDR capability allows adaptation to a wide range of related systems. Spectrum interoperability with legacy and other systems, such as in the VHF and L-Bands, is addressed in other sections. Broadband Software-Defined Radio technology is applicable to all user groups.

#### ***6.1.1.3 BBSDR Scalability over Time and Changing Industry Needs***

BBSDR is highly scalable: the software-defined operation allows a wide range of upgrades and adaptations to new link types, deployment of additional ground stations, adaptive modulation based on link quality, and other technical developments. The ability to meet more and more challenging price points is also promising, through the ability to have a single device serve multiple functions that currently require separate, purpose-built equipment, and through the switch from primarily analog to primarily digital components, and resulting increases in production volume and other economies of scale. Significant portions of the BBSDR can also be common between models for use in different bands; the DM interface, DSP and SDR infrastructure for both RX and TX, and much of the software can be used with different RF components to operate in different bands.

#### ***6.1.1.4 BBSDR Failure Modes, Effects, and Backup Options***

The application of a single SDR to multiple functions inherently increases the severity of failure effects; a single SDR failure can cause the loss of multiple functions, links, or capabilities. However, the solution is also inherent, in that backup equipment only requires a single type of Line Replaceable Unit (LRU) – two or three identical BBSDRs back up all SDR-enabled functions, instead of requiring separate backups for each type of communication, navigation, and/or surveillance radio device. In higher-end aircraft two or three identical SDR units (for each frequency band, i.e., VHF, L-Band, Ku-Band) may be required. For GA aircraft 2 identical units for each band used are expected to be acceptable.

#### ***6.1.1.5 BBSDR Relationship to Delivery Manager***

The capability of the BBSDR is not limited to the reception and output of the various communication payloads within its operating frequency range. Its processor will also dynamically derive a wealth of useful information about the performance of each link. Signal quality, link margin, improving and degrading channels as the aircraft moves (AeroWAN for example), sources and frequencies of interference, and other parameters will be available for use in making optimal use of available communications.

The Delivery Manager, described in the following section, will have access to this BBSDR-derived information as one of its many inputs in optimizing overall communications. Unlike a simple router, this access to link-level status and trend information gives the Delivery Manager

more powerful tools to deliver optimum communication performance using whatever individual links are available at any given time.

### **6.1.2 Delivery Manager (DM)**

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 could also allow for the use of non-aviation protected spectrum for certain functions, while still utilizing aviation protected spectrum where criteria require it.

Aircraft today are typically equipped with multiple separate communication links, with little or no interaction. Communication Management Units (CMUs) in larger aircraft provide some rudimentary coordination of communication payloads and individual links, but are limited in their capabilities. Optimized communications using future link technologies can be greatly improved by adding a more comprehensive overall management capability across all available links. In principle, this function can be described as an extrapolation of today's router, but with access to a large variety of links, access to status information from multiple layers of the communication process (link layer included), inputs and outputs in many different formats, and responsibility for delivery and integrity of payload information. The research team designated references to this larger set of delivery / integrity capabilities as the Delivery Manager (DM).

The Delivery Manager is the communications hub of the aircraft. It connects to the various information systems on the aircraft that use or generate information, and to the various communication links that the aircraft is capable of accessing. This includes both aviation-specific links and commercial or non-aviation specific links. It is the Delivery Manager's role to assure delivery of communications at or above the required levels of timeliness, reliability, and integrity, at the lowest practicable cost. Where high-speed, commercial links are available, the DM may use them to route larger data messages, using encryption or other means to assure appropriate integrity. When high-speed links are not available, the DM relies more on lower-speed, aviation-specific links to assure delivery, even if at reduced speeds. Information deemed to be integrity- or latency-critical may always be routed via aviation-specific links, with multiple such links available to assure delivery.

For example, CPDLC messages could "default" to the VDL-Mode 2 link, but if for any reason that link is temporarily unavailable, messages could be routed via AeroWAN; on the ground, CPDLC traffic could be routed via AeroMACS to reduce VDL-Mode 2 system loading. The DM has access to link-layer information such as specific stations currently in range, signal strength and noise level, and performance trends for each ground station; for example, which stations

are fading and which are improving as the aircraft moves. This allows the DM to route via the most viable link at all times, and to strategically switch from one ground station to another to maintain best communication capability at all times. In addition, for some links the DM participates in link-acceleration decisions under optimum conditions; for example, AeroWAN can switch to a higher-speed method of transmission when link margins are high, minimizing delivery times for large payloads, and back to more conservative methods as the link deteriorates with aircraft movement.

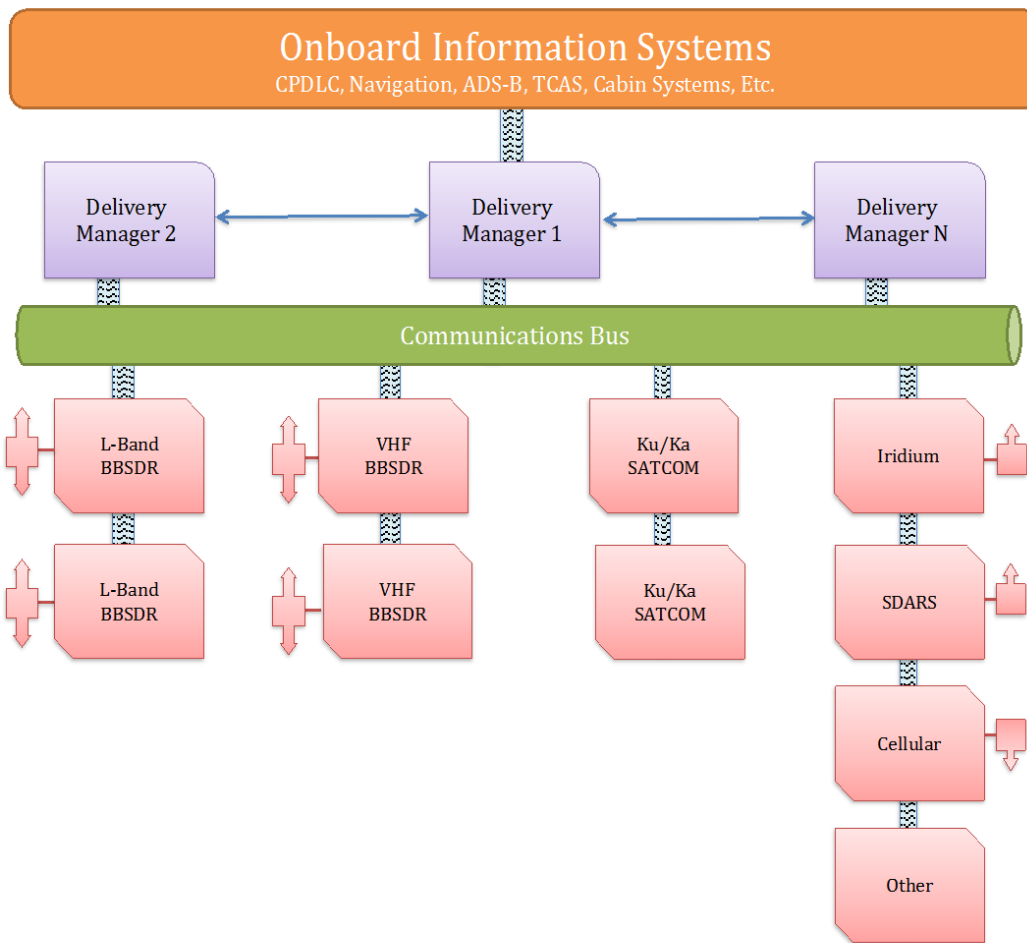
Delivery decisions are made dynamically and without crew interaction. Crews can access link status and current routing information, similar to a pilot accessing the GPS constellation status using today's GPS receivers, but under normal conditions the DM manages communications autonomously and transparently to the pilot. It should be noted also that some ground stakeholders may also use a subset of its capabilities; for example, an airline dispatch operation may use similar capabilities to assure delivery of AOC or AAC data to an aircraft via the various links available at a given time.

The viability of non-aviation specific candidate technologies for conduct of flight communications is greatly enhanced by the Delivery Manager function, because the DM is key to their applicability and its scope. For example, cellular technologies may be used for a wider range of functions with the presence of the DM and its ability to encrypt, and to switch to alternate links automatically to maintain the required link availability.

#### **6.1.2.1 DM Architecture**

The DM coordinates the use of the various specific links based on availability, timeliness, capacity, performance relative to requirements, cost, and other factors. The DM also addresses issues such as encryption and security, receipt verification, and probability of delivery across each link utilized from an approval/certification standpoint. A combination of aviation-specific links and commercial links are available to the DM, including but not limited to those described in this report. The DM is also capable of initiating relay communications using nearby aircraft (and their DMs), such as in the case of high-priority messages in primary link failure conditions. Polar route position reports, for example, could be relayed from aircraft to aircraft until access to an air-ground link is obtained.

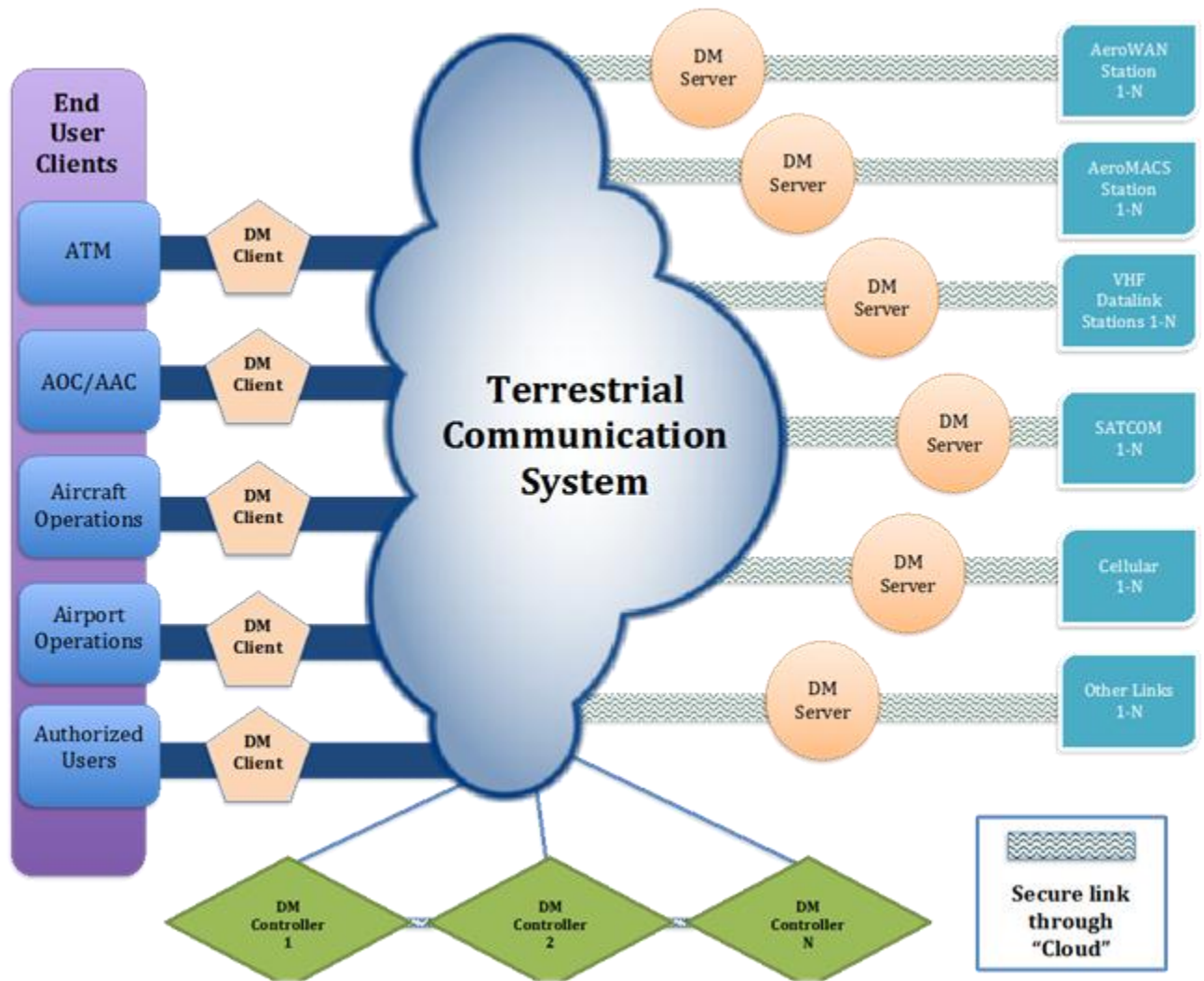
The DM presents some overall architecture considerations. To be fully effective, the DM must have access to most, if not all, available ground-air and air-air links. In the aircraft, the DM functions as the central manager for communications, interconnected with all source and user systems on one side, and each individual link on the other. Multiple links may be provided by a single BBSDR package, as described previously.



**Figure 6-2: Future Aircraft Communication Architecture with DM and BBSDR**

The conceptual communications architecture for a 2063-era aircraft is shown in Fig. 3. A Communications Bus connects the major components of the system, connecting primary and backup DMs with multiple link-specific devices. DMs have access to both communications payload data from each link, and detailed link status information for use in managing link availability as conditions change. To the extent that commercial link providers require separate, link-specific LRUs for their services, each such LRU would interface with the DM via the Communications Bus. The addition of multiple redundant LRUs, such as two or three L-Band BBSDRs, is architecturally simple, as additional nodes on the Communications Bus.





**Figure 6-3: Future Terrestrial Communication Distributed DM Client/Server Architecture**

On the ground, the DM function must have access to various communication links and networks, including those with widely distributed architecture such as networks of ground stations. Multiple ground users must have means to access the DM function to submit data for transmission, and to receive transmissions addressed to them. Ground user access to the ground-based DM constitutes another area of Cloud Communications, where different users may access the DM function via various means ranging from dedicated, secure links to a dynamic, web-based IP connection.

A distributed architecture is envisioned for the ground DM, where end users (i.e., an airline dispatch office) are equipped with a “DM Client” which accesses a “DM Server” to establish a secure, authorized user link to authorized DM functions, and perform link selection and routing, message prioritization, security, and other DM functions collaboratively. Different

ground users have different authorization profiles controlling which links may be accessed, information types which may be sent, encryption and security requirements, and other parameters. The DM client associated with each user negotiates via the cloud with one or more DM servers, through which communication access is established and maintained. A number of DM Controllers manage overall operation of the system, including client and server configuration management, security, traffic flow management and balancing, and other optimizations.

#### ***6.1.2.2 DM Interoperability***

##### **Aircraft:**

Proposed aircraft communication systems are interoperable with all relevant legacy and new systems. Existing CMUs and DMUs and other current purpose-specific link equipment are expected to have been replaced with DM-compatible equipment before 2063. Interim systems may have a stand-alone architecture with a DM interface that allows upgrade to DM architecture, possibly with reduced DM effectiveness due to limitations in the scope of DM access to detailed link information.

##### **Ground:**

A high degree of interoperability is required for the ground segment, due to the number and diversity of users, user locations, information types, links available, and geographically dispersed ground stations and other infrastructure. The ground system is expected to be fully interoperable with all relevant systems.

#### ***6.1.2.3 DM Applicability Across Multiple User Groups***

The architecture differs slightly from commercial aircraft to GA, but will be applicable to all user groups. Some specific links will only be practicable for larger aircraft, and a higher level of redundancy and integration is expected for higher-end aircraft. However, the overall system architecture, and the DM functionality, will apply to all.

Commercial aircraft typically will be equipped with two or more redundant DM units, cross-linked to maintain current status data for all, with dynamic fail-over from one to another. GA aircraft will typically have two redundant DM units, with a choice of manual or automatic switch to backup based on user needs and price sensitivity.

#### ***6.1.2.4 DM Scalability Over Time and Changing Industry Needs***

##### **Aircraft:**

The DM will be highly scalable, primarily through software upgrades to the DM itself and to the BBSDRs to add/upgrade capabilities of specific links. Backup DM units can also be used to manage some workload in a distributed processing environment as system loading increases over the life of the system.

**Ground:**

Also highly scalable, with upgrades of both software and hardware being more practicable due to easier access, the limited number of ground stations, and the ability to apply cloud-based communication and routing capabilities to the ground-to-ground user access functions.

***6.1.2.5 DM Failure Modes, Effects, and Backup Options***

**Aircraft:**

In the event of a DM failure, at least one backup DM unit will be required. Higher-end aircraft would have three redundant units with auto fail-over. Loss of any individual link is mitigated automatically by the DM function and its ability to switch to alternate links as needed.

**Ground:**

Three major types of failure are possible:

- Ground Station Failure;
- Ground Interconnect Failure;
- Ground DM Function Failure.

A failure of any specific ground station is mitigated first by in situ backup equipment and automatic fail-over. Complete failure of a ground station location is mitigated primarily by DM function, which immediately attempts to access an alternate link. Options include a more distant station of the same link type or use of an entirely separate link.

Failure of the interconnection between any one ground station and the network results in a similar situation to that of a complete ground station location failure. Failure of the entire ground interconnect system, between the DM and all link access points, is prevented by the distributed nature of the ground DM function, and the use of “cloud communication” to use diverse links to the various interconnect points.

Failure of the ground DM function is also precluded by the distributed nature of the DM function; there is no single DM location, but rather multiple DM entities operating in a collaborative fashion. Link capabilities are distributed across a number of DM servers in diverse spatial and connectivity locations, such that if one DM server does not respond to a request for a DM client, others do.

### **6.1.3 Influence of BBSDR and DM on Link Favorability**

Both BBSDR and DM were assumed to be available to all links at the 50-year reference point, with the exception of current ADS-B and UAT, and current VDL-2. Both are integral parts of the future datalink architecture envisioned by the research team, and are essentially integral with each other as well. In that context, it could be argued that their presence benefits all candidates equally.

In fact, there are some additional factors to be considered. Some links may derive more benefit from BBSDR and DM technology than others, such as in relation to steerable-antenna satellite links and links offering more different service types in the same contiguous bandwidth. Some commercial systems may be a good fit with BBSDR architecture for technical reasons, but precluded by business considerations such as subscription control and fee management, or protection of proprietary technology.

By the same token, such commercial candidates may derive significant benefit from the DM technology, a core purpose of which is to provide a link-independent, performance-based method for providing and maintaining information “delivery” regardless of specific link or provider. This link-independent “pedigree” can provide the means to obtain approval for using some commercial links for functions that otherwise would not be compatible with non-certified equipment, providers, and spectrum.

Taken as an overall system, it is likely that aviation-specific candidates such as AeroWAN and VDL Next will derive greater benefit from BBSDR than commercial links such as cellular and SDARS. However, the commercial links may also derive greater benefit from the Delivery Manager than some aviation-specific links. In total, the BBSDR and DM technologies together help provide a more flexible and capable system, with each complementing the other in multiple ways.

## **6.2 Link Technology Candidates**

The following section summarizes each candidate link, its proposed architecture, its anticipated interoperability with other systems and applicability to multiple user groups, and its scalability over time and changing industry needs. Related failures modes, effects, and back up options are also identified.

The team considered a combination of aviation-specific options and commercial candidates to provide the broadest overall capabilities and lowest overall cost, while always assuring the availability of aviation protected spectrum operations for critical functions. A wide range of solutions were considered, and the proposed candidate technologies fall into three categories: extensions and enhancements to current, existing aviation links, re-architecture of current

aviation systems and/or RF spectrum, and 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 are defined herein as “Aviation-Specific Candidates” due to their operation in aviation specific RF spectrum. The third is defined as “Commercial Link Candidates”, being designed primarily for use by non-aviation user populations, typically operating outside aviation spectrum, and on a fee-for-use basis.

### **6.2.1 Aviation-Specific Link Candidates**

Aviation-specific candidate technologies include:

- VDL Mode 2 (VDL-2) and aggregated VDL2, 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 ADS-B 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.

### **6.2.2 Commercial Link Candidates**

As noted previously, the DM increases the overall viability of using some non-aviation-specific candidate technologies, through its ability to manage their use according to availability, integrity, and cost. These DM capabilities allow expanded use of non-aviation specific links such as cellular technologies, commercial SATCOM, Iridium/Next and similar L-Band LEO systems, and SDARS, while maintaining required performance and integrity levels. For example, if required weather information is successfully received via SDARS or other broadcast means in a timely way, no further action is required; if not, the DM may request it via alternate means such as AeroWAN, cellular technology, VDL-2 or Iridium. Inventory lists of expected data can be sent via AeroWAN or VDL-2 and, if received successfully via commercial broadcast, no further communication loading (or cost) is required. AOC / AAC information may be transmitted via a commercial link (i.e., cabin internet) with appropriate encryption and segregation when those links are available. When they are not, the DM switches to alternate options such as VDL-2, Iridium, or AeroWAN.

Commercial candidate link technologies include:

- 4G/LTE and future generation technologies;
- Iridium/Next and similar L-Band LEO Satellite;
- Ku- and Ka-Band satellite systems.

### **6.2.2.1 VHF Data Link (VDL)**

Candidate links include three types of VHF Data Link: the currently operational VDL Mode 2, a modification of current VDL-2 allowing data broadcast to multiple aircraft, and a re-architected VHD data link system not limited to operations within the current 25 KHz channel structure of the VHF aviation band.

#### **VDL Mode 2:**

This category includes the current VDL Mode 2 VHF datalink (VDL-2), and the legacy ACARS links to the extent that they are still relevant in 2063. VDL-2 and the future VHF datalinks are expected to be available to all user segments, including GA, at market-compatible price.

#### **VDL-2B (Broadcast)**

Same as VDL-2 except with the additional capability of broadcast messages from ground-to-air; abbreviated in some tables herein as VDL-2B.

#### **VDL-Next**

Present capacity of single channel VDL-2 is limited, and recent saturation problems encountered in Europe with current VDL-2 highlight the potential problems in the current VDL-2 architecture. Aggregation of a number of predefined RF frequencies with a new connection protocol would greatly increase VDL-2 capability. For this study, an aggregated VDL structure based on the use of a total of 38 channels in the 136-137 MHz band, having 36 data channels and two control channels at 25 KHz intervals, was used. One or more channels would also be allocated to broadcast data, reducing loading on interactive channels from repetitive dissemination of data common to multiple aircraft. A BBSDR architecture allows simultaneous reception of control channels, broadcast channel, and assigned interactive channel. This type of aggregated-bandwidth VHF Data Link is referred to as “VDL Next”.

### **6.2.2.2 VDL Architecture**

A single BBSDR unit (TX and RX) can be used to accomplish all communication in the aviation VHF band, with one or more backups as needed. Current VDL-2 communication methodology would be accommodated along with future upgrades such as VDL-Next, and the advent of higher throughput link technologies. It is assumed that by 2063 the current analog voice operations in the VHF band will have been replaced by digital voice, CPDLC, and other alternatives. The DM will manage the information.

### **6.2.2.3 VDL Interoperability and Applicability**

BBSDR is interoperable with current VDL-2 and future proposed systems. BBSDR is also capable of supporting current VHF analog voice communications to the extent that it is still in use. BBSDR is applicable to all user groups.

#### **6.2.2.4 VDL Scalability over Time and Changing Industry Needs**

All current and future VHF data links are fully compatible with Broadband software Defined Radio technology, and BBSDR is highly scalable in terms of the adaptability of the BBSDR to expanded bandwidth operations, parallel channel operations, and future modulation upgrades. Scalability is somewhat limited by the inherent bandwidth limitations of VHF operations and the size of the aviation VHF band itself.

#### **6.2.2.5 Failure Modes, Effects, and Backups**

The application of a single BBSDR to multiple functions inherently increases the severity of failure effects; a single BBSDR failure can cause the loss of multiple functions, links, or capabilities. However, the solution is also inherent, in that backup equipment only requires a single type of LRU; two or three identical BBSDRs back up all BBSDR-enabled functions, instead of requiring separate backups for each. In higher-end aircraft two or more identical VHF BBSDR units are expected. For GA aircraft one or more units, similar to current VHF communication radios, are expected to be acceptable.

### **6.2.3 ADS-B**

ADS-B in this context includes both current ADS-B systems (1030/1090 MHz, and UAT), and the proposed restructured ADS-B NEXT system centered initially at 1030 MHz.

#### **6.2.3.1 Current ADS-B 1090/1030 MHz System**

By 2063 it is expected that the current 1090 MHz-based ADS-B system will have reached “legacy” status, but may still be in service in parallel with the new 1030 MHz system (see following sections) during a potentially lengthy transition period. This legacy system will be compatible with all proposed new systems, with no mutual interference expected. After the legacy 1090 system has reached its sunset, this spectrum can be re-allocated to provide additional bandwidth for the new 1030 MHz ADS-B Next system long into the future.

#### **6.2.3.2 ADS-B Next**

A new ADS-B system is proposed that reuses RF spectrum centered around 1030 MHz in a robust, efficient way to replace all current 1090 MHz and UAT ADS-B functions. The Technology Candidate Descriptions report includes an overview of the strategy for decommissioning all current functions that occupy the 1030 MHz spectrum, including active interrogations by ATCRBS, TCAS, and multilateration systems. A key enabler of this strategy is the premise that by 2063 ADS-B will be universally deployed on all aircraft operating under Instrument Flight Rules (IFR), and a majority of Visual Flight Rules (VFR) aircraft as well. Some realignment of DME channel assignments may also be needed to aggregate a single broadband channel centered around 1030 MHz.

### **6.2.3.3 ADS-B Next Architecture**

#### **Aircraft:**

Reception of the legacy 1090 ADS-B and UAT signals, and the new 1030 MHz ADS-B Next signals, will be among the multiple functions of the L-Band BBSDR. The DM will support delivery of legacy system data to the appropriate legacy systems as needed, as well as data from the new ADS-B Next system. Transmission of new ADS-B Next squitters will also be a function of the BBSDR; transmissions of legacy 1090 and UAT signals, during transition, can be done by legacy equipment or the L-Band BBSDR.

Both the legacy and new ADS-B systems will be applicable to both air-to-air and air-to-ground applications.

#### **Ground:**

New ADS-B Next ground receivers can be collocated with legacy equipment during transition. ADS-B Next stations will connect to users via the DM function. This will allow both Air Navigation Service Provider (ANSP) users and others (i.e., airline dispatch operations) to become “clients” of ADS-B ground station output data via their DM client and associated authorization profile if desired.

### **6.2.3.4 ADS-B Next Interoperability and Applicability**

The proposed system is fully interoperable with current 1090 MHz ADS-B, and proposed future 1030 MHz ADS-B Next systems. It is not interoperable with other current 1030 MHz functions including active interrogations by ATCRBS radar systems, TCAS, and multilateration systems. It is interoperable with DME/TACAN systems with the exception of the possible need to relocate some DME channel assignments adjacent to 1030 MHz to allow the aggregation of a single, broadband channel centered at 1030 MHz. This new system will be applicable to, and available to, all user segments at market-compatible price, including current users of the UAT system for ADS-B (primarily GA). Space-Based ADS-B systems would eventually need to be upgraded for compatibility with ADS-B Next transmissions at 1030 MHz, but due to the ability of the L-Band BBSDR to generate legacy ADS-B transmissions this would not be a requirement until the end of the transition period.

### **6.2.3.5 ADS-B Next Scalability over Time and Changing Industry Needs**

ADS-B Next is highly scalable due to inherently higher bandwidth than current systems, providing significant room for future growth in the number of users and in the addition of applications. It is also scalable due to the inherent scalability of BBSDR technology, as discussed in other sections. In addition, after the current 1090 MHz and UAT ADS-B systems are retired their spectrum can be reused to provide additional growth capacity for ADS-B and other functions in parallel with the new 1030 MHz system.



### **6.2.3.6 ADS-B Next Failure Modes, Effects, and Backups**

#### **Aircraft:**

Three primary types of failure modes need to be considered: RX failure, TX failure, and uncommanded transmissions (e.g., “stuck mic”). RX and TX failures are mitigated by the presence of backup BBSDRs and DMs and the inherent “fail-operational” architecture of the system. In addition, if the DM recognizes a multiple failure condition, it can attempt to establish position reporting via alternate links, at least to the ATM client for ATM-assisted separation. The ATM can also attempt to initiate similar connectivity to the aircraft if its DM recognizes the failure.

The uncommanded transmission condition is also unlikely, as system design will include multiple fail-safe provisions to prevent a single aircraft from “jamming” all nearby ADS-B signals. If this condition were to occur, ADS-B operations would be disrupted in the vicinity of the offending aircraft. All associated DMs would attempt to access an alternate link, and ATM instructions via other links would not be affected – for example, CPDLC messages via VHF datalink would continue to operate. It should be noted that this theoretical condition exists today with UAT ADS-B, and with intentional jamming of 1090 MHz ADS-B signals. ATM procedures will need to include provisions for this condition.

#### **Ground:**

Ground ADS-B system failures are similarly mitigated by redundant receivers and DM capabilities discussed in other parts of this report. In the event of widespread interruption, it should first be noted that air-to-air ADS-B would continue to operate, allowing self-separation. ATM DM clients would immediately seek alternate links, and could use VHF datalink, AeroWAN, AeroMACS (for surface movements), SATCOM, and available cellular links to restore capability. ATM procedures will need to include provisions for this condition, as they do now.

### **6.2.4 AeroMACS**

AeroMACS has been the subject of extensive study in other forums, and this report does not attempt to summarize that information. AeroMACS is a ground-aircraft system designed for communications while aircraft are on the ground. The system uses the IEEE 802.16 “Mobile WiFi” standard which provides for internet like connectivity and uses Internet Protocol (IP). It operates in a portion of the 5 GHz band designated for aircraft use, and is scalable for both large and small airports, with a range up to 3 Km. Data rates are comparable to broadband WiFi up to 54MB/sec. Applications include AOC messaging, ground traffic control, CPDLC messaging, weather information, and many other applications.

In the 2063 system AeroMACS is expected to have been deployed and matured significantly, and to be an important element of the future communication system, used by all segments. AeroMACS is primarily applicable to ground operations on and near airports. It provides

wireless networking connectivity for surface clients, including vehicles of various types, ATM, airport operations, airport operators, and others.

#### **6.2.4.1 AeroMACS Architecture**

Strategically located ground stations and antennas provide wireless signal coverage throughout the airport environment. This network of stations connects via the ground DM with various clients including ATM, airlines, aircraft operators, weather information providers, and other authorized users.

AeroMACS operates in the 5 GHz band currently allocated to MLS, and will require one or more AeroMACS transceivers to access the system, under the management of the aircraft's DM. Ground-Mobile Vehicles, with little or no need for alternate links, access AeroMACS directly from a user terminal device to their onboard AeroMACS transceiver.

#### **6.2.4.2 AeroMACS Interoperability and Applicability**

The future AeroMACS will be interoperable with current and proposed systems, with the caveat that as AeroMACS bandwidth needs grow over time, increased allocation of RF spectrum to AeroMACS will be required. It is expected that adequate spectrum will become available as legacy systems are decommissioned. AeroMACS is applicable to all user groups, including not only aircraft but also mobile ground vehicles and other ground users in the airport surface environment.

#### **6.2.4.3 AeroMACS Scalability over Time and Changing Industry Needs**

AeroMACS is highly scalable through assignment of additional spectrum and other channel management strategies, upgrades of BBSDR-based access equipment to improved throughput technologies, and deployment of additional ground stations at additional airports.

#### **6.2.4.4 AeroMACS Failure Modes, Effects, and Backups**

Three primary AeroMACS failure modes have been identified: Aircraft Equipment Failure, Ground Equipment Failure, and Interference.

##### **6.2.4.4.1 Aircraft Equipment Failure**

Aircraft AeroMACS equipment failure affects an individual aircraft which, in most cases, will be engaged in surface operations. In general, the inherent aircraft system architecture will provide backup via the redundant DM and link-specific equipment, and the DM's ability to switch to alternate links dynamically. Dynamic backup options include using ADS-B Next, VHF datalink, cellular, AeroWAN, or SATCOM for communication. In cases of multiple failures affecting not only AeroMACS but the DM and alternate links, removal of the aircraft from service for repair would be required. ATM procedures will need to include monitoring of the communication status of all participating aircraft, and practical, safe methods of recognizing and annunciating

communication failures, and of removing a communication-impaired aircraft from operations. These procedures will need to accommodate manned aircraft, reduced-crew operations, and unmanned aircraft operations.

#### 6.2.4.4.2 Ground Equipment Failure

Ground equipment failure presents a relatively straightforward mitigation in most cases, through redundant systems and automated fail-operational methods. The exception to this is a major outage of some type, such as damage to both primary and backup equipment, antennas or cabling, and other infrastructure. In such an event airport surface operations could be significantly disrupted, affecting a wide range of preflight planning, traffic flow management, and situational awareness functions including ground ADS-B, AOC/AAC, and airport operations coordination. In visual conditions, the loss of ADS-B capability could be mitigated by visual separation; during poor visibility, use of the ADS-B Next airborne ADS-B system is a viable reversion mode. For other functions the DM would switch automatically to other available links, including VHF datalink, cellular, and even SATCOM to continue operations, albeit at increased cost and possibly reduced pace. It should also be noted that events of this magnitude may cause interruptions of other airport operations as well for reasons unrelated to AeroMACS.

#### 6.2.4.4.3 Interference

Interference, whether malicious or unintentional, has the potential to disrupt AeroMACS-enabled airport operations to a significant degree. As with other failure modes, the first fallback is the inherent capability of the DM, both ground and aircraft, to dynamically switch to alternate links when needed. The availability of spectrally diverse link options at VHF, L-band and cellular frequencies, as well as SATCOM for larger aircraft, offers a range of inherent mitigations. In some cases, such as SATCOM, increased link latency must be taken into account, and would potentially impact the overall pace of operations.

In the event of a major, broad-spectrum RF attack, it is possible that airport operations could be seriously impacted. In such an event much more than AeroMACS would be affected, and contingency planning is outside the scope of this study. The necessity for ATM procedures to include loss-of-communication recognition and mitigation, discussed in the previous section, applies here as well. For example, in the event of a major, broad loss of communication connectivity, an “everyone stop” process may be the first step in resolving ground operations issues; air operations obviously present a more complex problem.

### **6.2.5 AeroWAN**

The proposed Aeronautical Wide-Area Network employs wireless network technology to provide broadband bidirectional communications between aircraft and ground access points in repurposed aviation L-band spectrum formerly used for DME and TACAN. AeroWAN is based on the same mobile WiFi technology used in AeroMACS, but adapted for use with aircraft in flight. The system is accessible to all user segments, and provides air-to-ground communications for multiple users and purposes, as well as air-to-air connectivity via routing similar to existing WiFi systems.

#### **6.2.5.1 AeroWAN Architecture**

A comprehensive network of ground stations spaced to provide access to all users at appropriate altitudes provides wireless network access to client aircraft in flight, complementing AeroMACS coverage for on-airport operations. Subnetworks of “high” and “low” ground stations may be required, to allocate bandwidth, power, and coverage to high-altitude aircraft with higher bandwidth needs, versus lower altitude and/or lower bandwidth aircraft such as small GA aircraft and UASs.

Ground stations are managed and interconnected by the ground DM function. Ground users access the network as clients via their DM client function depicted in Fig. 4.

Aircraft access AeroWAN via the BBSDR avionics, managed by the DM. A wide range of information types can be sent and received by AeroWAN, ranging from AOC/AAC and weather information to use as a backup link for key functions such as CPDLC and ADS-B.

#### **6.2.5.2 AeroWAN Interoperability and Applicability**

AeroWAN is interoperable with all proposed future systems, and with current/legacy systems including TACAN, DME, and ADS-B with the caveat that allocation of spectrum within the current DME/TACAN band will be required during transition. It is expected that by 2063 all TACAN operations, and a majority of DME stations, will have been decommissioned. The future concept of ground-based Pseudolites, which provide alternate position, navigation, and time transmissions to supplement and back up GPS and other SATNAV systems is also interoperable with AeroWAN through simple coordination of channel/spectrum assignments. More likely, the proposed AeroWAN and Pseudolite functions would be merged into a single, multi-purpose system with ample bandwidth for both functions. AeroWAN is applicable to all user groups.

#### **6.2.5.3 AeroWAN Scalability over Time and Changing Industry Needs**

AeroWAN provides significant scalability, through allocation of additional L-band spectrum bandwidth and /or deployment of additional access point ground stations. As TACAN channels become de-activated, each frequency available can be converted into a new channel providing

another 4 MB/sec. of capacity, operating in aviation-allocated protected frequency spectrum. This can be continued until there are dozens of channels available within the TACAN band. Using BBSDR radio technology, each aircraft can receive multiple ground-to-air transmissions simultaneously, and avionics can adapt to the addition and reassignment of channels dynamically without equipment changes. Higher bandwidth users can also be upgraded to adaptive modulation, dynamically switching to higher bandwidth link methodologies during favorable link conditions. The software-defined L-Band radio avionics facilitate this, coupled with the likelihood that large commercial aircraft, serving passenger connectivity needs, will be the most likely higher bandwidth users, and typically operate at higher altitudes where adaptive modulation can be used more effectively.

#### **6.2.5.4 AeroWAN Failure Modes, Effects, and Backups**

Failure modes are divided into four types: Ground Station Failure, Ground System Failure, Aircraft System Failure, and Interference.

In the event of a single ground station failure, higher-altitude aircraft will frequently have connectivity with more than one ground station, and the DM simply connects with a more distant station. When this is not possible, the DM accesses alternate links including VHF datalink, cellular, and SATCOM. In the event of complete loss of AeroWAN connectivity some support information services may be lost; however, conduct of flight services such as ADS-B, CPDLC and SATNAV can still be maintained using other links.

Aircraft system failures are mitigated by the redundant DM and L-Band BBSDR architectures. In the event of a complete loss of AeroWAN connectivity some support information services may be lost; however, conduct of flight services such as ADS-B, CPDLC and SATNAV can still be maintained using other links.

Interference, particularly in the form of intentional jamming, is expected to be localized in nature, and produces a similar effect to the loss of a single ground station.

#### **6.2.6 SDARS**

Satellite Digital Audio Radio Systems (SDARS) provide broadcast of audio programming and data services to mobile and other users from geosynchronous and Molniya orbiting satellites. SDARS is used today to deliver weather and other support information to aircraft, primarily for GA users. It is expected that this system or a comparable follow-on will continue to be available for aviation use, and provides a potentially valuable additional link option for GA aircraft, as well as other user segments.

#### ***6.2.6.1 SDARS Architecture, Interoperability, and Applicability***

SDARS uses orbiting satellites for broadcast transmission of predictable data sets such as weather information. Reception by aircraft is accomplished via the L-band BBSDR or a service provider supplied receiver (which may be necessary for subscription control), supported by the DM. Data to be transmitted is delivered by the supplier to the SDARS provider's gateway for uplink.

SDARS is interoperable with all current and proposed systems. SDARS is applicable to all user groups, with the possible exception of UAS, where it is technically available but less clear whether information applicable to UAS operations will be transmitted via this type of service.

#### ***6.2.6.2 SDARS Scalability, Failure Modes, and Backups***

SDARS scalability is limited primarily by the business case considerations of the commercial service provider. Substantial additional bandwidth is available in the overall system, but will only be allocated to aviation information broadcast if it promises to generate more revenue per unit bandwidth than audio programming.

Failure of the SDARS aircraft reception equipment, the terrestrial data delivery to the uplink, or the entire system result in the loss of some support information to the flight crew. The DM automatically switches to other, less efficient and/or more expensive links to obtain information from alternate sources as needed.

#### ***6.2.7 Cellular Technologies***

Cellular technologies can be expected to continue their rapid development and capability expansion over the study term. It should be noted that looking back 50 years, cellular technology was not yet available; the first cellular phone became available in the United States in 1983, just over 30 years ago. Thus the 50-year future research term will be nearly 40% longer than the entire lifetime of cellular communications to date. Given the rapid pace of its historical development, predicting the state of this technology nearly twice as far in the future as its total existence to date is a challenge. It is safe to assume that the cellular technology of 2063 will be far advanced from its current state.

Current cellular communication systems are purposely structured to limit signal coverage as closely as possible to ground users, for technical, regulatory, and commercial reasons. Cellular spectrum is re-used from cell to cell to maximize system bandwidth, facilitated by the limited range of a ground-based user device. An aircraft-based device has much longer range due to its antenna elevation, and would "blanket" a large number of cells in the current architecture, seriously impacting overall system available bandwidth. For current commercial cellular systems to have practical use for aviation, these problems need to be resolved. The research team identified straightforward technical and regulatory steps that could enable practical use

of cellular systems for aviation applications. This opens up potential access to significant communication bandwidth and related technical capabilities outside the limited aviation spectrum. Properly managed by the DM function, this offers an intriguing potential source of additional communication connectivity. In addition to technical and regulatory considerations, however, commercial services are also influenced by business case considerations. Section 8, Business Case Analysis, includes additional detail on some of the key business considerations related to the use of commercial, non-aviation services for aviation use.

For future applications in the mid-term study period and beyond, it is reasonable to assume that cellular providers may be induced to implement changes in the current architecture as described, in order to capture additional business, particularly in the non-urban areas where passengers are able to use cellular devices onboard aircraft. By that time 4G/LTE can be expected to have been supplanted by “5G/LTE”, or 6G, or additional generations. The key will be to stimulate the necessary regulatory and architectural changes to facilitate technical compatibility.

Another option is to make a portion of current aviation spectrum available for one or more providers to replicate their commercial infrastructure for aviation use. The research team has not studied this in detail, but conceptually it is feasible, and might help offset the commercial issues of reserving valuable mass-market bandwidth for a smaller aviation market segment.

#### ***6.2.7.1 General Aviation Cellular Options***

Cellular communications using 4G/LTE are, as a practical matter, already in use to some extent in GA. Pilot-owned cellular phones are operable to some extent at low altitudes, and are occasionally used by GA pilots in flight to access weather information and other conduct of flight functions. This is an application where a relatively minor change in ground antenna orientation could create significantly improved performance for GA users at low altitudes. Additional research in this area would be valuable.

#### ***6.2.7.2 Aviation Cellular Architecture***

Cellular systems use large numbers of base stations to communicate with mobile devices in close proximity. To adapt this architecture to aviation use, a small subset of these stations would be modified to include antennas oriented to provide signal to aircraft, coupled with modifications to the system’s algorithms for controlling cell size from the channels allocated to the aviation antennas, and for dynamically controlling channel assignments and bandwidth allocations. Modifying rural stations is a logical starting point, as they typically have fewer terrestrial users competing for the same bandwidth, cover larger areas already, and have fewer obstructions to antenna coverage for distant aircraft users.

Base stations are connected by the cellular provider's infrastructure. A bridge between that infrastructure and the ground DM function provides access to aviation users.

#### **6.2.7.3 Aviation Cellular Interoperability and Applicability**

Within the caveats discussed previously, the proposed cellular capability is interoperable with other relevant systems, most notably the ground users of the same system. It is also interoperable with all current and proposed aviation systems. The cellular system is applicable to all user groups, with the exception of oceanic aviation operations where no commercial cellular infrastructure exists. In particular, the GA user would be well served on a technical basis by the small size and cost of equipment and antennas, and excellent low-altitude coverage across a wide range of topography. Airline passenger users could also be well served by the inherent compatibility between existing personal communication devices and the proposed architecture, and by the potentially large bandwidth available at demonstrably acceptable commercial terms.

#### **6.2.7.4 Aviation Cellular Scalability, Failure Modes, Effects, and Backups**

With the cellular system, scalability may ultimately depend more on commercial considerations than technical ones. Technical scalability is high, being based on similar strategies of cell size and spectrum re-use to those applied to ground user services.

By definition, commercial cellular communication is considered an alternative to aviation-specific links for any type of conduct-of-flight functions. On that basis its failure effects are relatively benign, primarily impacting passenger access, except in cases of compound failures where it fails coincident with multiple aviation links. The likelihood of such coincident failure is small, but would need to be included in implementation planning.

One possible exception to the assumption that cellular links are only alternatives for conduct of flight information is GA. Cellular systems may be used more heavily by GA for flight support information such as in-flight updates of weather, NOTAMS, TFRs and similar data due to its relatively low, usage-related cost. In that case the GA user would be compelled to depend on other links and services, dynamically accessed by the DM, and/or possibly degraded visual displays for some flight support information. Cellular communications may also offer particular advantages to sUAS operations, an area that merits further study.

#### **6.2.8 Ku/Ka Band Links**

Ku/Ka-band links typically use geosynchronous (GEO) satellites, which can offer relatively high bandwidth communication to larger aircraft, including the oceanic regions. Geosynchronous satellite coverage is latitude limited, and is not accessible by aircraft operating in the polar regions. One notable exception is the Iridium/NEXT Low Earth Orbit (LEO) Ka-Band payload, which will be capable of providing Ka-Band connectivity globally, including the polar regions.



The research team believes that Iridium/NEXT will be the first of multiple LEO Ka- and possibly Ku-Band satellite systems, opening a new category of satellite links compatible with all aircraft sizes via small patch-type antennas. It should be noted, however, that Ku-band propagation is inherently weather-susceptible, and Ka-Band is even more so. For that reason, even with the higher link margins made possible by LEO-based architectures, use at low altitudes, such as by GA aircraft and sUAS, will have significant reliability considerations.

Ku/Ka-Band GEO systems use electronically steerable aircraft antennas, to connect aircraft systems via the satellite to a terrestrial earth station which functions as a communication gateway. In general, Ku/Ka GEO system steered beam antennas are relatively large, limiting their use to larger aircraft. Ka-band communications is a viable system for many aircraft applications; satellites will provide increased data rates over Ku-band satellites and will use smaller antennas for a given data rate. User costs should be lower than Ku-band. For two way messaging via satellite, round trip messaging delays need to be taken into account for each proposed application. In many cases the ground network is actually the largest contributor to the overall link delay. For broadcast applications including NOTAMS, graphical weather, and AAC, network delays should not be a factor. For transporting time critical messages, however, the inherent latency of Ku- or Ka-band systems is a significant concern.

A number of airlines have justified Ku/Ka-Band satellite installations by capitalizing on customer demands. Inflight Entertainment (IFE) and airline passengers have driven the push – and the business case - for faster data rates, leading to Ku- and Ka-Band equipage. Although the majority of airlines charge customers to utilize WiFi, and more customers continue to demand connectivity, very few are willing to actually pay for the service. Currently, less than 10 percent of passengers purchase connectivity. If every passenger did “log onto” these services, performance with currently available data rates would be severely degraded.

Airlines are beginning to leverage this passenger demand for connectivity to improve flight deck and inflight needs. The traditional means of obtaining such information forces flight crews to rely on antiquated systems such as ACARS. Slow bandwidth coupled with the high work load of flying the aircraft in critical phases of flight often do not allow this information to be disseminated. As cabin wireless becomes available, airlines are using dedicated onboard WiFi SSID's to equip pilots with access to real-time weather on the flight deck, to improve operational decision making and reduce block times. Further, flight attendants can check gate connections and passengers can even rebook themselves if necessary.

#### ***6.2.8.1 Ku/Ka-Band Aviation Architecture***

In the proposed architecture the terrestrial satellite communications gateway would in turn connect with the ground DM function to accomplish link selection from available options, message routing, and the required security, reliability, and other requirements for conduct of

flight information. Aircraft link equipment would also be managed by the aircraft DM, and information routed via the DM to various onboard users including passengers, cabin crew, and flight crew. For larger aircraft, either GEO or LEO systems will be viable; smaller aircraft will be compatible with future LEO systems only, subject to the weather interruption considerations discussed previously.

#### ***6.2.8.2 Ku/Ka-Band Interoperability and Applicability***

The future Ku/Ka-Band systems are expected to be interoperable with other proposed systems, including the DM, VHF and L-Band links, and legacy systems. Future Ku/Ka-Band SATCOM systems will be applicable primarily to larger aircraft that operate at cruise altitudes above the troposphere (and potential weather interruptions), such as airline and business jet aircraft and larger UASs. GA aircraft and smaller UASs will have very limited ability to support the antennas required for GEO systems, and will find equipment size and cost to be challenges as well. Aircraft whose primary operations take place within the troposphere will have limited applicability due to weather-induced service disruptions. Personal jets or VLJs may benefit from Ku/Ka-Band systems depending on their size and operating altitudes.

#### ***6.2.8.3 Ku/Ka-Band Scalability, Failures Modes, Effects and Backups***

For the compatible users, scalability of these systems is relatively high. Significant bandwidth is available, particularly at Ka-Band, and satellite architectures will become capable of delivering improved performance during the study period. By 2063 it is likely possible that antenna and filtering advances will allow closer spacing of geosynchronous satellites, with a direct increase in bandwidth as a result. LEO configurations also open a new area of scalability, allowing spectrum re-use across relatively small geographic areas within the footprints of the low orbiting satellites.

Three primary failure modes are involved: failure of the aircraft equipment, of the satellite itself, or of the earth station/ground connection segment. Due to their limited reliability at lower altitudes, the primary application of satellite systems will not be conduct of flight services, minimizing their failure effects in most cases.

Failure of aircraft equipment is primarily mitigated by the use of onboard backup systems. Specific backup architectures will be based on the criticality of the system to safe operations; if only passenger connectivity is affected, more limited backup capabilities may be needed. The DM function also dynamically attempts to find and access alternate links, again depending on criticality and end-user cost/priority criteria.

Satellite and ground segment failures may be mitigated by the DM and aircraft link equipment attempting to access an alternate satellite, particularly if satellite spacing has decreased by 2063. If an alternate satellite is unavailable, the DM will attempt to access alternate links – for

example, Iridium or other L-Band SATCOM or, over land, the various VHF, L-Band and cellular links available. In the case of LEO systems, an inoperative satellite quickly moves along its orbital track, limiting interruptions from individual spacecraft to a few minutes duration in most cases.

### **6.2.9 Iridium/Next (L band)**

The Iridium system of L-Band SATCOM is used today for air-to-ground communications, and its successor system Iridium/NEXT is expected to see increased aviation use. Iridium/NEXT is scheduled to become operational in 2017-2018, and was used as the baseline for evaluation of offerings of that type. Iridium/Next is also designed to provide a capability for true “Push-To-Talk” (PTT) voice communications in real time, anywhere in the world.

Iridium/Next will include not only communication but also a space-based ADS-B payload that will provide direct air-to-ground relay of aircraft ADS-B transmissions in the oceanic regions. This capability will allow radar-like air traffic surveillance in those regions, allowing tactical rather than procedural traffic separation techniques to be used, fundamentally changing air traffic practices worldwide, and increasing capacity significantly in many areas. This capability could also change the link loading and other aspects of the current ADS-B links (Mode S and UAT) in future applications in the oceanic regions where it will be available. Due to competition for capacity from ground/mobile users in populated areas, Iridium space-based ADS-B will not be offered in populated land areas. It should be noted that space-based ADS-B capabilities have also been proposed based on both Globalstar and INMARSAT platforms; for various technical reasons the XCELAR team expects the Iridium-based offering, called AIREON, to be the most viable of these.

Iridium/NEXT also includes global Ka-Band capability (see previous section). By 2063, Iridium/NEXT will have reached its design life and is expected to have been replaced with a new generation system offering further capability enhancements.

User costs on Iridium/Next are expected to be relatively high. Pre-paid phone use is currently hovering around \$1.00/minute and SMS messaging is \$ 0.60 per message. Generic data rates are \$1.80 per 1000 bytes. As an illustration, a typical NEXRAD weather radar image in compressed format is about 100 Kbytes. If the present addressing scheme is used, this graphic would cost \$180.00. Iridium/Next is an addressed system, and does not appear to be well suited to broadcast operations.

Iridium deployment and use on aircraft will continue to increase, but is expected to be used primarily for specialized needs (such as polar communications) and backup capability due to its relatively high cost.

### **6.2.9.1 Iridium/Next Architecture**

The architecture for Iridium/Next is a Low Earth Orbit (LEO) satellite constellation with aircraft link equipment connecting to one or more earth station gateways. The DM function on aircraft and ground manage the link and information transported.

### **6.2.9.2 Iridium/Next Interoperability and Applicability**

Iridium communication will not interfere with any future or existing systems, and will be interoperable with all proposed future links. Specific capabilities and backward compatibility between the Iridium/NEXT follow-on and its predecessor is beyond the scope of this study. Iridium-based communication will be applicable to all user groups, including commercial, business, GA, personal jets, and large and small UASs.

### **6.2.9.3 Iridium/Next Scalability, Failure Modes, Effects, and Backups**

The Iridium/Next L-Band system itself may be subject to growth limits due to its current spectrum allocation. However, its successful application to space-based ADS-B and growing role in aviation communication may facilitate either additional spectrum allocations, or a new generation of similar competing commercial services. For air transport users, its primary L-Band use may be as a backup to Ku/Ka-Band SATCOM at high latitudes and/or low altitudes, and as a low-bandwidth link for ATM-related messaging. In these applications its scalability is moderate or better. Iridium/NEXT's Ka-Band capability could provide much higher bandwidth connectivity globally.

The Iridium constellation itself is relatively failure tolerant due to its large number of spacecraft and their rapid motion – for any given user, any single spacecraft failure quickly propagates to other locations. Aircraft equipment failure could result in loss of ATM communications in certain conditions, such as during polar operations, and onboard backup equipment architectures should be determined accordingly. Multiple, geographically diverse ground gateways provide inherent backup, particularly in conjunction with the Iridium system architecture and its intersatellite link capability.

A major failure of the Iridium system, such as from an extreme space weather event, could cause significant disruptions in polar and oceanic operations as its use becomes more central to those operations. Self-separation of aircraft via air-to-air ADS-B provides one mitigation element; in addition, ATM communication fallback procedures will need to be developed.

## 7 Candidate Technology Comparison

The parallel efforts to identify and characterize future NAS communication functions, and candidate link technologies, converged in the candidate comparison process. Each function defined in Section 5 was used to rank each relevant link in terms of its suitability, on a scale from 1 to 10. Those rankings were then analyzed in a series of comparative steps to identify the best-suited candidates for each function, under the most relevant conditions. This section summarizes the results of the comparison process.

### 7.1 Candidate Suitability Ratings

This section summarizes the relationship between each function, one or more candidate communication links, and a relative ranking of overall merit for each candidate from a technical standpoint. A numerical suitability rating is given for each candidate, relative to its suitability for that specific function, on a ten-point scale based on its capabilities and characteristics relative to the requirements of each function. Only links with a suitability rating of 5 or higher are shown for brevity. In cases where several links had ratings of 5 or more, only the top 3 or 4 are shown, again for conciseness. Candidates are listed in order of relative suitability, and a brief summary of underlying rationale for ratings and other relevant ranking factors is included where applicable. The same link candidate may receive different ratings for its suitability for different functions. It should be remembered that this assessment is based on technical considerations only; business case considerations were addressed in the next phase of the program, and are summarized in Section 8, Business Case Analysis.

Each function is referenced by its Function Code, as defined in Section 5 and summarized in the Future Datalink Technology Candidate Matrix in Appendix 1.

#### 7.1.1 Airborne Aircraft, Inbound Communications

The recommended data links below are listed in priority order based on our assessment of their ability to most effectively and economically accomplish the mission.

##### **AAI-1:** Location/State Vector:

Three attributes are drivers: latency, system capacity, and communications range.

Candidates Include:

- |                                                                                          |                      |
|------------------------------------------------------------------------------------------|----------------------|
| 1. ADS-B Next                                                                            | <b>Suitability 9</b> |
| 2. AeroWAN                                                                               | <b>Suitability 9</b> |
| 3. ADS-B present implementation<br>(With phased modulation and low-power on-ground mode) | <b>Suitability 7</b> |
| 4. UAT<br>(Air-to-air, supplemented by TIS-B ground-to-air)                              | <b>Suitability 5</b> |

Rationale: Multiple data links carrying location/state vector information may be necessary in the future to guarantee the continuity of service to achieve airborne self-separation. ADS-B Next offers the best throughput and long-term capacity. ADS-B Next has the capacity to support 4 times as much traffic as the present ADS-B, or 6,400 squitters per second within a service volume, supporting increased future traffic density.

Current ADS-B, when enhanced via phased modulation and low-power ground operation mode, is capable of meeting the requirement, with acceptable throughput and potentially fewer transition issues than ADS-B Next, but with much less capability for future expansion. UAT, when supplemented by TIS-B ground-to-air, provides a multi-use link, but lower overall performance than either ADS-B or ADS-B Next.

It is worthy of note that current ADS-B has the capacity to accommodate additional traffic without becoming overloaded for many years, if transmissions are limited to collision avoidance messages at 1 or 2 per second. It is not necessary to send 6 pulse groups per second per aircraft as in current practice. Increased message rates provide no additional position/state vector information. One feature that should be added is anti-spoofing (coded) preambles into the message to avoid detection of false messages from hackers.

AeroWAN provides an alternate method of broadcasting state vector messages. It has sufficient range and enormous capacity. It will be able to support additional messages and larger messages than present ADS-B. AeroWAN operates in similar aviation protected spectrum to that of ADS-B Next, but uses multiple frequencies in a mobile Wide-Area Network (WAN) architecture for greater flexibility and bandwidth capability.

**AAI-2, AAI-3:** Same as AAI-1, same rationale.

**AAI-4, AAI-5, AAI-6:** Vehicle (in) Hazardous messages, AMDAR reports are expected to be broadcast to aircraft.

Candidates Include:

- |                             |                      |
|-----------------------------|----------------------|
| 1. ADS-B Next               | <b>Suitability 9</b> |
| 2. UAT FIS-B with revisions | <b>Suitability 8</b> |
| 3. AeroWAN                  | <b>Suitability 8</b> |

Rationale: Messages are expected to be larger than 112 bits, therefore current ADS-B would not be a good choice. UAT FIS-B message lengths are a maximum of 422 bytes which can support a variety of broadcast messages. If AMDAR and Hazmet Weather reports were limited to less than 422 bytes or multiple 422 byte messages were combined, then UAT would be applicable – but UAT is currently limited to lower altitude use.

At present UAT FIS-B data is limited to a maximum reporting altitude of 24,000 ft. This is suitable for GA and some turboprops at these cruise altitudes and may also be useful for air transport aircraft during climb or descent. Weather data for air transport aircraft will require support from other data links or revision of the UAT data messages to include higher altitudes.

For these reasons, ADS-B Next is recommended, as it can serve both high and low-altitude aircraft, and offers superior bandwidth and flexibility. In addition, the ADS-B Next 1030 MHz data link could easily handle broadcast message sizes of 10K bytes and larger. Larger data files transmitted by UAT must be partitioned into smaller blocks and transferred slowly or be truncated.

AeroWAN can support transfer of larger text messages without truncation of graphical hazardous area files. Its WAN-based architecture could introduce some additional latency in routing messages from a source aircraft to all other aircraft logged onto the network, but this is expected to be minimal, especially with SDR-enabled multi-channel reception of the proposed broadcast channel.

VDL-2 is not recommended as a single channel data link, as it is expected to quickly become congested.

#### **AAI-7: Traffic Flow Management**

Candidates Include:

- |               |                      |
|---------------|----------------------|
| 1. AeroWAN    | <b>Suitability 9</b> |
| 2. VDL-2 Next | <b>Suitability 7</b> |
| 3. UAT        | <b>Suitability 5</b> |

Rationale: Data is not time critical but acknowledgement is required; coverage area is localized to a few hundred miles and perhaps less. AeroWAN is well suited to this type of data, offers robust bandwidth and growth capability, and operates in the aviation spectrum. VDL-2 Next can meet the requirements, but

is more bandwidth and growth constrained. UAT's inherent spectrum limitations make future saturation a serious consideration.

**AAI-8: NOTAMS Broadcast**

Candidates Include:

- |                         |                      |
|-------------------------|----------------------|
| 1. AeroWAN              | <b>Suitability 9</b> |
| 2. SDARS                | <b>Suitability 7</b> |
| 3. VDL-2 Next Broadcast | <b>Suitability 6</b> |
| 4. UAT FIS-B            | <b>Suitability 5</b> |

Rationale: AeroWAN offers high bandwidth and flexibility, and is compatible with all altitudes of operation. SDARS offers wide-area broadcast coverage, but may have bandwidth limitations; also, use of a wide-area satellite system to distribute regional data has efficiency limitations. Both UAT FIS-B and VDL-2B are capable of providing the required information; however, UAT has altitude limitations, and VDL-2B may be capacity limited.

**AAI-9 through AAI-13: Weather information (various types)**

Required range of information is up to 1000 miles; same information is useable by many aircraft.

Candidates Include:

- |                      |                      |
|----------------------|----------------------|
| 1. AeroWAN           | <b>Suitability 9</b> |
| 2. SDARS             | <b>Suitability 8</b> |
| 3. VDL-2 Next        | <b>Suitability 6</b> |
| 4. Ka band broadcast | <b>Suitability 6</b> |

Rationale: AeroWAN offers high bandwidth, flexibility, and potential expandability as traffic grows over time; range of any single ground station is limited to 100 miles, so coverage may not be available in certain geographical areas at low altitudes. SDARS has the largest area coverage and high data capacity, allowing more efficient distribution overall. Ka band broadcast has the highest data capacity, and large area coverage, but reception is highly dependent upon antenna size, limiting compatibility with smaller aircraft in particular. Ka band can also be subject to weather attenuation, which also affects smaller aircraft users. VDL-2 and UAT are not expected to have the



remaining capacity in 2063 to provide high resolution graphics over a large area.

**AAI-14 through AAI-16:** AOC, AAC, Optimization data

File sizes are indeterminate, latency is modest. ACK/NAC is required.

Candidates Include:

- |                           |                      |
|---------------------------|----------------------|
| 1. AeroWAN                | <b>Suitability 9</b> |
| 2. Iridium / Iridium/Next | <b>Suitability 8</b> |
| 3. VDL Next               | <b>Suitability 6</b> |
| 4. Cellular               | <b>Suitability 6</b> |
| 5. Ka band ACK/NAC.       | <b>Suitability 6</b> |

Rationale: Routine traffic, data latency is not critical. Any link that can support routine traffic across CONUS coverage with modest queueing delay is suitable. AeroWAN provides high bandwidth, the flexibility to accommodate traffic from both ATM and AOC/AAC sources, and compatibility with all aircraft types. Iridium may be more bandwidth limited, but offers global coverage. VDL Next has bandwidth limitations, but is compatible with all aircraft types, whereas interactive Ka band has high bandwidth but antenna size issues for smaller aircraft. Cellular can address the AOC/AAC applications, given changes to the current operating altitude limitations.

**7.1.2 Airborne Aircraft, Outbound Communications**

**AAO-1:** Location/State vector:

Candidates Include:

- |               |                      |
|---------------|----------------------|
| 1. ADS-B Next | <b>Suitability 9</b> |
| 2. ADS-B      | <b>Suitability 7</b> |
| 3. UAT        | <b>Suitability 7</b> |
| 4. AeroWAN    | <b>Suitability 5</b> |

Rationale: The three key attributes are data latency, system capacity and communication range. ADS-B Next has higher capacity than present ADS-B, and the inherent capability to expand capacity through additional spectrum allocation which current ADS-B does not. UAT has additional data latency if traffic is derived from surveillance radars. Otherwise UAT air-to-air and current ADS-B air-to-air are equal. AeroWAN offers an interesting option as a backup

or fallback link in case of primary link failure; its latency would be comparable to UAT when traffic is derived from surveillance radars. It operates in the aviation spectrum, has high bandwidth, and compatibility with all aircraft types.

AAO-2, AAO-3, AAO-4:

**Same as AAO-1.** Note that aircraft on ground should use ADS-B at low power (1 watt) to reduce airborne spectrum congestion, while allowing for more aircraft to aircraft information transfer using short messages.

AAO-5, AAO-6:

Message sizes are expected to be larger than 112 bits. ACK/NAC is required. Data latency is not critical

Candidates Include:

- |                     |                      |
|---------------------|----------------------|
| 1. AeroWan          | <b>Suitability 8</b> |
| 2. Iridium/Next     | <b>Suitability 8</b> |
| 3. Ka band ACK/NAC. | <b>Suitability 7</b> |
| 4. Cellular         | <b>Suitability 6</b> |

Rationale: AeroWan has high capacity to download significant engine and other maintenance data. Iridium or Iridium/Next have similar capabilities but data rate on L band Iridium will be lower. Interactive Ka band offers very high capacity, but has limited compatibility with smaller aircraft and UASs. Cellular links would meet the requirements, and serve all aircraft types, if current altitude operation limits were changed.

AAO-7, AAO-8:

Candidates Include:

- |                       |                      |
|-----------------------|----------------------|
| 1. VDL-2 / VDL-2 Next | <b>Suitability 8</b> |
| 2. AeroWAN            | <b>Suitability 8</b> |
| 3. ADS-B Next         | <b>Suitability 7</b> |
| 4. UAT downlink       | <b>Suitability 7</b> |

Rationale: Wind and temperature data represent a relatively small traffic segment; data latency is not critical. Multiple links are capable of meeting the requirements. VDL-2 and AeroWAN are compatible with all aircraft types, and offer routing capability to both ATM and non-ATM data users. ADS-B Next and UAT also meet the requirements, but offer more limited routing options to non-ATM users.

**AAO-9:** Special Requests.

A general category to include various specialized needs such as medical information for passenger emergencies.

Candidates Include:

- |                 |                      |
|-----------------|----------------------|
| 1. AeroWAN      | <b>Suitability 9</b> |
| 2. Iridium/Next | <b>Suitability 8</b> |
| 3. Cellular     | <b>Suitability 6</b> |

Rationale: AeroWAN is the best candidate as it can support increasing file sizes and high network capacity, compatibility with all aircraft types, and robust routing to non-ATM ground users. Range is more than adequate for reporting. ACK/NAC is available.

Iridium/Next can support large file sizes with good transfer rate. Network delays of a few hundred milliseconds are not an issue for these types of messages. ACK/NAC protocol is built in to the two way messaging. Alternately Iridium/Next Push to Talk (PTT) could be used as a common channel for a number of aircraft as long as the transmit percentage of each aircraft is low. A continued issue for Iridium is network availability as satellite connectivity is limited by design although once connected, data transfer rates are more than sufficient.

Cellular links would meet the requirements, and serve all aircraft types, if current altitude operation limits were changed.

**7.1.3 Aircraft on Ground, Inbound Communications**

**AGI-1 through AGI-6:** Airspace System information and Atmospheric

Requirements include support of large number of aircraft at close range, and variable message sizes including graphics. Latency requirement is modest, and ACK/NAC is not needed.

Candidates Include:

- |                     |                      |
|---------------------|----------------------|
| 1. AeroMACS         | <b>Suitability 9</b> |
| 2. Cellular (4GLTE) | <b>Suitability 8</b> |
| 3. VDL-2 Next       | <b>Suitability 6</b> |
| 4. SDARS            | <b>Suitability 5</b> |

Rationale: AeroMACS is well suited for this application. Link has high capacity and spectrum is reserved for aircraft applications. Many aircraft can use this system at the same time. AeroMACS information will be localized for the specific airport. It should be noted that there may be airports which are not equipped with AeroMACS, but may be within ground range of an AeroWAN station, which could provide similar capability.

Cellular links can provide the same information as AeroMACS but spectrum will be shared by consumers and data transfer rates may lag due to network delays. SDARS also has capacity for graphic files but localized information may not be available and data rate will be slower with greater information latency.

**AGI-7 through AGI-10:** Taxi instructions, departure clearance, gate assignments

Candidates Include:

- |                          |                      |
|--------------------------|----------------------|
| 1. AeroMACS with ACK/NAC | <b>Suitability 9</b> |
| 2. VDL-2 Next            | <b>Suitability 8</b> |
| 3. VDL-2                 | <b>Suitability 7</b> |
| 4. Iridium               | <b>Suitability 5</b> |

Rationale: Small file sizes similar to ACARS information, ACK/NAC protocol is required. There may be several messages sent to the vehicle in a period of a few minutes. VDL-2 and AeroMACS are packet switched, and within the capacity limits of both; AeroMACS can service more aircraft.

Iridium is circuit switched, and keeping a channel open during all of ground movement for each aircraft may saturate the satellite's capacity. Iridium Push to Talk networked users on a single frequency could greatly increase capacity. Message initiation may take many seconds to minutes.

Cellular links can meet requirements for AOC and AAC in AGI-9 and -10, but are less likely to be deemed acceptable for AGI-7 and -8 messages.

**AGI-11, AGI-12:** Information from proximate vehicles on their location and intentions

Low latency, to include other ground vehicles, high capacity on airport.

Candidates Include:

- |               |                      |
|---------------|----------------------|
| 1. ADS-B Next | <b>Suitability 9</b> |
|---------------|----------------------|

- |                    |                      |
|--------------------|----------------------|
| 2. AeroMACS        | <b>Suitability 7</b> |
| 3. ADS-B Low Power | <b>Suitability 5</b> |
| 4. UAT             | <b>Suitability 5</b> |

Rationale: ADS-B messaging is vehicle to vehicle. AeroMACS information needs to go through a router. Latency here is very important; a delay of just a few seconds may give flight crews and ground personnel misleading information. UAT could theoretically meet the needs of GA-only airports, but latency induced by relay of messages between 1090- and UAT-equipped vehicles compromises its performance where there is mixed equipage. Capacity of all systems is adequate.

**AGI-13, AGI-14:** Wake vortex reports; AMDAR reports

Candidates Include:

- |               |                      |
|---------------|----------------------|
| 1. AeroMACS   | <b>Suitability 9</b> |
| 2. ADS-B Next | <b>Suitability 8</b> |
| 3. VDL-2      | <b>Suitability 8</b> |
| 4. Cellular   | <b>Suitability 7</b> |

Rationale: Reports are broadcast and file sizes are small. Communication range is small. Latency is not a significant consideration. AeroMACS is well suited to this application. ADS-B Next and VDL-2 B are also well suited, but may require routing capability of data to ground ATM and non-ATM users. AeroMACS and VDL-2B can continue connectivity until out of range of ground stations.

For cellular links, pilots will need to stay connected to the network prior to and during taxi maneuvers to takeoff; under current FCC regulations, 4GLTE communications must be discontinued when aircraft is off the ground. Local network coverage could affect reliability.

**7.1.4 Aircraft on Ground, Outbound Communications**

**AGO-1, AGO-2:** Vehicle position and velocity information

Low latency, other ground vehicles should be capable of receiving A/C squitter and sending their own position reports. High total capacity on airport is required.

Candidates Include:

- |                          |                      |
|--------------------------|----------------------|
| 1. ADS-B Next, Low Power | <b>Suitability 9</b> |
|--------------------------|----------------------|

- |             |                      |
|-------------|----------------------|
| 2. AeroMACS | <b>Suitability 7</b> |
| 3. ADS-B    | <b>Suitability 5</b> |
| 4. UAT      | <b>Suitability 5</b> |

Rationale: ADS-B Next offers the best combination of low latency, capacity, and compatibility with all aircraft types. AeroMACS offers similar advantages, but is dependent on the presence of a ground station on or near the airport, whereas ADS-B Next works directly from vehicle to vehicle.

Both current ADS-B and UAT can meet the performance requirements, but share the drawback of interoperability versus latency in a mixed-equipage environment. Resolution of the interoperability problem requires a local ground station, and introduces latency.

**AGO-3, AGO-4:** Maintenance data

Candidates Include:

- |                                     |                      |
|-------------------------------------|----------------------|
| 1. AeroMACS;                        | <b>Suitability 9</b> |
| 2. Cellular, with ACK/NAC protocol. | <b>Suitability 8</b> |
| 3. VDL-2 Next                       | <b>Suitability 7</b> |
| 4. VDL-2                            | <b>Suitability 5</b> |

Rationale: Data latency is not critical, a few seconds delay is acceptable. Message sizes may be highly variable. Cellular links can support data transfer with ACK/NAC. VDL-2 Next is expected to have the capacity. Maintenance data file sizes may become too large for VDL-2 to manage without significant delays.

**AGO-5, AGO-6:** Local wake turbulence, winds

Note: This is broadcast data for local conditions.

Candidates Include:

- |               |                      |
|---------------|----------------------|
| 1. AeroMACS   | <b>Suitability 9</b> |
| 2. Cellular   | <b>Suitability 8</b> |
| 3. VDL-2 Next | <b>Suitability 8</b> |
| 4. VDL-2      | <b>Suitability 6</b> |

Rationale: Small file size, local data favor the use of local links versus satellite; capacity limits of VDL-2 are a consideration.

**AGO-7:** Special requests, medical information

Candidates Include:

- |                                     |                      |
|-------------------------------------|----------------------|
| 1. AeroMACS                         | <b>Suitability 9</b> |
| 2. Cellular(Using ACK/NAC protocol) | <b>Suitability 8</b> |
| 3. VDL-2 Next                       | <b>Suitability 6</b> |

Rationale: Data file sizes are indeterminate. Either AeroMACS or Cellular can handle variable file sizes. VDL-2 Next may have delays with large free text messages or graphics.

**7.1.5 Suitability Rating Summary**

Fig. 5 summarizes the suitability ratings assigned to each applicable link for each function. This rating data was used to perform a series of comparisons between candidates, the results of which are summarized in the Section 7.2. Additional detail on functions, applicable links, and suitability ratings can also be found in Appendix 1, Future Datalink Technology Comparison Matrix.

Airborne Aircraft, Inbound Communications														
Function	ADS-B Next	ADS-B/ Lo Pwr	Aero MACS	Aero WAN	UAT	VDL-2 Next	VDL-2	SDARS	Cellular	Iridium /Next	Ka Bcast	Ka Inter	Avg/ Function	
AAI-1	9	7		9	5								30	7.5
AAI-2	9	7		9	5								30	7.5
AAI-3	9	7		9	5								30	7.5
AAI-4	9			8	8								25	8.3
AAI-5	9			8	8								25	8.3
AAI-6	9			8	8								25	8.3
AAI-7				9	5	7							21	7.0
AAI-8				9	5	6		7					27	6.8
AAI-9				9				8			6		23	7.7
AAI-10				9				8			6		23	7.7
AAI-11				9				8			6		23	7.7
AAI-12				9				8			6		23	7.7
AAI-13				9				8			6		23	7.7
AAI-14				9		6			6	8		6	35	7.0
AAI-15				9		6			6	8		6	35	7.0
AAI-16				9		6			6	8		6	35	7.0
Avg/Link	54	21		141	49	31		47	18	24	30	18	433	120.6
Avg/Link	9.0	7.0		8.8	6.1	6.2	0.0	7.8	6.0	8.0	6.0	6.0		7.5

Airborne Aircraft, Inbound Communications														
Function	ADS-B Next	ADS-B/ Lo Pwr	Aero MACS	Aero WAN	UAT	VDL-2 Next	VDL-2	SDARS	Cellular	Iridium /Next	Ka Bcast	Ka Inter	Avg/ Function	
AAO-1	9	7		5	7								28	7.0
AAO-2	9	7		5	7								28	7.0
AAO-3	9	7		5	7								28	7.0
AAO-4	9	7		5	7								28	7.0
AAO-5				8					6	8		7	29	7.3
AAO-6				8					6	8		7	29	7.3
AAO-7	7			8	7		8						30	7.5
AAO-8	7			8	7		8						30	7.5
AAO-9				9					6	8			23	7.7
Avg/Link	50.0	28.0		61.0	42.0		16.0		18.0	24.0		14.0	253.0	65.2
Avg/Link	8.3	7.0	0.0	6.8	7.0	0.0	8.0	0.0	6.0	8.0	0.0	7.0		7.2

Aircraft on Ground, Inbound Communications														
Function	ADS-B Next	ADS-B/ Lo Pwr	Aero MACS	Aero WAN	UAT	VDL-2 Next	VDL-2	SDARS	Cellular	Iridium /Next	Ka Bcast	Ka Inter	Avg/ Function	
AGI-1			9					5	8				22	7.3
AGI-2			9					5	8				22	7.3
AGI-3			9					5	8				22	7.3
AGI-4			9					5	8				22	7.3
AGI-5			9					5	8				22	7.3
AGI-6			9					5	8				22	7.3
AGI-7			9				7		5	5			26	6.5
AGI-8			9				7		5	5			26	6.5
AGI-9			9				7		5	5			26	6.5
AGI-10			9				7		5	5			26	6.5
AGI-11		9	7		5								21	7.0
AGI-12		9	7		5								21	7.0
AGI-13	8		9		8				7				32	8.0
AGI-14														0.0
Avg/Link	8.0	18.0	113.0		18.0		28.0	30.0	75.0	20.0			310.0	92.0
Avg/Link	8.0	9.0	8.7	0.0	6.0	0.0	7.0	5.0	6.8	5.0	0.0	0.0		6.6

Aircraft on Ground, Outbound Communications														
Function	ADS-B Next	ADS-B/ Lo Pwr	Aero MACS	Aero WAN	UAT	VDL-2 Next	VDL-2	SDARS	Cellular	Iridium /Next	Ka Bcast	Ka Inter	Avg/ Function	
AGO-1	9	5	7		5								26	6.5
AGO-2	9	5	7		5								26	6.5
AGO-3			9			7	5		8				29	7.3
AGO-4			9			7	5		8				29	7.3
AGO-5			9				6		8				23	7.7
AGO-6			9				6		8				23	7.7
AGO-7			9				6		8				23	7.7
Avg/Link	18	10	59		10	20	22		40				179	50.5
Avg/Link	9.0	5.0	8.4	0.0	5.0	6.7	5.5	0.0	8.0	0.0	0.0	0.0		7.2
Aggregate/link	130.0	77.0	172.0	202.0	119.0	51.0	66.0	77.0	151.0	68.0	30.0	32.0		

Figure 7-1: Link Candidate Suitability Ratings



## 7.2 Candidate Comparison Results

The candidate ranking data was subjected to a number of analysis steps in order to understand how the candidates compare to each other in various ways. Three levels of result analysis were used, each building on its predecessors:

- Baseline Analysis
- Function Priority Weighted Analysis
- Weighted Score with Obsolescence

For each level of analysis, two comparison summaries were developed. One was based on the aggregate score for each link across all functions for which it was deemed applicable, and the other was an average score for each link based only on those functions for which it was deemed applicable. This provides two perspectives:

- **Aggregate Scores** illustrate how well each link serves a wide range of functions; for example, a link that provides excellent service for only one of the identified functions would score lower than a link that provides suitable service for many functions;
- **Average Scores** highlight how well each link serves those functions for which it is used, without considering how broad-based its applications may be.

The Baseline Analysis was done based on the suitability scores for each function summarized in Fig. 5, and Aggregate and Average scores determined for each candidate link. Then two types of weighting factors were applied. In the Function Priority Weighted Analysis, each candidate's score was weighted based on each function's priority level (i.e., Must-have, Highly Desirable, or Nice-to-have). This produces a higher score when a link enables a must-have function than a nice-to-have one, based on the relative importance of each function to the conduct of flight. A 5-point weighting scale was used, with Must-have weighted at 5 points, Highly Desirable at 3 points, and Nice-to-have weighted at 1 point.

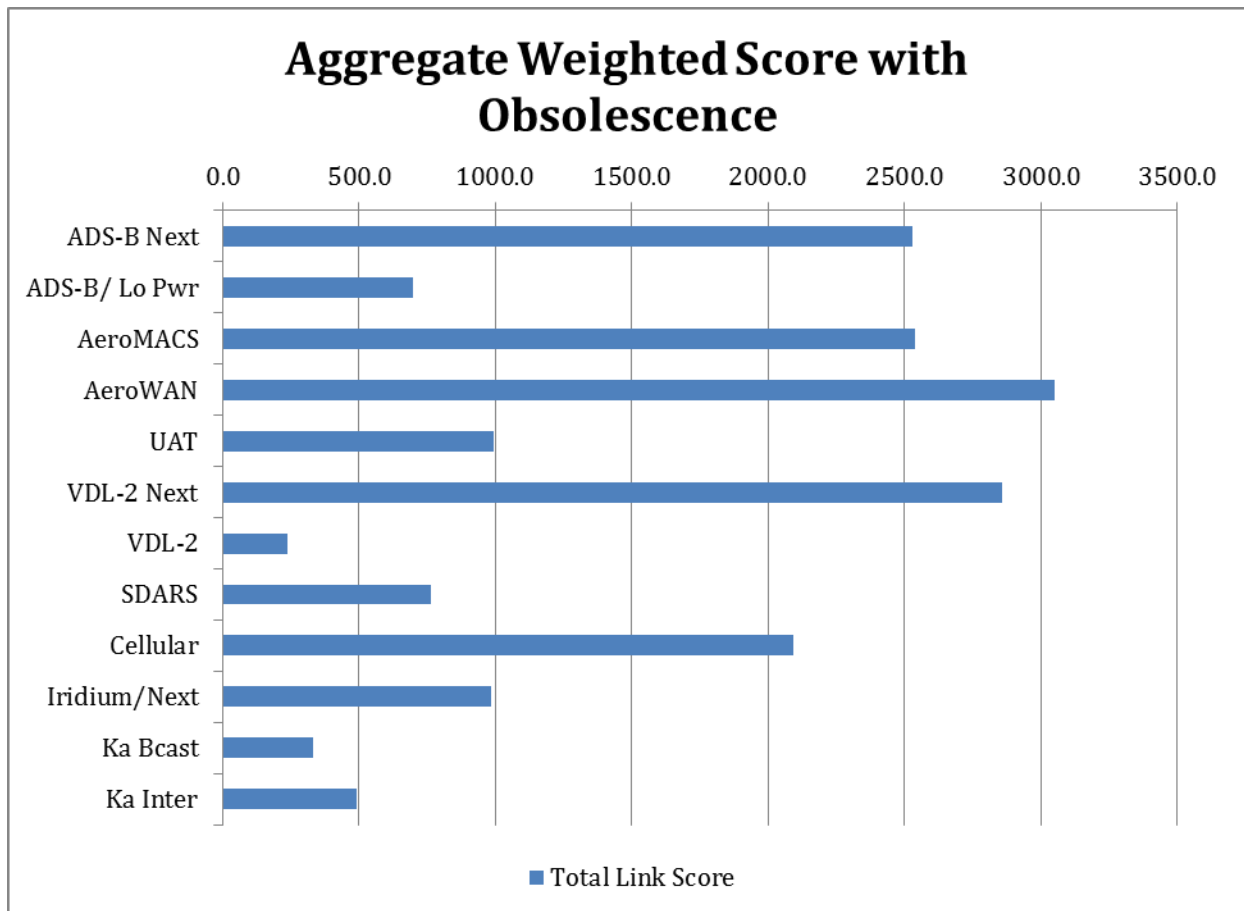
In the Weighted Score with Obsolescence, a second factor was then applied to the Function Priority Weighted Analysis scores based on the team's assessment of each link's susceptibility to obsolescence, again using a 5 point scale. This produces higher scores for those links deemed to be less susceptible to obsolescence, in the context of looking forward from the 50-year future research reference point. Those links offering the lowest susceptibility to obsolescence were scored higher than those deemed more susceptible to becoming obsolete in the 50+ year time period.

The results of the various analyses were compared and evaluated in terms of the overall research goals, and the research team determined that the final step, Weighted Score with Obsolescence, provided the best overall guidance toward the optimum future solutions. A

summary of all the analysis steps and their results is included in Appendix 6 for reference; notes regarding obsolescence susceptibility can be found there as well.

### 7.2.1 Weighted Scores with Obsolescence

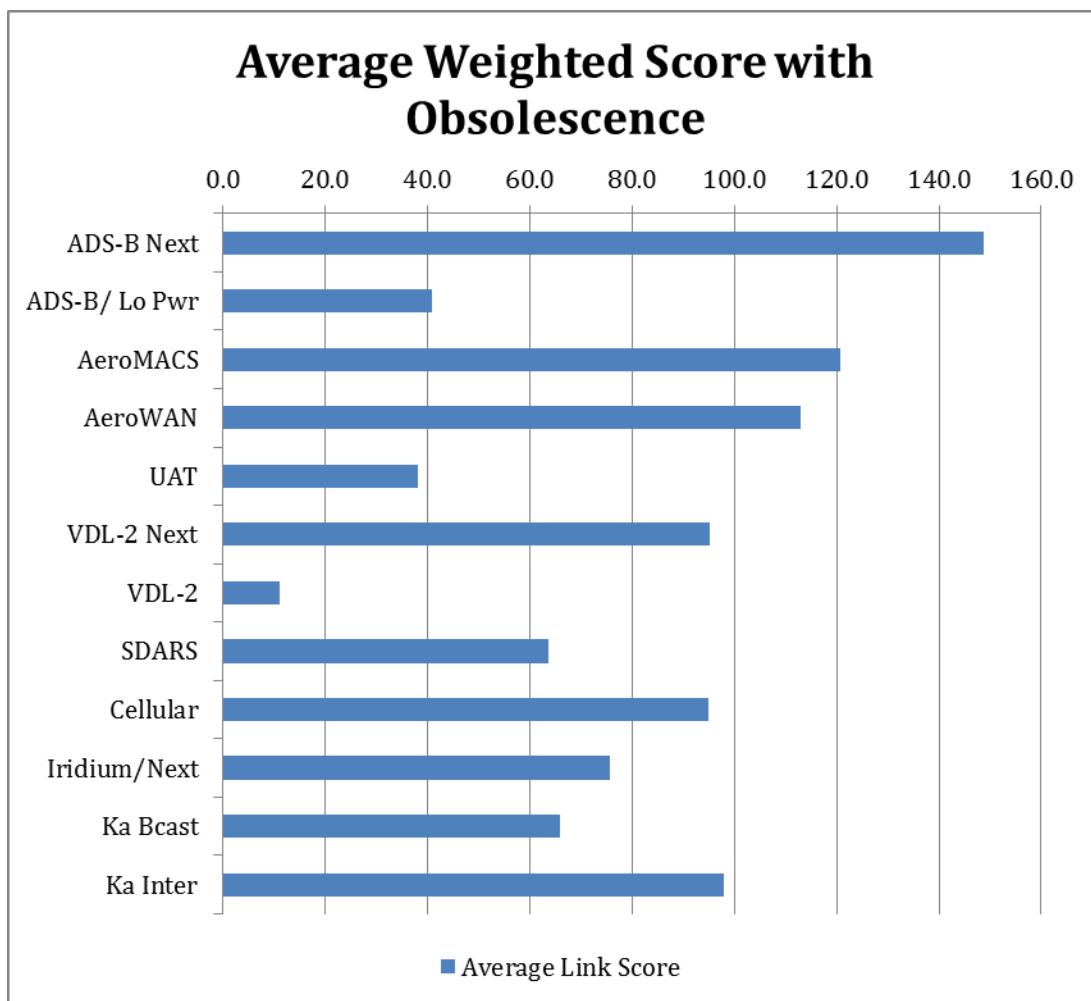
Fig. 6 shows the aggregate scores for all candidates with obsolescence taken into account. This may provide the clearest “investment case” perspective of which candidates merit the most investment in research and development to realize the maximum future benefit. It can be seen that the highest ranking candidates, in order, 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.



**Figure 7-2: Aggregate Weighted Score with Obsolescence**

The average scores with obsolescence considered, shown below in Fig. 7, show a somewhat different order of the same four top candidates, with ADS-B Next scoring highest in performance within its more limited areas of application, followed by AeroMACS, AeroWAN, and VDL-2 Next. Note that both cellular and interactive Ka-band also score well.

ADS-B Next, AeroMACS, and interactive Ka-Band all score well in part because they are purposely designed to address specific needs in specific areas rather than broad-based links for many applications. AeroMACS only serves ground-based users in close proximity to airports, Ka-Band serves large aircraft at cruise altitudes in oceanic areas, and ADS-B Next is purposely limited to proximate aircraft awareness functions. Cellular candidates also score well for similar reasons, being primarily applicable to ground-based uses not unlike AeroMACS.



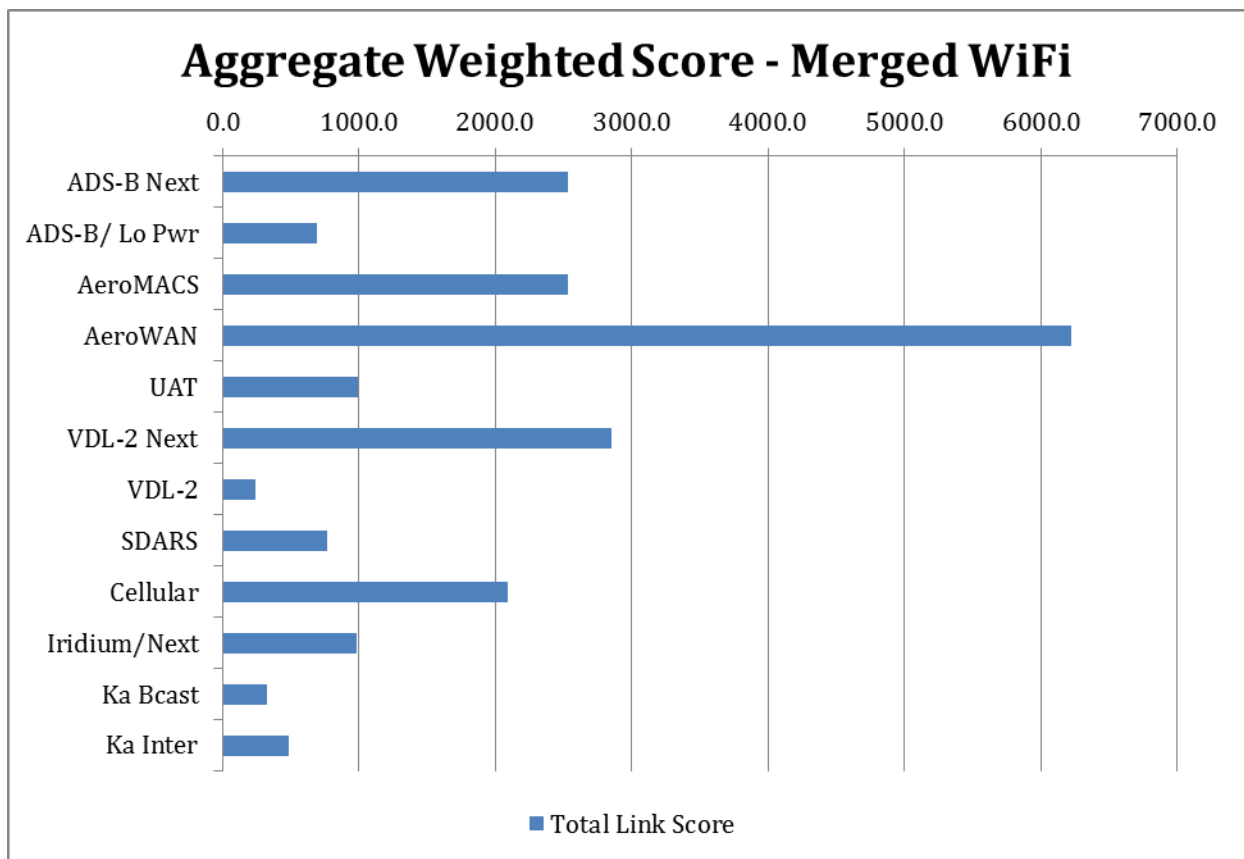
**Figure 7-3: Average Weighted Score with Obsolescence**

### 7.2.2 Merged AeroWAN and AeroMACS Rankings

One special case was also analyzed by the team. AeroWAN and AeroMACS, as currently defined, are based on similar technology and operate in similar ways, but serve two disparate operational contexts using two relatively divergent frequency bands. As a result, each scores very well in its own area: AeroWAN in airborne functions only, and AeroMACS in ground functions only. If these two systems could be merged over the 50 year research period, a number of advantages would be gained, including commonality of both ground and airborne

equipment, potentially one less avionics device needed, and increased coverage by using airport systems to also serve as AeroWAN ground stations and vice versa.

The team opted to model a merged system in the AeroWAN L-Band spectrum primarily due to the broader applications of an L-Band SDR; however, more detailed technical analysis would be needed to formulate a considered recommendation. The aggregate scores under this scenario are shown in Fig. 8 below. It can be seen that the “Merged WiFi” system outscores all other candidates by a significant margin, due to its broad-based range of functions served coupled with its high bandwidth and other strong performance rankings. This suggests that, of all the candidates analyzed, such a merged AeroWAN/AeroMACS system would serve the most users and functions, across all user segments, of any single link studied.



**Figure 7-4: Aggregate Weighted Scoring Showing Merged AeroWAN / AeroMACS Score**

The Gap Analysis input downselect 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. This indicates that suitable performance can be obtained for each function from two or more candidates. As a result, while the Average rankings provide an interesting look at optimum options, which may be useful in choosing between two qualified candidates, in general the research team concluded that the Aggregate Rankings provide a more compelling measure of

overall candidate merit, particularly in the context of defining development priorities going forward. A link candidate that provides suitable service for many functions may well support a better business case for development investment than one that provides somewhat better service for a small number of functions. Using the Aggregate Weighted Score with Obsolescence analysis results, as shown in Fig. 6, the highest-ranking candidates are AeroWAN, VDL-2 Next, ADS-B Next, and AeroMACS.

### **7.2.3 Minimum Candidate Set to Enable All Functions**

Analysis of the Baseline scoring data shows that, technically, all identified functions could be served at some level by AeroMACS and AeroWAN. However, there are two fallacies in this. First, the defined functions do not break out oceanic operations separately from others, and neither AeroMACS nor AeroWAN is well suited to oceanic operations. Second, this would require serving some Priority 1 functions with a suitability level of 5 (AeroWAN for ADS-B related functions). AeroWAN is better suited to serve as a backup for this high-priority service rather than as the primary link.

As a result, a realistic minimum candidate set would need to include at least four links for adequate service. Based on the analysis, the optimum minimum set would consist of ADS-B Next, AeroWAN, AeroMACS, and either Iridium or Ka-Band satellite for oceanic operations. If AeroWAN and AeroMACS were merged, only three links would be required.

## **7.3 Technical Analysis Conclusions**

A total of twelve candidate link technologies were compared against the future NAS functions identified previously in the study, five systems currently in service or being deployed within the next three years, and seven new or significantly enhanced candidates. Using all twelve candidates, all functions were deemed to be successfully enabled.

The comparison also shows the important potential role of some future technologies studied in a successful future NAS. This can be seen in the top four candidates, with the highest aggregate ratings, all of which are new candidate technologies. The four highest aggregate scores (considering obsolescence) were, in order:

- AeroWAN
- VDL-2 Next
- AeroMACS
- ADS-B Next

Another important point is the impact of two elements that do not appear in the comparison scores, as they are not link technologies per se, but are important enabling technologies for

both technical and business case viability of the overall system: BBSDR, and the Delivery Manager. These two capabilities allow much broader application of multipurpose hardware than current architectures, and the seamless use of multiple links. They also are expected to extend the service life of communication avionics, due to their ability to implement enhancements via software rather than replacement of hardware onboard the aircraft.

Both BBSDR and DM were assumed to be available to all links at the 50-year reference point, with the exception of current ADS-B and UAT, and current VDL-2, as discussed previously. Both are integral parts of the future datalink architecture envisioned by the team, and are essentially integral with each other as well. In that context, it could be argued that their presence benefits all candidates equally.

#### **7.4 Technical Gap Analysis**

The preceding comparison data allows examination of possible gaps, or functions not adequately enabled by the candidate technologies. It can be seen that in the context of current technologies only, there are functions that are expected to be required in the 2063 aviation industry that are unlikely to 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 research, all identified future functions could be enabled successfully.

The research team did not address any hypersonic vehicles at speeds beyond Mach 8. This would include inbound traffic reentering from space. These vehicles are likely to require specialized datalinks tailored to their operational environments, and they will have physical limitations such as radio black-out periods during very high speed flight or reentry periods. These highly specialized considerations were deemed to be outside the scope of this study.

For each function, at least the top three candidates were scored; in some cases as many as five were deemed suitable enough to merit comparison. In each case, all candidates scored showed ratings of 5 out of 10 or better, and for each function there were at least 2 candidates scoring 7 or higher. This indicates that each function could be successfully supported by at least two of the candidates; this is the primary criterion used by the research team to define the presence or absence of a gap. It should be noted, however, that gaps do exist if consideration is limited to currently available links only; for some functions there is no current link available, and in others current links are not expected to be capable of suitable performance. When obsolescence aspects are considered, additional gaps emerge using current technologies alone.

The team's conclusion is that no technical gaps were identified in this analysis, within the defined scope of the study, that were not adequately addressed by previously identified

candidates. The next phase of the study included analysis of business case factors, which presents another source of potential gaps, but from a technical standpoint there are no gaps that require development of additional candidate solutions.

## 8 Business Case Analysis

This section summarizes the process used, and results of, the business case analysis phase of the research. Of the twelve link candidates compared technically, nine were included in the business case analysis, along with two underlying enabling technologies that facilitate or enable all of the link candidates. Three of the lowest-scored candidates technically were determined not to merit further consideration, both because of their low technical ratings and because they would be fully supplanted by other, enhanced equivalents: current ADS-B, UAT, and current VDL-2.

### 8.1 Business Case Analysis Approach

The research resulted in a new approach to the underlying architecture of ground-air and air-air communications as a whole, rather than simple “link to function” paired solutions. Two foundational technologies of that architecture are in fact not link-specific at all: The Delivery Manager (DM) and Broad Band Software Defined Radio (BBSDR) technologies.

The rapidly maturing BBSDR technology allows broadband reception and processing of various disparate signals and modulation/encoding techniques in proximate bands using an architecture that allows a single receiver to receive and process a broad band of frequency spectrum to decode/encode multiple link technologies for different purposes. This significantly increases the flexibility of individual communication devices and the system as a whole. The BBSDR concept reduces overall cost, weight of multiple radios and associated wiring, and complexity. All of these improvements become an important enabling factor in the migration from current to future 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, security, cost Required Communication Performance (RCP), and other criteria. This allows seamless ground-air and air-air information transfer using a number of disparate links, including facilitating the use of non-aviation protected spectrum for certain functions, while still utilizing aviation protected spectrum where criteria require it.

BBSDR and DM are core technologies that facilitate or enable a number of “link technologies” even though they are not links per se. In addition, a number of specific link candidates were identified and determined to meet the functional requirements from a technical standpoint, including ADS-B Next, VDL-Next, and AeroWAN. These technologies and candidates are described in detail in previous reports. In most cases, specific link candidates are implemented by means of software configurations in the BBSDR hardware, making their link-specific costs of



deployment very low, but each requiring the BBSDR platform to be useful. Thus in a sense, if taken separately, the BBSDR platform business case requires justifying a hardware installation that in itself meets no functions, and each link-specific software definition business case looks very attractive but are all predicated on the need for the platform.

This produced a set of potential solutions that in many cases are based on the intersection of multiple technologies, such as DM/BBSDR (L-Band for example), and ADS-B Next, as a group that together offer significant technical and business advantages. Further, within the BBSDR concept each specific link implementation is essentially a software-only addition, which to a large degree renders the normal business case analysis inapplicable; the link-specific business case that “buys on” the BBSDR avionics would appear to be much more expensive than subsequent software-based added links. Any one link could be placed in that position, depending on deployment, operational, development/approval, and other future factors that cannot be fully predicted at this time. Any arbitrary assignment of such order of deployment would unduly skew the business case results for a particular link candidate in relation to the others.

For these reasons, the team developed an architecture-based approach to business case analysis, wherein a reference architecture was defined for representative user groups based on a combination of technologies harmonized within the new architectural approach, and guided by the technical rankings resulting from the previous candidate comparison process. Three user groups were selected as reference architecture platforms, to characterize the range of business case factors that need to be considered: General Aviation, Domestic Air Transport, and Oceanic Air Transport aircraft.

A reference data exchange architecture was defined for each of those groups, which successfully addresses all future NAS data exchange functions identified previously in the research, with appropriate levels of redundancy and reversion modes based on the type of operations and regulatory requirements analogous to those applied today. The team then established typical costs for both current and future communication solutions for each user group within the context of each reference architecture. For the future architectures, costs were estimated based on the combination of the avionics itself (i.e., the BBSDR hardware/installation, DM), and each added link-specific upgrade (i.e., ADS-B Next software on L-Band BBSDR). Then the overall solution sets were compared from the business case perspective, for each representative user group.

The team assessed the relative costs of current and anticipated future certification and production approval processes, as a function of final product pricing. The conclusion was reached that, while future processes may be based on different criteria and implemented in

different ways, the relative cost of such approvals and related engineering, documentation, testing, and time are expected to be similar as a percentage of final product pricing.

Installation costs were also analyzed as a comparison of current and future architectures. The future architectures offer some installation advantages based on a lower number of LRUs and LRU types, and allowance was made on that basis. Some economies of scale are possible in antenna installations, but for the most part physical limitations of intermodulation distortion and other proximity issues will require provisions for antenna diversity between systems. Coupled with the need to address possible failure or impairment of an antenna in flight, the research team elected to assume that the antenna installation requirements will not differ significantly between the current and the future architecture.

Recommendations for most promising technology alternatives were then formulated based on the comparative costs of the future versus the current architecture for each user group, on an overall solution basis. Recommendations are summarized in Section 9.

## **8.2 Underlying Assumptions**

A number of underlying assumptions were adopted to guide and clarify the analysis process. The following three sections summarize significant underlying assumptions applied to the analysis.

### **8.2.1 Future Technology Assumptions**

- Advances in basic enabling technologies such as microprocessor capabilities, memory capacity and density, Digital Signal Processors, and RF device performance, all versus cost, size and power consumption, will continue to evolve at a pace close to that of the past 30 years;
- RF power components will continue to advance in terms of power capacity and cost reduction;
- End-product avionics designs will continue to see reductions in size, weight, power consumption, and cost, along with increasing technical capabilities, at a rate approaching that of the past 30 years;
- RF filtering capabilities will advance, but at a slower rate than digital technologies due to physical considerations of RF energy propagation and interaction;
- Antenna considerations will require similar allowances for locations diversity, directionality, and time-coordinated transmit and receive operations for certain operations, due to physical considerations of RF energy propagation and interaction

combined with the inherently limited physical separation distances possible within a single aircraft;

- Aviation communications will continue to be an especially challenging field in which to realize major gains in link performance, due to the inherently wide ranges of distance, speed, antenna limitations and other factors that affect system link margins, dynamic ranges, and the relatively limited production volumes for aviation-specific components;
- Advances in GA and VLI aircraft design and capabilities will increase demand for oceanic communications in smaller aircraft;
- Future high bandwidth satellite communication systems (i.e., Ku- or Ka-band) will increasingly migrate to LEO-type configurations, allowing smaller link margins and the use of smaller, simpler and less expensive antennas for aviation applications. This will allow increased GA use of Ku- and Ka-Band links, and allow air transport aircraft to utilize multi-satellite links for higher bandwidth, increased reliability, and lower cost than current systems.
- In the future all aircraft will have a much higher level of onboard navigation capability, both from external and internal (i.e., inertial) sources, than they do today. This is relevant to communications because loss of GNSS guidance can be mitigated for substantial periods of time without the need for Minimum Operating Networks (MON) of current-technology ground-based navigation aids such as VOR, DME, or ILS. This in turn allows re-use of that aviation spectrum for more broad-based communication purposes such as AeroWAN and VDL-Next.
- The future architectures assume that the AeroWAN systems will include as a core capability a form of “Pseudolite” capability in AeroWAN ground stations that serves as a backup to GNSS navigation reception in events of GNSS failure, jamming, or other interruptions. This is also relevant to the cost analysis because it increases the importance of the L-Band BBSDR in maintaining safety; as a result a minimum configuration requiring two or more L-Band BBSDRs was applied.
- The future architectures include an inherent radio altimetry function as one of the software-defined capabilities of the 4 – 5 GHz BBSDR; this is to allow precision landing capabilities using a combination of either non-augmented GNSS (i.e., without GLS-type differential correction) or onboard inertial navigation position data, augmented by radio altimetry for vertical position accuracy. This allows both a primary and backup precision landing capability (equivalent to Category 3c) without the need for legacy ILS

or MLS landing systems, and helps to increase aviation RF spectrum available for broader-purposed communication applications.

### **8.2.2 Future Technology Cost Assumptions**

- Cost comparisons were made in terms of current rather than future dollars, to focus the results on comparative costs without the unnecessary variables of economic projections of future currency fluctuations. Factors were applied to allow for future changes in costs of components, production, product volumes and other factors.
- A nominal avionics LRU price point of five times direct cost, including hardware and software development, certification, and production, will continue to be a valid basis for end product pricing;
- Components developed and produced in large volume for mass-market applications (i.e., cell phones) can facilitate significant reductions in avionics cost where they are applicable; conversely, it is assumed that aviation-specific components, where they remain necessary for certain functions, will continue to be severely production volume limited and cost reduction potential;
- Pricing for air transport aircraft on a fleet-wide basis assumed a median discount level of 30% under list pricing, based on current market practice
- The relative cost of regulatory approvals, certifications, and production approvals are expected to be similar as a percentage of final product pricing.
- For air transport, a typical major airline in current terms was modeled, based on a total fleet of 700 aircraft, and a mix of domestic and international operations. Typical current equipage costs were defined, along with spares allowances and other factors. It should be noted that the same allowance for spares (10%) per LRU type was assumed for the future configuration, on the basis that the underlying logistics of fleet support, spares positioning across the system, and dispatch reliability drivers will remain similar over time. However, it can be seen that the future architecture requires a smaller number of different LRU types, and that is reflected in the model as well.
- For the purposes of cost analysis, Business Aviation was deemed to be similar to Part 121 operators in terms of reference architecture and current versus future equipage cost. Decision drivers are somewhat different, but in practice the typical business aircraft is equipped with similar, or in many cases better, capabilities than the typical air transport aircraft. This trend was deemed to be unlikely to change significantly over the study period.

### **8.2.3 UAS Considerations**

UAS aircraft and operational situations vary widely in size, weight, power, and cost, and their sensitivity to those factors in avionics equipment are equally diverse. In addition, basic NAS requirements are still being determined, making it very difficult to analyze quantitatively at this time. General Aviation is a good representative case for all but very small UAS, which also may have additional functional and communication requirements for operations at very low altitudes, which are also still in flux. Further study is needed into the probable NAS functional requirements in the UAS sector as regulatory guidance and UAS technology mature; both have undergone significant movement during the course of the research.

### **8.3 Reference Architectures**

Future reference architectures were defined for three representative user groups: Air Transport – Domestic, and Air Transport – Oceanic, and General Aviation. A “current practice” architecture was developed for comparison with each future reference architecture. For clarity, these current and future architectures are summarized in the following sections, and both architectures and costs are shown in tabular form in Appendices 2 – 5. Each table includes reference architecture components, costs and LRU count for each current and future architecture, and relative comparisons between them.

All future architectures share some common features, as depicted in Fig. 3. One or more DMs communicate with each other and with various BBSDRs and other link-specific LRUs via a Communications Bus, and one or more of each type of BBSDR (i.e., L-Band, VHF, SATCOM, etc.) implement various specific software-defined links and connect to appropriate antennas. In practice, the DM function will be physically integrated with BBSDR units, with one designated as primary and the other(s) as backup. Definitions for abbreviations and acronyms can be found in Appendix 8, Acronyms and Terms.

The future air transport analysis is based on a hypothetical carrier consisting of a total fleet of 700 aircraft, with 400 of those considered to be domestic use only, and the remaining 300 configured for oceanic operations as well. This fleet size and breakdown resembles the structure of a number of major air carriers today. It allowed the analysis to consider the differences in number of LRUs, and related spares cost, for the two different sub-fleets, as well as the overall costs of the “blended” fleet of a typical carrier of today and the future.

It should be stressed that these reference architectures are intended to be a tool for relative comparison of current and proposed future solution sets, and capture a notional implementation of the proposed future data link technologies. These reference architectures are not meant to address the many optimizations and tailored architectures that will undoubtedly be part of any actual implementation.

### **8.3.1 Air Transport – Domestic Architecture**

Domestic air transport aircraft differ from their oceanic counterparts in communication terms primarily due to the need for oceanic aircraft to have robust capabilities for communicating without ground infrastructure to support various links. Thus oceanic aircraft require one or more high-bandwidth satellite links, where domestic aircraft may not. In addition, in some cases domestic air transport aircraft (regional jets, for example) may be small enough in size to pose significant installation problems for GEO satellite communication systems.

The Domestic Air Transport reference architecture for the future system includes four primary components, which between them comprise all required data link functions identified in the course of this research: VHF BBSDR, L-Band BBSDR, AeroMACS/5 GHz BBSDR, and a Commercial Cellular Datalink. Table 3 below correlates the future architecture and its LRUs to the current typical configuration of a domestic air transport aircraft.

**Table 8-1: Air Transport Domestic, Current and Future Architecture**

<b>Domestic Air Transport – Future Architecture</b>		<b>Domestic Air Transport – Current Architecture</b>	
<b>LRU Type</b>	<b>LRU Configuration</b>	<b>LRU Type</b>	<b>LRU Configuration</b>
VHF BBSDR / DM	2 LRUs, primary and backup	CMU	Individual LRU
		DMU	Individual LRU
		VHF Comm 1	Individual LRU
		VHF Comm 2	Individual LRU
		VHF Comm 3	Individual LRU
		VDL-2 #1	Individual LRU
		VDL-2 # 2	Individual LRU
		VOR / ILS / GS - 1	Individual LRU
		VOR / ILS / GS 2	Individual LRU
L-Band BBSDR	3 identical LRUs	Transponder 1	Individual LRU
		Transponder 2	Individual LRU
		GPS / All GNSS	Individual LRU
		GPS 2 / MMR 2	Individual LRU
		DME 1	Individual LRU
		DME 2	Individual LRU
		TCAS	Individual LRU
AeroMACS 5 GHz BBSDR	2 identical LRUs	Radar Altimeter	Individual LRU
Commercial Cellular Datalink	1 LRU	Cellular IFE System	Individual LRU
<b>8 LRUs</b>	<b>4 LRU Types</b>	<b>18 LRUs</b>	<b>11 LRU Types</b>

In addition, these LRUs are interconnected by the Communications Bus, and each requires its own antennas and other support provisions.

#### VHF BBSDR / DM

The VHF BBSDR performs all current VHF radio functions, both digital and analog. This includes current voice and VDL communication, to the extent that they are still needed in the future, along with the proposed VDL-Next. Dual, independent software defined receivers process the entire VHF band, coupled with two or more 50 watt, frequency agile, software defined transmitters. It should be noted that a single VHF BBSDR provides at least two independent voice and VDL capabilities; in addition, hardware redundancy in the form of dual VHF BBSDRs is included in the reference architecture for air transport, essentially providing 4 VHF voice and 4 VDL datalink systems under normal conditions. VHF-based GLS functions will also be performed by the VHF BBSDR.

The Delivery Manager function is also integrated into the VHF BBSDR. This function is a key component of the future system, but does not need to be a stand-alone LRU from an architecture standpoint, and is expected to be integrated into other LRUs for efficiency and cost reasons. It could be integrated into either the VHF or L-Band BBSDR, and in fact was included in both in the reference architecture to provide triple redundancy provisions. The DM, as part of its overall function, also addresses all functions currently performed by the CMU and DMU in the current architecture.

#### L-Band BBSDR

The L-Band BBSDR serves a broad range of current and future functions, and is of sufficient importance in the future architecture to merit assignment of triple redundancy, particularly in the oceanic configuration. Each L-Band BBSDR includes four software defined receivers, each processing the entire L-Band simultaneously, including all GNSS signals, ADS-B, ADS-B Next, legacy UAT for GA aircraft), multiple DME channels, SDARS, and AeroWAN. Dual 300 watt software defined, frequency agile transmitters with switchable antennas are managed by the DM to provide bidirectional communication as needed.

It should be noted that from a technical standpoint legacy TCAS could also be accommodated, but due to the requirement for specialized antennas and other provisions, this is not included in the 50-year future cost analysis. It is assumed that by that point, over 40 years after the global mandates for universal ADS-B equipage, TCAS in its current form will have become fully obsolete. As discussed in the previous section, DM capability can also be integrated into the L-Band BBSDRs, and was included in the reference architecture.



## AeroMACS 5 GHz BBSDR

The 5 GHz BBSDR platform is designed to host two currently known functions that reside within that spectral band, and also to accommodate additional future functions that may be defined in that band. Each AeroMACS BBSDR LRU includes dual software defined receivers and transmitters to support simultaneous and independent AeroMACS and Radio Altimeter (RA) operations. For air transport two separate LRUs are included for redundancy due to the importance of both RA and AeroMACS to effective flight operations.

It should be noted that AeroMACS capability could have been incorporated into the system in a number of ways. For example, it is likely that in the future there will be small, inexpensive stand-alone AeroMACS transceivers or chipsets that could be integrated into any of the other LRUs. However, for air transport applications the team decided to define a separate LRU for various 5 GHz software defined functions, including AeroMACs. The primary reasons were:

- Hosting AeroMACS on a BBSDR platform provides maximum forward flexibility for addition of bandwidth as additional spectrum becomes available and system needs grow;
- This allows the RA function to also be hosted on the same platform, further reducing LRU/type count and again providing software-defined forward flexibility for technical advancements in RA technology;
- Defining a 5 GHz BBSDR platform lays the groundwork for implementation of other, future software defined functions using 5 GHz spectrum;
- A more conservative approach to future architecture cost estimation.

## Commercial Cellular Datalink

As discussed in previous reports, the future of commercial cellular systems as far as 50 years in the future, as they might apply to aviation applications, is difficult to define in detail from a technical standpoint. The large numbers of potential subscribers, associated revenue, and their effect on regulatory processes can bring about significant changes in the communications landscape as a result of the powerful commercial and political forces they influence – far more so than the comparatively miniscule numbers of aviation users, even when large numbers of UAS are included. As a result, it is difficult to predict even fundamental technical drivers such as frequency bands of future cellular operations, modulation and bandwidth management techniques, etc. Current air transport uses of commercial cellular technology are typically focused primarily on In Flight Entertainment (IFE) uses rather than flight deck functions. Thus IFE equipment today is typically based on a commercially-driven business case, justified

by a revenue segment comprising significant numbers of potentially fee-paying cabin users, rather than a small number of flight deck users who represent an operator cost center rather than a revenue segment. This is unlikely to change over time. It is difficult to predict what the future cabin entertainment / passenger communication marketplace will look like, beyond the fact that it will continue to demand higher bandwidth, in keeping with the terrestrial mobile sector. For modeling purposes, the research team based those architecture elements on a market-driven demand for 500% increase over current capabilities.

Another important business consideration is the degree to which terrestrial commercial cellular operators may be motivated to make accommodations for capturing aviation users in their revenue base. Cellular operators, by their technical definition, base their business on the principle of re-using their RF bandwidth again and again, on a geographical basis, to provide services to large numbers of terrestrial users equipped with purposely range-limited transceivers. Aviation applications are in many ways diametrically opposite to this, with fast-moving platforms covering large distances, with relatively long-range antenna footprints, occupied by relatively small numbers of potential service users. While there are some technical options for mitigating these divergent service models, as discussed in previous reports, the ultimate business consideration is the cost / benefit relationship for both provider and subscriber. In particular, the provider will be required to invest in initial and ongoing provisions to capture and serve airborne users, including technical development, regulatory change, capital asset investments and maintenance, and some concessions of RF bandwidth to a smaller pool of potentially higher-rate service users. Of these, the business cost of allocating scarce bandwidth to aviation users may be the most difficult to justify.

From the subscriber side, and the aircraft operator side, there are also hurdles to overcome. Avionics must be developed and capitalized that are suitable for air transport aircraft, at much higher development and production cost than consumer equipment. Typical cellular systems only serve land-based users, so either alternate sources of oceanic service will be needed, or the development of oceanic provider systems (i.e., satellite) – to serve a miniscule subset of the population that justifies terrestrial system development. And finally, providers must have a revenue model that justifies the opportunity costs for serving the aviation population, resulting in potentially much higher service costs for aviation than that for terrestrial users.

Despite those hurdles, it is likely that commercial cellular systems will be adapted to aviation to some extent; in fact, that is happening to some degree today. For example, several airlines use cellular technology to update navigation charts, download FOQA

data, or engine health monitoring data, but it is quite limited today and geographically constrained. It is difficult to predict a compelling enough business case for the provider to postulate adapted cellular systems becoming any sort of primary or backbone link for aviation operations. As a result, the air transport reference architectures assumed that the future cellular system would be a stand-alone system, rather than being integrated into other BBSDR avionics, and would primarily serve passenger entertainment rather than flight deck needs. It was also assumed that these systems would primarily serve domestic rather than oceanic operations.

### 8.3.2 Air Transport – Oceanic Architecture

Oceanic air transport architectures are essentially identical to those for domestic operations, with one key addition: the need for added connectivity when out of range of land-based communication systems, as illustrated in Table 4. This includes both flight deck and passenger applications. Aside from these additional oceanic connectivity solutions, oceanic and domestic air transport aircraft are essentially identically equipped, and were covered in the previous section. This section covers only the differences between oceanic and domestic air transport aircraft.

**Table 8-2: Air Transport Oceanic, Current and Future Architecture**

<b>Oceanic Air Transport – Future Architecture</b>		<b>Oceanic Air Transport – Current Architecture</b>	
<b>LRU Type</b>	<b>LRU Configuration</b>	<b>LRU Type</b>	<b>LRU Configuration</b>
VHF BBSDR / DM	2 LRUs, primary and backup	CMU	Individual LRU
		DMU	Individual LRU
		VHF Comm 1	Individual LRU
		VHF Comm 2	Individual LRU
		VHF Comm 3	Individual LRU
		VDL-2 #1	Individual LRU
		VDL-2 # 2	Individual LRU
		VOR / ILS / GS - 1	Individual LRU

		VOR / ILS / GS 2	Individual LRU
L-Band BBSDR	3 identical LRUs	Transponder 1	Individual LRU
		Transponder 2	Individual LRU
		GPS / All GNSS	Individual LRU
		GPS 2 / MMR 2	Individual LRU
		DME 1	Individual LRU
		DME 2	Individual LRU
		TCAS	Individual LRU
		Iridium LEO L-Band	Individual LRU
AeroMACS 5 GHz BBSDR	2 identical LRUs	Radar Altimeter	Individual LRU
Ku- or Ka-Band BBSDR	1 LRU	HF Radio / SATCOM	Individual LRU
		Ku-Band or INMARSAT	Individual LRU
Commercial Cellular Datalink	1 LRU	Cellular IFE System	Individual LRU
<b>9 LRUs</b>	<b>5 LRU Types</b>	<b>21 LRUs</b>	<b>14 LRU Types</b>

To some degree it will be possible to use AeroWAN, VDL-Next and other systems for oceanic communications via aircraft-to-aircraft relay to land-based systems. This is included in the proposed capabilities for both AeroWAN and VDL-Next for this reason. However, this is dependent on the presence of proximate aircraft located at suitable distances between a given oceanic aircraft and a land-based system. Although the DM function is expected to leverage these conditions when available, it is not reliable enough to be considered a primary mode of operation, and is expected to serve more as a cost reduction opportunity and backup capability when conditions permit.

Satellite communications offer the most practical solution today, and are expected to increase in technical capabilities, cost effectiveness, and availability in the future. LEO-based L-band communications, such as the current Iridium and Iridium/Next, are accommodated in the future architecture by the addition of software defined functions in the L-Band BBSDRs. Ku- and Ka-Band satellite links are in use today for oceanic communications, and are expected to grow in availability, capabilities and cost

effectiveness over the research period. Ku- and Ka-Band systems today are based on GEO orbital orientations and relatively high gain, steerable antennas on aircraft large enough to accommodate them. Similar future systems are expected to be available, and offer greater bandwidth, lower cost, and compatibility with BBSDR architectures.

In addition, it is expected that future Ku- and Ka-Band satellite systems will be available using LEO orbital configurations, allowing much more favorable link margins, lower power uplink transmitter requirements, and use of small, lightweight, and low-drag patch type antennas. The Iridium/Next system currently beginning its deployment will offer this capability to a limited degree, and it is expected that in 50 years there will be multiple, high-bandwidth options available. For this business case analysis, future cost estimates were limited to GEO-based systems with antenna systems similar to current offerings, in the interest of conservative cost estimation.

It is also technically feasible to serve Ku/Ka-Band communications using the L-Band BBSDR rather than an additional, dedicated Ku/Ka-Band LRU. It is not uncommon today for Ku/Ka-Band systems to actually use antenna-mounted amplifiers and downconverters to convert received signals to L-Band for coaxial cable transmission to the avionics, and to use L-Band modulators and upconverters to separate High Power Amplifier (HPA) units. Adding two additional software defined, frequency agile transmitters to the L-Band BBSDR for example, along with additional antenna switching, would provide further flexibility, cross-functional redundancy, and low additional cost. Upconverters and HPA's could even be antenna-mounted, as downconverters frequently are today, decreasing cable losses and HPA power requirements. However, for several reasons this analysis placed the Ku/Ka-Band avionics in its own LRU. Those reasons included cost conservatism, maintenance simplicity, and separation of commercial provider systems from conduct-of-flight systems.

### **8.3.3 General Aviation Architecture**

The GA architecture is similar to domestic air transport in many ways, with some important differences. Less redundancy is required, and simpler aircraft systems and architecture reduce overall LRU complexity. GA avionics packaging is typically different from air transport, emphasizing smaller, lighter enclosures, different mounting provisions, and a growing trend toward integration of communication functions into other avionics, such as panel-mounted multifunction displays, due to economies of scale and limitations of space, weight and power capacity. In order to avoid the complications of attempting to predict the 50-year future of GA panel displays and other non-communication products, which is beyond the scope of this research, the GA

reference architecture assumes that all communications functions will be packaged as individual LRUs as summarized in Table 5 below, which communicate with other systems and control/display interfaces via a data bus. In keeping with the team's conservative approach to future cost estimates, the chosen approach does not include potential further reductions in communication LRU cost through integration with other, non-communication avionics.

For a typical installation, a single VHF BBSDR provides the functions of current dual Nav/Com units, including VHF voice, VDL, VOR, ILS and Glide Slope functions to the extent that they are still needed 50 years in the future. The proposed future VDL-Next, GLS, and other VHF functions are also supported as software defined capabilities. Dual software defined receivers and dual 10 watt software defined transmitters emulate current dual Nav/Com operation when needed, in addition to supporting the additional future capabilities. The software defined architecture facilitates transitional operations as the current VHF systems migrate to the future VDL-Next structure while maintaining legacy capabilities as needed.

It is anticipated that by the 50-year future point, very little analog voice communication, VOR, or ILS systems will remain in common use, with even Minimum Operating Networks (MON) of VORs having been replaced with other, more efficient and effective means such as CPDLC, digital voice, all-GNSS reception, high-precision/long persistence onboard inertial navigation systems, and AeroWAN-based navigation "pseudolites". For this reason the reference architecture only includes a single VHF BBSDR LRU with its dual Nav/Com capabilities. In event of the loss of that VHF BBSDR LRU from service, the broad capabilities of the dual L-Band BBSDRs are expected to provide adequate backup communication capability.

Two L-Band BBSDR LRUs are included, due to their importance in primary and backup navigation, surveillance, and communication. Each LRU includes dual software defined receivers and dual 100 watt software defined transmitters. Each LRU can provide all L-Band functions, including GNSS, ADS-B, ADS-B Next, AeroWAN, multi-channel DME, L-Band LEO communications (e.g., Iridium/Next), SDARS, and legacy UAT and Mode S Transponder functions. For GA, the DM function is integrated into the L-Band BBSDR due to its typical dual LRU hardware redundant configuration; a third DM is not expected to be needed for GA, so no DM function is included in the VHF BBSDR for the reference architecture.

The GA architecture also includes a single AeroMACS 5 GHz BBSDR, providing both the ground-ground AeroMACS digital connectivity and the radio altimeter function similar

to air transport. Based on the low price point expected for this SDR-based unit, the addition of RA capability to a GA aircraft, equipped with all-GNSS navigation, adds significant new options for precision landing aids as discussed in previous reports. As in air transport, this also positions the future GA aircraft to take advantage of other potential future communication and/or navigation options that may be developed in 5 GHz aviation spectrum as it is re-used.

The application of commercial cellular networks for common aviation use is most likely to take place in GA, where aircraft operate at lower altitudes, at lower speeds, and users more closely resemble the mainstream ground-based mobile customer. For this reason the architecture also includes a commercial cellular link LRU, which can provide various data and digital audio communication functions. By linking it to the DM in the L-Band BBSDR, its availability can be monitored and leveraged by the DM along with other available links as appropriate.

**Table 8-3: General Aviation, Current and Future Architecture**

<b>General Aviation – Future Architecture</b>		<b>General Aviation – Current Architecture</b>	
<b>LRU Type</b>	<b>LRU Configuration</b>	<b>LRU Type</b>	<b>LRU Configuration</b>
VHF BBSDR / DM	Single LRU, provides Dual Nav/Com	VHF Nav/Com #1	Individual LRU
		VHF Nav/Com #2	Individual LRU
L-Band BBSDR	2 identical LRUs	GPS / All GNSS	Individual LRU
		Mode S Transponder or UAT	Individual LRU
		GPS / All GNSS	Individual LRU
		GPS 2 / VOR-2 / DME/DME Substitute for sole means navigation	Individual LRU
		DME	0 LRUs: GA A/C typically not equipped

			today
AeroMACS 5 GHz BBSDR	1 LRU	No Equivalent Link	
Commercial Cellular Datalink	1 LRU	Handheld Cellular WX Service	Individual LRU
<b>5 LRUs</b>	<b>4 LRU Types</b>	<b>7 LRUs</b>	<b>6 LRU Types</b>

#### **8.4 Business Case Findings**

Business case inputs and numerical outputs are shown in tabular form in Appendix 3 - 5 for reference. Estimated costs were assigned to each current and future LRU in the context of each current and future reference architecture, and results compared in various ways. This section summarizes the results of each comparison, organized by reference architecture groups.

In general, future architectures were deemed to be feasible from a business case perspective if the overall cost of the future architecture is equal to or less than the current architecture. Simply put, if the new solution costs less than the current solution, it will probably constitute a workable value proposition; the greater the reduction in cost, the more compelling the equipage case will be.

Conversely, if the future solution costs more, there needs to be a significant functional, safety or operational efficiency benefit to offset the difference; in particular, measurable financial gains in operating efficiency would constitute the most effective mitigator to higher cost. The greater the increase in future over current cost, the harder the value proposition will be to gain industry acceptance. In general, an increase of more than 10 – 15% over current conditions was deemed to be a very difficult value proposition for which to gain acceptance.

It should be noted that antenna considerations were considered to be a similar for both current and future architectures, due to governing physical limitations; for example, in some cases different software-defined systems in the same band would require different antennas, potentially mounted in different locations on the aircraft, to function correctly. Future transmit antennas will need to be located as far away from reception systems as possible, as they are today. One possible exception to this is future LEO-based Ku/Ka systems, which could use a patch versus beam-steered antenna. For cost conservatism though this case was not included.



#### **8.4.1 Number and Type of LRUs**

The total number of LRUs included in an overall avionics package, along with the number of different types of LRUs, can have a significant impact on both initial and long-term costs of the package to the operator. Obviously if initial equipage requires the purchase of a larger number of LRUs, the cost can be expected to be higher, but other less apparent factors come into play as well. Each additional LRU also adds weight, size, cost, and maintenance complexity to the overall system. In addition, for air transport, each LRU type drives the business planning for purchase, positioning, and repair strategies for spares across and air carrier's system. Typically the more LRU types there are in the package, the more spares must be purchased and maintained to achieve the necessary dispatch reliability. These factors were included in the business case analysis, for both the current and future architectures.

Another consideration is the expected reliability of each LRU, along with its contribution to overall maintenance costs and strategy. Historically, a higher level of functional integration per LRU has had both advantages and disadvantages in real-world maintenance: an LRU that performed multiple functions reduced the number of spares needed, but a failure of any one function required the replacement and off-line repair of the entire unit. However, in the proposed future architecture there are important mitigators to this consideration. First, the overall reliability of components and systems has steadily increased over the years, and is expected to continue to improve over the 50-year research period. Both the number of components subject to failure, and the technical factors that influence failure, will continue to decrease. From vacuum tubes to transistors, to integrated circuits, to the highly integrated microprocessor and DSP based architecture of the future, each LRU contains fewer and fewer components that are subject to failure. In parallel, the factors of heat, voltages, currents, and vibration susceptibility will continue to decrease; typical circuit voltages, for example, have gone from hundreds of volts to tens, to five, to three and below over the past 50 years.

Finally, it should be remembered that the future architecture will derive its ability to deliver multiple functions from a single LRU primarily through the SDR technology, wherein additional functions are primarily software enabled, rather than requiring significant additional hardware for each function. In this context the reliability of the underlying SDR platform becomes the controlling factor, rather than the number of functions performed.

The team's research concluded that no additional sparing allowance would be needed based on the number of functions performed by each LRU, in light of the expected reliability levels of the future technologies and the levels of redundancy built into the reference architectures. As a result, the future architecture offers some significant cost advantages over the current norm due to a smaller number of spares required for both initial purchase and ongoing maintenance

and repair. For air transport, a common current industry allowance of 10% was applied to both current and future architectures.

For GA, no direct spares allowance was included in the model. Typical GA aircraft are either individually owned and operated, or are operated in relatively small fleets. Maintenance is typically done on an outsource basis to third-party shops, who either stock spares or order as needed. In few cases is the quantity of owner/operator maintained spares large enough to affect the overall value proposition of equipage significantly.

#### **8.4.2 Air Transport, Domestic**

The proposed future solution set compared very favorably to the current architecture for domestic air transport aircraft. Eight different comparisons were made, examining various aspects of the overall system, culminating in an overall aggregate comparison of total costs for equipage and spares for a reference fleet of 400 domestic aircraft.

The first four comparisons examined the comparative cost of the four major types of future LRU:

- VHF functions only;
- L-Band functions only;
- 5 GHz functions only, and;
- Cellular datalink.

The other four comparisons focused on different aspects of the overall cost of equipage and support:

- Cost of equipping a single aircraft;
- Cost of equipping a 400 aircraft “reference fleet” of domestic aircraft, including typical quantity discounts;
- Spares cost for the 400 aircraft reference fleet, including typical quantity discounts;
- Aggregate total cost for the reference fleet, including both aircraft equipage and spares.

Industry-typical quantity discounts of 30% below list price for fleetwide purchases were applied, and similarly typical spares allocations of 10% per LRU type were also used. Note that sparing is based on LRU type, rather than number of LRUs – for example, if the architecture (current or future) includes 3 VHF LRUs, each LRU is allocated a spares allowance of (10% / 3), in accordance with current practice. Based on the technical assessment that the future LRUs are likely to have a higher overall reliability than current systems, and that the smaller number of LRUs and LRU types will have a positive impact on MTBF and MTTR, these assumptions were considered to be conservative.

Table 6 summarizes the eight comparison criteria and their results:

**Table 8-4: Air Transport – Domestic Business Case Results**

<b>Air Transport – Domestic Business Case Results</b>			
<b>Criterion</b>	<b>Current Architecture</b>	<b>Future Architecture</b>	<b>Future / Current %</b>
Total LRU Count	18	8	44 %
Total LRU Types	11	4	36 %
VHF Functions Only	\$135,408,000	\$6,160,000	5 %
L-Band Functions Only	\$148,176,000	\$53,760,000	36 %
5 GHz Functions Only	\$24,640,000	\$6,160,000	25 %
Cellular Datalink	\$12,320,000	\$9,240,000	75 %
Single A/C Equipage	\$1,021,000	\$250,000	24%
400 A/C Fleet Equipage	\$285,880,000	70,000,000	24%
Spares Cost	\$17,892,000	\$3,080,000	17%
Aggregate Total Cost	\$303,772,000	\$73,080,000	24%

The future architecture shows a very significant cost improvement over the current architecture in every category, with and without quantity discounts. The overall aggregate cost of the future system is less than one fourth of the current architecture, and this trend is consistent across the single aircraft and fleet equipage as well. Future spares cost is slightly lower, at 17% of current cost, due to the smaller number of LRU types required.

The future system has a significantly lower number of total LRUs (44%), but of commensurate importance is the lower number of LRU types (36%). The decreased number of LRUs directly decreases the purchase cost of spares; the smaller number of LRU types also will have a beneficial effect on more indirect cost drivers, such as reduced maintenance training (fewer LRUs to train for), reduction in test equipment, decreased MTTR due to simpler diagnostics, and reduced spares storage and logistics costs. These benefits were not quantified in the analysis, but can be expected to have a significant positive effect on overall life cycle cost for the aircraft operator.

When viewed in terms of individual LRU types, the future architecture again shows clear cost improvement, but more variation is seen. For VHF, the incorporation of the currently expensive CMU and DMU functions into the overall DM, coupled with the lack of need to triple redundant, limited-function LRUs as in the current architecture, produce a sharp cost difference: 5% of current cost. This is less visible for L-Band (36%), partly because the cost reduction benefit for eliminating the stand-alone CMU and DMU has already been ascribed to VHF. In addition, the future L-Band LRU requires triple redundancy due to the breadth of its functions, whereas the future VHF only requires two.

Of note is the AeroMACS 5 GHz LRU which, even with dual redundant LRUs, shows a very favorable 25% of current system cost. This is interesting, since there is currently no AeroMACS equipage at all in the current architecture; integrating the current Radio Altimeter function, in itself, produces the future vs. current cost reduction.

Regarding cellular data links, a number of unknowns are involved which make the comparison less meaningful than the other LRU types. As previously discussed, the future commercial environment for adaptation of high-volume, low cost personal cellular products to aviation are difficult to predict as far as 50 years in the future. The future business model for equipage is uncertain, and may involve commercial provider owned equipment onboard aircraft, leasing of aircraft equipment, and other factors that make comparison to current systems difficult. For the purpose of comparison, the research team assumed that the carrier would own the aircraft equipment, and estimated future cost based on extrapolation of current cost and capability trends toward a future performance goal of a 500% improvement over current system performance. This analysis yielded a future cost of 75 % of current architecture cost.

### **8.4.3 Air Transport, Oceanic**

As discussed in previous sections, the oceanic air transport architecture is identical except for three additional LRU categories for enhanced communications in areas distant from land-based communications. The same comparison criteria were used with one category added for Ku/Ka-Band satellite communications, and the same industry-typical discount and spares allowance were applied. An oceanic reference fleet of 300 aircraft was used.

Table 7 summarizes the eight comparison criteria and their results:

**Table 8-5: Air Transport – Oceanic Business Case Results**

<b>Air Transport – Oceanic Business Case Results</b>			
<b>Criterion</b>	<b>Current Architecture</b>	<b>Future Architecture</b>	<b>Future / Current %</b>
Total LRU Count	21	9	43 %
Total LRU Types	14	5	36 %
VHF Functions Only	\$101,556,000	\$4,620,000	5 %
L-Band Functions Only	\$132,846,000	\$40,320,000	30 %
5 GHz Functions Only	\$18,480,000	\$4,620,000	25 %
Ku/Ka-Band SATCOM	\$47,040,000	\$5,145,000	11 %
Cellular Datalink	\$9,240,000	\$6,930,000	75 %
Single A/C Equipage	\$1,315,000	\$270,000	21 %
300 A/C Fleet Equipage	\$276,150,000	\$56,700,000	21 %
Spares Cost	\$16,506,000	\$2,730,000	17 %
Aggregate Total Cost	\$292,656,000	\$59,430,000	20 %

The future architecture again shows significant reductions in cost relative to the current architecture. LRU Count and LRU types are similar to air transport domestic. VHF, 5 GHz and cellular all are based on the same data as domestic air transport, and show the same improvement. L-Band scores slightly better at for oceanic than domestic, at 30%, due to the incorporation of additional software defined functions that replace current LRUs for HF radio and/or L-Band Iridium oceanic communications.

The added LRU type, Ku/Ka-Band satellite communications, also shows a significant reduction from current to future cost. This is due to several factors, including the application of BBSDR technology, anticipated advances in component performance versus cost, and the probable advent of LEO-based Ku- and Ka-Band communication systems, which reduce required transmit power levels, antenna complexity, and other design requirements. As noted previously, a further reduction on future cost could be realized by incorporating Ku/Ka Band communications into the L-Band BBSDR, which was not included in this analysis.

Overall cost reduction from current to future is slightly better than domestic air transport, due to the added improvements in L-Band and Ku/Ka-Band previously discussed. Aggregate total cost for the 300 aircraft reference fleet is 20% of current architecture, an improvement from the 24% for domestic air transport.

#### 8.4.4 General Aviation

The General Aviation analysis is much simpler than those for air transport, due to the simpler reference architecture, reduced number of required functions and redundancies, the lack of fleet discounts and oceanic configurations, and the absence of spares as a significant consideration. As previously discussed, spares were not considered because GA fleets are typically single aircraft or small fleets with limited opportunities for economies of scale; typical maintenance scenarios often rely on outsourcing to a commercial provider who orders on demand or handles stocking in accordance with their overall business model. On that basis spares were deemed to be a negligible business case consideration for GA.

A total of seven comparison criteria were used, structured similar to the air transport analyses. LRU count is compared in the same way as air transport, although with the lack of sparing as a consideration, the impact of the number of LRU types is insignificant. Only five cost criteria were used: the four major LRU types, and aggregate total cost for a single aircraft.

Table 8 summarizes the eight comparison criteria and their results:

**Table 8-6: General Aviation Business Case Results**

<b>General Aviation Business Case Results</b>			
<b>Criterion</b>	<b>Current Architecture</b>	<b>Future Architecture</b>	<b>Future / Current %</b>
Total LRU Count	7	5	71 %
Total LRU Types	6	4	67 %
VHF Functions Only	\$11,000	\$5,000	45 %
L-Band Functions Only	\$31,500	\$24,000	76 %
5 GHz Functions Only	N/A	\$5,000	N/A
Cellular Datalink	\$1,700	\$1,000	59 %
Aggregate Total Cost	\$44,200	\$35,000	79 %

All categories except one show a clear and advantageous reduction in cost over the current architecture, although of a much lesser magnitude than seen in air transport. This is due in large part to the much smaller number of LRUs, functions, and costs for GA equipage than air transport. The reduced LRU count (71 %) does offer advantages in reduced space, weight, and power consumption, in addition to the simple reduction in cost from acquiring fewer devices.

The one exception to clear cost reduction is due to the lack of any current analogous function or system in GA to the AeroMACS/5 GHz technology, so no direct comparison could be made. Most GA aircraft are not equipped with Radio Altimeters, and AeroMACS has not yet been deployed operationally in any user segment.

The largest LRU-specific improvement is the VHF BBSDR, at 45% of current architecture. Although the future VHF LRU does provide all functions of dual Nav/Com installations, however, it should be noted that the cost reduction is largely due to its single hardware LRU configuration, whereas the current architecture includes dual LRUs. It should also be noted that the VHF BBSDR also provides dual VDL Mode 2 and/or VDL-Next capability, along with expandability to include other software-defined future VHF functions, which the current architecture does not.

The L-Band BBSDR shows a cost of 76% of the current architecture, even though there is no equivalent to several future L-Band functions in the current architecture. It is worthy of note, for example, that fully compliant ADS-B capability is not included in the current architecture, as most GA aircraft have yet to be equipped. An intermediate assumption was made instead, including a Mode S transponder. Also, as previously discussed, the current GA architecture does not include DME, another L-Band function. Nonetheless, the L-Band BBSDR is able to address multiple current functions including GNSS, Transponder (or UAT, which is also L-Band), and SDARS, along with providing backup functions to the single VHF LRU via AeroWAN. The necessity for dual redundant L-Band LRUs, due to the broad scope of its functions, offsets the artificially favorable cost score of the VHF BBSDR.

As with air transport, definitive comparison of commercial cellular links is hampered by both future uncertainties and the lack of current equipage with avionics-type cellular links. In the current architecture, cellular communication is often accomplished using handheld personal devices using existing ground-based infrastructure, mainly at low altitudes. Some derivatives of corporate and airline-oriented cellular services are becoming available, but volumes are low, making cost estimates unreliable. It should be noted that the potential for adoption of commercial cellular links for conduct of flight related functions may be much greater for GA than for air transport. Future cellular systems may require smaller adaptations for airborne use at low altitude, and usage-measured commercial fees may be more palatable for occasional GA operations than for continuous, high-volume airline operations. Thus the

likelihood of aircraft-resident devices, connected via the DM to other flight deck systems, may be much greater for GA than air transport. For these reasons the research team felt it was important to define estimates for both current and future costs. A production volume of 100,000 units, developed primarily using components and subsystems from consumer products with volumes in the millions of units, was used to compare current and future costs. A modest reduction of 59% resulted from that analysis.

Overall, the future architecture GA business case is quite favorable compared to the current architecture, indicating over 20% reduction over current cost (future cost being 79% of current cost) – a favorable shift for a very cost-conscious market segment. In addition, the future architecture offers significant non-financial gains over the current system. There is also a significant gain in capabilities, functions, and redundancy gained for that decreased cost; examples include:

- VHF datalink (redundant) – VDL M2 and/or VDL-Next
- Dual all-GNSS navigation reception
- Functional equivalent of 4 VHF Nav/Coms during normal conditions
- Dual DME capability; ability to participate in DME/DME backup of GNSS
- Dual ADS-B systems
- Fully interoperable ADS-B system with all other user segments, no ground segment needed
- AeroWAN capability (does not exist now)
- AeroMACS capability (does not exist now)
- Radio Altimeter – improved safety, potential for new precision approach options
- All major functions software defined for upgradability and transitional compatibility

#### ***8.4.5 Commercial Considerations for Cloud Communication***

The use of commercial services for aviation applications requires that both technical and commercial criteria be satisfied to achieve success. In some cases the commercial or business case considerations needed to induce a commercial (i.e., terrestrial services) operator to make the service available for aviation users may be more challenging than the technical ones. Commercial communication service providers are fundamentally in the business of turning bandwidth and infrastructure into revenue, and generally allocate those resources where the greatest revenue is expected, at the lowest risk. Aviation applications may not compare favorably to other market segments from a business case standpoint for several reasons, including:

- Limited market size compared to “core” terrestrial markets



- Perceived high liability of aviation applications for conduct-of-flight use
- Cost of specialized infrastructure to access aviation markets
- Relative Market Size

On average, the number of aircraft that are likely to be served by any given cellular station is very small compared to the number of ground-based mobile phone users served by the same station. To accommodate the aviation users, some business incentive is needed to balance that disparity, and this is exacerbated by any specialized infrastructure needed to access those users. The most obvious incentive is rate structure, charging proportionately higher rates for the “minority” airborne users. While this may solve the problem, it also changes the incentive basis for aviation to use cellular services – the more expensive it is, the less attractive it may become relative to other link options.

#### **8.4.5.1 Aviation Liability Climate**

Aviation applications, particularly where any connection with conduct of flight is involved, are perceived to have a significantly higher potential legal liability risk than service to terrestrial mobile users, and this is unlikely to change substantially over the study period, without focused effort. There are electronic component manufacturers today who prohibit the use of components from use in avionics for this reason. Commercial service operators will need to either justify this higher risk profile from a business perspective, or find ways to mitigate the risk through legal, legislative, or other means. Limiting use to passenger services is an option, but does not serve the goal of having the service as a “cloud communication” link option from an overall aviation industry standpoint.

#### **8.4.5.2 Infrastructure Costs**

The technical steps required to adapt current cellular systems to aviation use include addition of antennas and associated equipment, and alterations to system software and algorithms. These infrastructure needs represent a capital investment by the service provider, who again needs to justify that investment with commensurate revenue; aviation user service fees may need to be adjusted accordingly.

For high altitude use, such as by commercial aircraft, a relatively small number of ground stations would need to be modified. Amortizing a relatively small infrastructure investment against the number of airline passenger users could well provide a workable fee structure and business case. However, for GA use a much larger number of modified ground stations would be needed, due to the lower altitude operations. Unfortunately, this higher infrastructure investment would need to be amortized across a much smaller population of GA users than the airline case, resulting in a much less attractive business case. This is particularly unfortunate since GA aircraft have fewer alternatives than airline aircraft (e.g., Ku/Ka-Band

SATCOM) due to limitations on antenna size, equipment size/weight, and cost, and would arguably benefit more from having the cellular option.

These business case considerations may be the deciding factor in determining which links are actually practical for future aviation use, and must be carefully weighed in the evaluation process.

### ***8.5 Business Case Gap Analysis***

Overall, the business case analysis established the financial viability of the future architectures in comparison to current practice. This was established as the primary criterion: if the industry has demonstrated the viability of the current business case through widespread adoption of the current architectures, and the future architectures are less expensive while delivering equivalent or greater capabilities, then the proposed future architecture has a high probability of business acceptance. In most cases the future architectures were found not only to be less expensive, but substantially less expensive. Previous research has established that the proposed future architectures analyzed herein are fully viable from various technical standpoints as well. In all cases, the future architectures also deliver not only equivalent or greater capabilities, but significantly greater capabilities. Thus it is reasonable to conclude that the proposed future solution set can be expected to be viable from a business perspective, and leaves no gaps or unmet needs within the construct of the defined future NAS functions.

## 9 Most Promising Technologies

The convergence of the technical and business analysis efforts research allows the identification of the overall most promising technology alternatives for the ground-air and air-air datalink needs of the future aviation system. The candidates best suited technically were identified in the Section 7, and were used as inputs to the business case analysis summarized in Section 8. The business case analysis validated the viability of those candidates from a business perspective, and does not identify any gaps, unmet needs, or unworkable solutions.

Among those candidate solutions, the most promising have been identified based on several criteria:

- Breadth of applicability;
- Scope of impact on future system capabilities;
- Cost / benefit contribution to the overall business case, and
- Long-term growth and adaptation potential.

Identifying and ranking the most promising of the technologies that make up the future architectures is complicated by the fact that some represent specific links, and others are enabling or underlying technologies that enable or facilitate multiple different links. The results are summarized in this section, and comprise a mix of both types. Each technology described in this section has been summarized in technical detail in previous sections. This section is focused on the reasons for their “most promising” selection and ranking.

Two enabling technologies top the list, based on their breadth of applicability and fundamental contributions to system capabilities, cost/benefit, and future growth and adaptability: BBSDR, and DM. Following those are a number of specific link types: AeroWAN/AeroMACS/Merged WiFi, ADS-B-Next, VDL-Next, and LEO Ku/Ka-Band SATCOM.

### 9.1 BBSDR

Broad Band Software Defined Radio (BBSDR) technology is a key enabling platform for early all of the proposed future link candidates. BBSDR enables a single LRU to host multiple software defined links simultaneously, establishing a new and much lower price/capability point for avionics. Its software-driven nature also greatly facilitates both initial transition from current to future architectures, and future growth and adaptation to added bandwidth, the advent of new and more efficient modulations and other link innovations, and protection from obsolescence. BBSDR technology is applicable to all frequency bands currently allocated to aviation, including VHF, L-Band, and the 5 GHz band used by AeroMACS and radio altimetry. It is also applicable to Ku/Ka-Band applications and various commercial cellular bands.

## **9.2 Delivery Manager**

The DM provides the cohesion between the various specific links and the ultimate goal of all communication systems: the effective, timely and secure transfer of information. The DM function addresses link selection and prioritization, based on link availability, information transfer needs, timeliness requirements, security and integrity considerations, cost considerations, Required Communication Performance (RCP), and many other factors. The DM function takes place both on the ground and onboard the aircraft, and has both distributed and centrally managed elements. The existence of an effective DM function allows the seamless, coordinated use of both aviation-specific and commercial links, allows access by a broad range of ground and air users while maintaining system security, and minimizes user costs by selecting the lowest cost suitable link for any given information transaction and any given time.

## **9.3 AeroWAN, AeroMACS, and Merged WiFi**

AeroWAN is a new link proposed as part of this research effort, and is technically based on the existing AeroMACS concept and much of its underlying technology. AeroWAN is designed to function as an in-flight implementation of the AeroMACS concept, using L-Band aviation spectrum repurposed from DME and other previous aviation services. AeroMACS, conversely, is designed only for communication to and from aircraft when they are on the ground, and resides in repurposed 5 GHz aviation spectrum. Each in its own area of use offers the broadest and most flexible range of applications, highest bandwidth, and networking capabilities, and together serve as the “work horse” communication resource of the future system.

If the AeroMACS and AeroWAN technologies, being so similar in underlying architecture and components, could somehow be merged into a single system that served both air and ground operations with a single system, the advantages of the resulting system would be even more compelling. This concept, called “Merged WiFi” was discussed in more detail in a previous report.

## **9.4 ADS-B Next**

The re-architected ADS-B Next link offers significant advantages over the current ADS-B system. Advantages include higher initial bandwidth and improved performance, much more efficient bandwidth usage, significant expansion capability, and universal service to all aircraft without ground relays. Its applicability includes aircraft from large transports, to GA, to small UAS, and potential functions include air to air and air to ground communications for surveillance, collision avoidance, wake turbulence and other environmental data, and space-based ADS-B.

## **9.5 VDL-Next**

VDL-Next is similar to ADS-B Next in that is based on a re-architecture of the existing aviation VHF spectrum to allow much greater efficiency, bandwidth, and range of applications than current VHF systems. VDL-Next is ranked below ADS-B Next primarily because its range of uses are primarily communication versus aircraft separation, and because those communication functions in the future could in many cases also be fulfilled by AeroWAN and AeroMACS. However, the propagation characteristics of VHF versus L-Band (or 5 GHz for AeroMACS) give it some specific advantages for some communication applications, particularly for GA.

## **9.6 Commercial Cellular Data Systems**

Commercial Cellular links offer an impressive range of capabilities today to mobile users, and can only be expected to improve enormously over the 50 year research period. However, even with the DM to address security and other robustness considerations, the business case for commercial providers to make technical and commercial concessions to capture relatively limited numbers of aviation users is unclear at best. As discussed previously, however, cellular systems are already in limited use for air transport IFE applications, and offer a clearer path to even broader use in GA. Commercial cellular systems may also prove to be a vital link option with small, low altitude UAS aircraft – potentially the largest aviation user segment by far by 2064, subject to the business case caveats discussed in Section 8.

## 10 Conclusions and Recommendations

The research team has identified a combination aviation-specific and commercial links which can provide a practical, cost-effective communication solution for the aviation needs circa 2063. Harnessed and organized by a Delivery Manager function, such a combination will allow robust, high speed connectivity in all phases of flight, at or above required levels of reliability, latency, and integrity, at lowest practicable cost.

Practical opportunities exist to make much more efficient use of aviation RF spectrum using technology that will be readily available long before 2063. Transitions from current to these future solutions can be made practical and cost-effective, with compelling business cases to stimulate equipage during the transition period. New and legacy systems can be made fully interoperable throughout the transition phase.

This section summarizes the research team's conclusions in three groups: overall conclusions, specific recommendations for the industry to consider in preparing for the future, and recommendations for follow-on research to facilitate progress toward meeting the future industry datalink needs.

### 10.1 Overall Conclusions

This section summarizes eighteen conclusions reached by the research team during the course of the two-year research effort, which may offer insights into issues and considerations that affect the industry's progression from the current state of aviation data link to meeting its future needs:

- 1) Current communication systems are not adequate to meet the needs of the 50-year future NAS;
- 2) Current systems make very inefficient use of scarce aviation spectrum in the context of current and future technical capabilities;
- 3) Currently allocated aviation spectrum can serve nearly all future NAS CNS needs if used effectively;
- 4) Communication, Navigation, and Surveillance are all interrelated in any study of future communication optimization;
- 5) Viewing all RF-enabled systems as software functions on a BBSDR platform facilitates optimization, integration, simplification of avionics architectures, and reduced cost / size / weight / power footprints;
- 6) Future onboard navigation capabilities can be an important facilitator to bandwidth optimization;

- 7) The proposed future architecture offers significant functional and cost advantages over current systems;
- 8) The proposed future architecture offers a workable transition path from current to future configuration;
- 9) BBSDR technology is a key enabler of re-architecting existing aviation spectrum;
- 10) DM-enabled “cloud communications” architecture offers a compelling combination of performance, robustness, and cost;
- 11) AeroWAN and AeroMACS could serve as the “workhorse” of future systems;
  - Aviation protected spectrum
  - High bandwidth
  - Broadcast and interactive
  - Ground – Air – Ground
  - Air – to – Air, including aircraft to aircraft message relay
  - Suitable for C, N and S functions
- 12) A “Merged WiFi” system would offer even greater advantages than AeroMACS and AeroWAN Separately;
- 13) Expanded use of commercial communication links is feasible for aviation, but will require a DM-type manager to realize significant use outside of passenger entertainment applications;
- 14) The security issues associated with use of cellular links for aviation applications should not be underestimated;
- 15) Cellular providers will need to realize sufficient revenue volume to justify system changes and bandwidth diversion from their primary customer base;
- 16) Cellular links may be best suited to passenger communications, use as backup links, and other non-critical information applications;
- 17) GA and small UAS operations could be good potential applications of cellular links;
  - Low altitude operations in particular
  - Widespread coverage
  - Usage-metered cost structure could be attractive to occasional users
  - Security & lost-link management will be necessary
  - Commercial provider cost/benefit considerations must be addressed
- 18) UAS revenue volume could become the enabler for commercial service provider interest in pursuing aviation markets.

## **10.2 Recommendations**

The research team formulated six recommendations based on the research and its results, which could help guide the aviation industry toward a successful long-term communication strategy:

- I. An overall strategy for efficient use of aviation bandwidth should be developed, encompassing communications, navigation, and surveillance functions;
- II. Serious consideration should be given to a carefully planned, strategic realignment of RF spectrum currently allocated to aviation use for optimum benefit to the aviation industry over the long term. Objectives should include:
  - Efficiency of spectrum utilization;
  - Multipurpose usage of bandwidth and avionics where practicable;
  - Cost/benefit considerations for all aviation user segments, and
  - The preservation of aviation spectrum against efforts to reassign portions of it to non-aviation usage;
- III. Focused effort should be undertaken toward the development of a multi-purpose, ground-air and air-air aviation communications network, residing in aviation protected RF spectrum, analogous to the AeroWAN concept proposed in this research;
- IV. The aviation industry should explore the concept of implementing a privately funded, commercial technology based multipurpose communications system residing within unused aviation spectrum;
- V. Additional research should be conducted into options and development strategy for a “Merged WiFi” system combining the AeroMACS and AeroWAN concepts into a single system using a single LRU;
- VI. The aviation industry should explore ways of accomplishing future oversight and approvals of communication capabilities on a functional performance assurance basis, rather than a link- and hardware-specific basis as is often the case today.

## **10.3 Follow-On Research Recommendations**

The scope of the research undertaken under this contract was necessarily limited, by program definition, and by available time and resources. A number of areas were identified in the course of the research that merit additional exploration. In particular, the following eight areas should be considered for follow-on research.



- A. Propose, characterize and quantify benefits of specific methods and opportunities for greatly improved efficiency in the use of existing aviation spectrum;
- B. Develop a holistic approach and strategy for future CNS in terms of RF spectrum utilization, particularly current aviation spectrum;
- C. Develop a conceptual transition path from current to future RF systems architecture, allowing seamless implementation of new systems while maintaining full operational capability for existing systems over ample periods for industry equipage, infrastructure deployment, and other factors;
- D. Examine interim points between current and 50-year architectures, and develop “snapshot” scenarios illustrating what is achievable in the nearer term;
- E. Develop detailed definition, requirements, and performance models for a multi-link communications system management function similar to the “Delivery Manager” function cited in this research. Include both air and ground systems, functional considerations including communication and security aspects, and the capability to utilize both aviation-specific and commercial communication links. Develop a concept design to enable the safe, effective, and secure use of cloud communications for aviation;
- F. Focused research is needed into the near- and long-term needs, and potential solutions, for communications to, from, and between UAS operating at low altitudes;
- G. Develop detailed definition, requirements, and performance models for a potential ground-air and air-air wireless utility network similar in concept to the AeroWAN technology proposed in this research; include potential merging of AeroWAN and AeroMACS functions into a single network;
- H. In-depth analysis of the requirements and options for the adaptation of terrestrial cellular communication systems to aviation applications, particularly GA and low-altitude UAS, is needed; commercial provider business case considerations and potential motivators must be considered equally with technical aspects.

#### **10.4 Summary**

The combination of overall architectures and specific link solutions proposed by this research constitute a viable and effective solution to the future communication needs of the NAS in the target 50-year future. The research illustrates the significant potential service capabilities that can be attained by more effective use of currently allocated aviation spectrum, and the advantages of moving to a multi-purpose approach to link design and utilization in contrast to

the current paradigm. By combining optimized aviation links with commercial systems, carefully managed by a Delivery Manager function, aviation can leverage true cloud communications to meet its needs 50 years, and much farther, into the future. By leveraging BBSDR technology as a multi-link, software modifiable platform, tremendous capabilities can be provided to the future aircraft at a fraction of today's cost.

The research team maintained a conservative approach throughout the effort, and believes that the concepts, capabilities, and costs proposed are not only feasible within the nominal 50-year period, but are in fact possible in a shorter time, from a technical standpoint. The controlling factors to realizing what is technically practicable are primarily issues of planning, consensus, regulatory adaptation, and initiative. Looking back at the progress of aviation over the past 50 years suggests that the industry is certainly capable of achieving the degree of progress that would be required. It is the XCELAR research team's hope that its presenting an example of what the future can be will help stimulate progress toward a reality that far eclipses the proposals in this report.

## 11 Appendices

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## 11.1 Future Datalink Technology Candidate Matrix

Table 11-1: Airborne Aircraft, Inbound Communications

1A(1)(f2)

Function Code	Function Type	A/C type (U, G, A, H)	Information Use	Content (examples)	Update Rate	Range	Ack/Nac or Broadcast	From: Air (A), Ground (G)	Priority: Must (1), HD (2), Nice (3)	Origin of data	Latency	File Size	Best Datalink Candidates and Merit Scores (1-10)
	Other proximate vehicle status / Info									Other aircraft			
AAI-1	Location / State Vector / Intentions	G, A, U	Flight path deconfliction, collision avoidance, wake vortex avoidance	Present position, velocity vector, Flight ID, Aircraft category	6/sec	80 miles	B	A	1	Other aircraft	<1 sec	112 b	9- ADS-B Next 9- AeroWAN 7- ADS-B 5- UAT
AAI-2	Other vehicle information	G, A, U	General information	Vehicle type/size/major characteristics	Every 30 sec	80 miles	B	A	2	Other aircraft	5 sec	112 b	9- ADS-B Next 9- AeroWAN 7- ADS-B 5- UAT
AAI-3	Other vehicle information	G, A, U	Vehicle information necessary to predict the intensity, transport, and decay of wake vortices	Gross weight, initial vortex circulation, flap setting	Every 30 sec	80 miles	B	A	2	Other aircraft	5 sec	112 b	9- ADS-B Next 9- AeroWAN 7- ADS-B 5- UAT
AAI-4	Atmospherics (e.g. Turbulence)	G, A, U	Hazard avoidance, wake vortex avoidance, weather forecasting	AMDAR reports (terminal), wind speed and direction, Eddy Dissipation Rate (EDR), temperature, humidity level	Every 10 sec	20 miles	B	A	2	Other aircraft	5 sec	2 Kb	9- ADS-B Next 8- UAT FIS-B with Revisions 8- AeroWAN
AAI-5	Atmospherics (e.g. Turbulence)	G, A, U	Flight management of ride quality, hazard avoidance, wake vortex avoidance, weather forecasting	AMDAR reports (Enroute), wind speed and direction, Eddy Dissipation Rate (EDR), temperature, humidity level	Every 60 sec	80 miles	B	A	2	Other aircraft	5 sec	2 Kb	9- ADS-B Next 8- UAT FIS-B with Revisions 8- AeroWAN
AAI-6	Atmospherics (e.g. Turbulence)	G, A, U	Avoidance of immediate weather hazards (i. e. moderate or greater turbulence, icing, volcanic ash)	EDR, icing information, volcanic ash concentration	As needed	80 miles	B	A	2	Other aircraft	1 sec	112 bit	9- ADS-B Next 8- UAT FIS-B with Revisions 8- AeroWAN
AAI-7	Enroute	G, A	Traffic flow management to allow for flight and systemic optimization	Arrival slot times, arrival capacity versus demand, flow constrained areas	As needed	Regional	Ack	G	1	ATM	2 min	10KB	9- AeroWAN 7- VDL-2 Next 5- UAT
AAI-8	Destination	G, A		Delay probability, NOTAMS, ATIS	Every 5 min	Regional	B	G	2	ATM	2 min	<10K B	9- AeroWAN 7- SDARS 6- VDL-2 Next Broadcast 5- UAT FIS-B

**Table 11-2: Airborne Aircraft, Inbound Communications (Cont'd)**

Function Code	Function Type	A/C type (G, A, U)	Information Use	Content (examples)	Update Rate	Range	Ack/Nac or Broadcast	From: Air (A), Ground (G)	Priority: Must (1), HD (2), Nice (3)	Origin of data	Latency	File Size	Best Datalink Candidates and Merit Scores (1-10)
	Atmospherics												
AAI-9	Atmospherics	G	Flight crew situational awareness information regarding weather along their flight path	Graphical or 4-D Matrix Wx for manned aircraft (pilot/crew use)	Every 60 sec	500 miles	B	G	2	Ground non-ATM	2 min	50KB	9- AeroWAN 8- SDARS 8 - Cellular
AAI-10	Atmospherics	A	Flight crew situational awareness information regarding weather along their flight path	Graphical or 4-D Matrix Wx for manned aircraft (pilot/crew use)	Every 5 min	1,000 miles	B	G	2	Ground non-ATM	2 min	100KB	9- AeroWAN 8- SDARS 6- Ka band broadcast
AAI-11	Atmospherics	A	Textual Wx for flight management use	Wind, temp, EDR	Every 30 min	Global	B	G	2	Ground non-ATM	2 min	2KB	9- AeroWAN 8- SDARS 6- Ka band broadcast 6 - VDL-2 Next
AAI-12	Atmospherics	G	Textual Wx for flight management use	Wind, temp, EDR	Every 30 min	500 miles	B	G	2	Ground non-ATM	2 min	2KB	9- AeroWAN 8- SDARS 6- VDL-2 Next
AAI-13	Atmospherics	U	Numerical Wx for flight management use	Wind, temp, EDR	Every 30 min	variable	B	G	3	Ground non-ATM	2 min	20KB	9- AeroWAN 8- SDARS 7- VDL-2 Next 6- Ka band broadcast
AAI-14	ATM guidance & Relevant Information	A, G, U	Separation & optimization	Routing, RTA, hazards	As required	Regional	Ack	G	1	ATM	2 min	100KB	9- AeroWAN 8- Iridium / Iridium Next 6- VDL-2 Next 6- Ka band ACK/NAC 6- Cellular
AAI-15	Non-ATM	A	AOC (airline operational control)	Gate assignment, non-routine crew scheduling, flight planning, irregular operations	As required	Individual	Ack	G	3	Non-ATM	2 min	50KB	9- AeroWAN 8- Iridium / Iridium Next 6- VDL-2 Next 6- Ka band ACK/NAC 6- Cellular
AAI-16	Non-ATM	A	AAC (airline admin. Comm)	Connecting flights	As required	Individual			3	Non-ATM	2 min	50KB	9- AeroWAN 8- Iridium / Iridium Next 6- VDL-2 Next 6- Ka band ACK/NAC 6- Cellular

**Table 11-3: Airborne Aircraft Outbound Communications**

Function Code	Function Type	A/C type- (G, A, U)	Information Use	Content (examples)	Update Rate	Range	Ack/nac or Broadcast	From: Air (A) Ground (G)	Priority Must (1), HD (2), Nice (3)	Destination (V, ATM, N-ATM)	Datalink Candidates and Merit Scores
	Vehicle Status										
AAO-1		G, A, U	Flight path deconfliction, collision avoidance, wake vortex avoidance	Present position, velocity vector, Flight ID, Aircraft category	6/sec	80 miles	B	A	1	V, ATM	9- ADS-B Next air-to-air 7- ADS-B present implementation 7- UAT air-to-air 5- AeroWAN
AAO-2		G, A, U	General information	Vehicle type/size/major characteristics	Every 30 sec	80 miles	B	A	2	V, ATM	9- ADS-B Next air-to-air 7- ADS-B present implementation 7- UAT air-to-air 5- AeroWAN
AAO-3		G, A, U	Vehicle information necessary to predict the intensity, transport, and decay of wake vortices	Gross weight, initial vortex circulation, flap setting	Every 30 sec	80 miles	B	A	2	V, ATM	9- ADS-B Next air-to-air 7- ADS-B present implementation 7- UAT air-to-air 5- AeroWAN
AAO-4		U	Flight path deconfliction, collision avoidance, wake vortex avoidance	Present position, velocity vector, Flight ID, Aircraft category	1 / sec	10 miles	B	A	1	V, ATM N-ATM	9- ADS-B Next air-to-air 7- ADS-B present implementation 7- UAT air-to-air 5- AeroWAN
AAO-5		G, A	Maintenance data / System Status / Departure from normal	Engine data, other vehicle health data	As required, Departure from normal (Tx immediately)	as needed	A	A	2	N-ATM	8- AeroWAN 8- Iridium / Iridium Next 7- Ka band ACK/NAC 6- Cellular
AAO-6		U	Maintenance data / System Status / Departure from normal	Engine data, other vehicle health data	As required, Departure from normal (Tx immediately)	as needed	A	A	1	N-ATM	8- AeroWAN 8- Iridium / Iridium Next 7- Ka band ACK/NAC 6- Cellular
AAO-7	Local Environment Atmospherics	G, A, U	Terminal Area Atmospheric reports for high-granularity model input	Wind, Temp, EDR, shear-layers	Every 15 sec (Terminal)	as needed	B	A	3	V, ATM, N-ATM	8- VDL-2 Next 8- AeroWAN 7- ADS-B Next 7- UAT downlink
AAO-8	Local Environment Atmospherics, higher update rate	G, A, U	Enroute atmospheric reports	Wind, Temp, EDR, shear-layers	Every 5 min (Enroute)	as needed	B	A	3	V, ATM, N-ATM	8- VDL-2 Next 8- AeroWAN 7- ADS-B Next 7- UAT downlink
AAO-9	Special Requests	A		Medical	As needed	as needed	A	A	2	ATM, N-ATM	9- AeroWAN 8- Iridium Next 6- Cellular

**Table 11-4: Aircraft on Ground, Inbound Communications**

**1C (1 of 2)**

Function Code	Function Type	A/C type U,G,A	Information Use	Content (examples)	Update Rate	Range	Ack/nac or Broadcast	From: Air (A) Ground (G)	Priority Must (1), HD (2), Nice (3)	Origin of Data	Datalink Candidates
AGI-1	Airspace System Information (From Ground)	G, A	General / non-instructional, Situational Awareness	NOTAMS, Traffic Flow Management restrictions	As needed / variable	Local	B	G	1	ATM, N-ATM	9- AeroMACS 8- Cellular (4GLTE) 6- VDL-2 Next 5- SDARS
	Atmospherics									ATM & N-ATM	
AGI-2		G	Graphical or 4-D Matrix Wx for manned aircraft (pilot/crew use)	4-D Numerical Matrix, NEXRAD, Maps, Sat imagery, etc.	Every 5 min	Local	B	G	1	N-ATM; Pvt or Gov Source	9- AeroMACS 8- Cellular (4GLTE) 5- SDARS
AGI-3		A	Graphical or 4-D Matrix Wx for manned aircraft (pilot/crew use)	Includes LLWAS, TDWR, WSDM, Etc.	Every 5 min	Local	B	G	1	N-ATM; Pvt or Gov Source	9- AeroMACS 8- Cellular (4GLTE) 5- SDARS
AGI-4		A	Textual Wx for flight management use	Wind, temp, EDR	Every 15 min	Local	B	G	2	N-ATM; Pvt or Gov Source	9- AeroMACS 8- Cellular (4GLTE) 5- SDARS
AGI-5		G	Textual Wx for flight management use	Wind, temp, EDR	Every 15 min	Local	B	G	2	N-ATM; Pvt or Gov Source	9- AeroMACS 8- Cellular (4GLTE) 5- SDARS
AGI-6		G, A, U	Numerical Wx for flight management use	Wind, temp, EDR	Every 15 min	Local	B	G	1	N-ATM; Pvt or Gov Source	9- AeroMACS 8- Cellular (4GLTE) 5- SDARS

**Table 11-5: Aircraft On Ground, Inbound Communications (Cont'd)**

Function Code	Function Type	A/C type U,G,A	Information Use	Content (examples)	Update Rate	Range	Ack/nac or Broadcast	From: Air (A) Ground (G)	Priority Must (1), HD (2), Nice (3)	Origin of Data	Datalink Candidates
	ATM guidance & Relevant Information		Separation & optimization							ATM	
AGI-7	Taxi	U, G, A	Taxi separation and optimization	Taxi instructions	As needed	Local	Ack	G	1	ATM, UAS Operator	9- AeroMACS w/ACK/NAC 8- VDL-2 Next 7- VDL-2 5- Iridium
AGI-8	Departure Information	U, G, A	Departure planning	Departure instructions / clearance, queue assignment, ground hold, de-icing	As needed	Local	Ack	G	1	ATM, UAS Operator	9- AeroMACS w/ACK/NAC 8- VDL-2 Next 7- VDL-2 5- Iridium
AGI-9	Non-ATM	A	AOC (airline operational control)	Gate assignment, non-routine crew scheduling, flight planning, irregular operations, De-icing	As required	Local	Ack	G	3	N-ATM	9- AeroMACS w/ACK/NAC 8- VDL-2 Next 7- VDL-2 5- Iridium
AGI-10		A	AAC (airline admin. Comm)	Connecting flights	As required	Local	Ack	G	3	N-ATM	9- AeroMACS w/ACK/NAC 8- VDL-2 Next 7- VDL-2 5- Iridium
	Other proximate vehicle status / Info									V	
AGI-11		U, G, A	Relative Distance / Path convergence / Intentions	Includes a/c, ground vehicles and equipment	1/sec	Local	B	A	1	Other vehicles, ATM	9- ADS-B Next 7- AeroMACS 5- ADS-B/Low Power 5- UAT
AGI-12		U, G, A		Vehicle type/size/major characteristics	1/ sec	Local	B	A	3	Other vehicles, ATM	9- ADS-B Next 7- AeroMACS 5- ADS-B/Low Power 5- UAT
AGI-13		U, G, A	Pre-takeoff	Wake Vortex	Every 30 sec	Local	B	A	2	Other vehicles, ATM	9- AeroMACS 8- ADS-B Next 8- VDL-2 Broadcast 7- Cellular
AGI-14		U, G, A	Hazard avoid	AMDAR reports, (terminal)	Every 30 sec	Local	B	A	2	Other vehicles, ATM	9- AeroMACS 8- ADS-B Next 8- VDL-2 Broadcast 7- Cellular



**Table 11-6: Aircraft on Ground, Outbound Communications**

Function Code	Function Type	A/C type	Information Use	Content (examples)	Update Rate	Range	Ack/nac or Broadcast	From: Air (A) Ground (G)	Priority Must (1), HD (2), Nice (3)	Destination (V, ATM, N-ATM)	Datalink Candidates and Merit Scores
	Vehicle Status										
AGO-1		G, A	Location / State vector / Aero / Intentions	Non-UAS	1 / sec	Local	B	A	1	V, ATM	9- ADS-B Next 7- AeroMACS 5- ADS-B/Lo Power 5- UAT
AGO-2		U	Location / State vector / Aero / Intentions	UAS	1 / sec	Local	B	A	1	V, ATM?, N-ATM	9- ADS-B Next 7- AeroMACS 5- ADS-B/Lo Power 5- UAT
AGO-3		G, A	Maintenance data / System Status / Departure from normal	Engine data, other vehicle health data	As required, Departure from normal (Tx immediately)	Local	A	A	2	N-ATM	9- AeroMACS 8- Cellular w/ ACK/NAC proto 7- VDL-2 Next 5- VDL-2
AGO-4		U	Maintenance data / System Status / Departure from normal	Engine data, other vehicle health data	As required, Departure from normal (Tx immediately)	Local	A	A	1	N-ATM	9- AeroMACS 8- Cellular w/ ACK/NAC proto 7- VDL-2 Next 5- VDL-2
AGO-5		A	Wake Turbulence Information	Initial circulation strength	Every 10 sec (Terminal)	Local	B	A	2	V, ATM	9- AeroMACS 8- VDL-2 Next 8- Cellular 6- VDL-2
					Every 5 min (Enroute)						
AGO-6	Local Environment Atmospherics	U, G, A		Wind, Temp, EDR	Every 15 sec (Terminal)	Local	B	A	3	V, ATM, N-ATM	9- AeroMACS 8- VDL-2 Next 8- Cellular 6- VDL-2
AGO-7	Special Requests	A		Medical	As needed	Local	A	A	1	ATM, N-ATM	9- AeroMACS 8- Cellular w/ ACK/NAC proto 6- VDL-2 Next

## 11.2 Appendix 2 - Literature Review Bibliography and Notes

Table 11-7: Literature Review Bibliography and Notes

Document	Pub date	Notes	Location	Lead Re-viewer
NASA/CR-2012-217590  Surveillance and Datalink Communication Performance Analysis for Distributed Separation Assurance System Architectures	July, 2012	Investigates effects of two technical enablers: ADS-B and digital datalink communication in the FAA NextGen. Report is done under both ground based and airborne System Architectures (SA).  Datalink performance is examined under various operational conditions. Required SA performance is evaluated as a function of subsystem performance to establish overall required separation assurance performance, under normal and off-nominal conditions.	65 pages as a PDF file  <a href="http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120013095_2012013878.pdf">http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120013095_2012013878.pdf</a>  Abstract and document info  <a href="http://ntrs.nasa.gov/search.jsp?R=20120013095">http://ntrs.nasa.gov/search.jsp?R=20120013095</a>	Jarrett
OPTIMIZING AIRPORT SURFACE OPERATIONS USING DATALINK AND THE TAXIWAY NAVIGATION AND SITUATION AWARENESS (T-NASA) DISPLAY SUITE	Not provided in document	Report on T-NASA s efficiency and safety benefits for surface operations with potential for taxi efficiency improvement by implementing changes to current procedures that include airborne taxi clearances and datalink communications.	Single page PDF  <a href="http://human-factors.arc.nasa.gov/groups/HCSL/publications/Hooey_hfesposter_00.pdf">http://human-factors.arc.nasa.gov/groups/HCSL/publications/Hooey_hfesposter_00.pdf</a>	Jarrett

Document	Pub date	Notes	Location	Lead Reviewer
Taxiway Navigation and Situation Awareness (T-NASA) Display Suite	Not provided in document	List of additional documents and reports generated by the T-NASA Display Suite	T-NASA Web site  <a href="http://human-factors.arc.nasa.gov/ih/hcsl.inactive/T-NASA_studies.html">http://human-factors.arc.nasa.gov/ih/hcsl.inactive/T-NASA_studies.html</a>  <a href="http://human-factors.arc.nasa.gov/ih/hcsl.inactive/publications.html#TNASA">http://human-factors.arc.nasa.gov/ih/hcsl.inactive/publications.html#TNASA</a>	Jarrett
AIAA-2012-5618 Simulation Evaluation of Conflict Resolution and Weather	September 2012	Pilot- and controller-in-the-loop simulation of conflict resolution using near term equipped systems	12 page PDF  <a href="http://www.aviationsystemsdivision.arc.nasa.gov/publications/2012/AIA-2012-5618.pdf">http://www.aviationsystemsdivision.arc.nasa.gov/publications/2012/AIA-2012-5618.pdf</a>	Jarrett
Flight Deck Procedural Guidelines for Datalink Trajectory Negotiation	Based on content post 2007	4-D trajectory information exchange for conflict resolution using datalink	19 page PDF  <a href="http://www.aviationsystemsdivision.arc.nasa.gov/publications/modeling/ATIO_Mueller_Lozito_final.pdf">http://www.aviationsystemsdivision.arc.nasa.gov/publications/modeling/ATIO_Mueller_Lozito_final.pdf</a>	Jarrett
CONVEYING MESSAGE CRITICALITY VIA DATALINK	Appears around 2003	Establishing notification priority from a Psychology perspective	6 page PDF  <a href="http://humansystems.arc.nasa.gov/groups/hcsl/publications/Andre_AvP_syc03.pdf">http://humansystems.arc.nasa.gov/groups/hcsl/publications/Andre_AvP_syc03.pdf</a>	Jarrett
Controller-pilot communications using a VDL Mode	Tests conducted in 2000 at	NASA Runway Incursion Prevention System (RIPS) test report using	PDF available to members of IEEE at <a href="http://ieeexplore.ieee.org">http://ieeexplore.ieee.org</a>	Jarrett

Document	Pub date	Notes	Location	Lead Re-viewer
2 datalink for the NASA runway incursion prevention system	the Dallas Fort-Worth International Airport (DFW)	Controller-Pilot Datalink Communications (CPDLC)	<a href="http://rg/xpl/freeabs_all.jsp?reload=true&amp;arnumber=963335">rg/xpl/freeabs_all.jsp?reload=true&amp;arnumber=963335</a> for \$10.00 (\$31.00 for non members)  Has NOT been downloaded yet	
AOS SPACE DATA LINK PROTOCOL	September 2005	Draft Recommendation for Space Data System Standards. NOT a final document but a recommendation for standards	<a href="http://standards.gsfc.nasa.gov/reviews/450-502/450-502.pdf">http://standards.gsfc.nasa.gov/reviews/450-502/450-502.pdf</a>	Jarrett
AN OPERATIONAL CONCEPT FOR FLYING FMS TRAJECTORIES IN CENTER AND TRACON AIRSPACE	Post 2000	Near and far term operational concepts for how an ATM automation system like CTAS could work more effectively with the airborne automation in FMS equipped aircraft.	7 page PDF  <a href="http://humanfactors.arc.nasa.gov/ih/research_groups/air-ground-integration/publication_papers/Pa1999-CTASFMStraj.pdf">http://humanfactors.arc.nasa.gov/ih/research_groups/air-ground-integration/publication_papers/Pa1999-CTASFMStraj.pdf</a>	Jarrett
THE APPLICATION OF SATELLITE COMMUNICATIONS TO THE DATA LINK REQUIREMENT FOR UNMANNED GROUND VEHICLES	Undated, appears to be late 90s	Application of Datalink between satellites and unmanned GROUND vehicles	6 page PDF  <a href="http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/30339/1/95-0928.pdf">http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/30339/1/95-0928.pdf</a>	Jarrett

Document	Pub date	Notes	Location	Lead Re-viewer
Is ACARS and FANS-1A Just Another Data Link to the Controller?	2011 Or 2012	Report on investigation of TBO procedure issues for current aircraft fleet when requesting deviations around weather.	10 page PDF excerpt from 453 page document  <a href="http://pdars.arc.nasa.gov/publications/acars_fans.pdf">http://pdars.arc.nasa.gov/publications/acars_fans.pdf</a>	Jarrett
RTCA DO-242, MASPS for Automatic Dependent Surveillance - Broadcast (ADS-B)	Feb. 19, 1998	See appendix E on other applications, also appendices D and J may be useful (from RTCA SC-186)	No longer in print or distribution from RTCA	Stone
RTCA Task Force 3 final report	Oct. 1995	Free flight rationale	RTCA	Stone
RTCA Free Flight Action Plan	Aug. 15, 1996	Talks about data link requirements, architecture decisions	RTCA	Stone
Study of Alternative Beacon-based Surveillance and Data Link Systems, S.R. Jones	April 1974	FAA Report EM-74-7,11	MITRE document	Stone
RTCA DO-242A, MASPS for Automatic Dependent Surveillance - Broadcast (ADS-B)	June 25, 2002	Revised ADS-B Requirements (from RTCA SC-186)	RTCA	Stone
RTCA DO-263, Application of Airborne Conflict	Dec. 2000	Conops for ADS-B conflict management and resolution (from RTCA SC-	RTCA	Stone

Document	Pub date	Notes	Location	Lead Re-viewer
Management: Detection, Prevention, & Resolution		186)		
RTCA DO-317A, Minimum Operational Performance Standards (MOPS) for Aircraft Surveillance Applications (ASA) Systems	Dec. 13, 2011	Detailed requirements for Interval Management (from RTCA SC-186)	RTCA	Stone
RTCA DO-328, Safety, Performance, and Interoperability Requirements for Airborne Spacing, Flight Deck Interval Management	June 22, 2011	Detailed requirements for Interval Management (from RTCA SC-186)	RTCA	Stone
Technical Link Assessment Report	March 2001	Comparison of 1090 MHz Extended Squitter, UAT, and VDL Mode 4	FAA document	Stone
RTCA DO-305A, Future Air Navigation System 1/A (FANS 1/A) - Aeronautical Telecommunications Network (ATN) Interoperability Standard	March 2012	ATC data link interoperability requirements (from RTCA SC-214)	RTCA	Stone
RTCA DO-306,	March	FANS data link	RTCA	Stone

Document	Pub date	Notes	Location	Lead Re-viewer
Change 1, Safety and Performance Standard for Air Traffic Data Link Services in Oceanic and Remote Airspace (Oceanic SPR Standard)	2012	requirements (from RTCA SC-214)		
RTCA DO-308, Operational Services and Environment Definition (OSED) for Aeronautical Information Services (AIS) and Meteorological (MET) Data Link Services	Dec. 2007	Conops for weather/NOTAM data link services (from RTCA SC-206)	RTCA	Stone
RTCA DO-339, Aircraft Derived Meteorological Data via Data Link for Wake Vortex, Air Traffic Management and Weather Applications – Operational Services and Environmental Definition (OSED)	June 2012	Conops for weather downlink from aircraft. (from RTCA SC-206)	RTCA	Stone
RTCA DO-340, Concept of Use for Aeronautical Information Services (AIS) and	Sept. 2012	Use cases for uplinked weather	RTCA	Stone

Document	Pub date	Notes	Location	Lead Re-viewer
Meteorological (MET) Data Link Services				
RTCA DO-xxx (draft), AIS and MET Services Delivery Architecture Recommendations	Draft	Draft architecture recommendations for weather/NOTAM data link communications	Draft RTCA document from SC-206	Stone
NextGen Implementation Plan	March 2012	High level overview of NextGen plans and objectives	FAA document	Stone
European ATM Master Plan, edition 2	October 2012	High level overview of SESAR plans and objectives	Eurocontrol document	Stone
Minimum Performance Standards - Airborne Selective Calling Equipment	February 1959	Example of an early data communications standard, valuable for looking at what the state of data link standards were 50 years ago	RTCA document	Stone
Measurements of ADS-B squitter Performance in the LA basin region	2000	Authors: J. Bernays, S.Thompson & W.H. Harmon, MIT Lincoln Lab	<a href="http://www.11.mit.edu/mission/aviation/publications/publication-files/m..">www.11.mit.edu/mission/aviation/publications/publication-files/m..</a>	Haendel
Air Traffic Bulletin	2005	VP. Systems Operations Service, FAA	<a href="http://www.faa.gov/air_traffic/publications/bulletins/media/atb_aug_05">www.faa.gov/air_traffic/publications/bulletins/media/atb_aug_05</a>	Haendel
Technical Link Assessment Report	2001	RTCA Safe flight 21		Haendel



Document	Pub date	Notes	Location	Lead Re-viewer
FCC frequency Spectrum Table	May 2012	List of Frequency allocations including those for Aero Mobile		Haendel
ADS-B airborne system measurements	2002	Tests in Frankfurt ADS-B, W. H. Harmon	<a href="http://www.journalogy.net/Publication/50285544/ads-b-airborne-measurements-in-frankfurt">http://www.journalogy.net/Publication/50285544/ads-b-airborne-measurements-in-frankfurt</a>	Haendel
Data Fusion Algorithms based on ADS-B and Radar	2000	IEEE International Radar Conference, Madrid Spain	<a href="http://doc.mbalib.com/view/12163729dc2baf05f11419e093c32e06.html">http://doc.mbalib.com/view/12163729dc2baf05f11419e093c32e06.html</a>	Haendel
ADS-B “out” performance	May 2010	Docket No. FAA–2007–29305; Amdt. No. 91-314]	<a href="http://www.eaa.org/News/2010/ADS-B-FinalRule.pdf">http://www.eaa.org/News/2010/ADS-B-FinalRule.pdf</a>	Haendel
Third Meeting of ADS-B Study and implementation	25 March 2005	ICAO ADS-B TF/3	<a href="http://legacy.icao.int/icao/en/ro/apac/2005/ADSB_ADSB_TF3/ip15.pdf">http://legacy.icao.int/icao/en/ro/apac/2005/ADSB_ADSB_TF3/ip15.pdf</a>	Haendel
ADS-B Technical Issues	2011	W. A. Thedford PhD, USAF Tradeoff Analyses, different systems	<a href="http://www.afceaboston.com/documents/events/cnsatm2011/Briefs/02-Tuesday/Tuesday-PM%20Track-1/03-Thedford-ADS-B%20In_Out%20Tech%20Issues-Tuesday%20Track1.pdf">http://www.afceaboston.com/documents/events/cnsatm2011/Briefs/02-Tuesday/Tuesday-PM%20Track-1/03-Thedford-ADS-B%20In_Out%20Tech%20Issues-Tuesday%20Track1.pdf</a>	Haendel
ADS-B 1090 MOPS	Jan 2003	RTCA SC-186	<a href="http://adsb.tc.faa.gov/WG3_Meetings/Meeting17/1090-WP-17-03.pdf">http://adsb.tc.faa.gov/WG3_Meetings/Meeting17/1090-WP-17-03.pdf</a>	Haendel
Worlds Busiest	Feb 2013		<a href="http://en.wikipedia.org/wiki/World%27s_busiest">http://en.wikipedia.org/wiki/World%27s_busiest</a>	Haendel

Document	Pub date	Notes	Location	Lead Re-viewer
Airports			<a href="#">airports by aircraft movements</a>	
LAX aircraft Movements	2012	19 year summary	<a href="http://www.lawa.org/welcome_LAX.aspx?id=806">http://www.lawa.org/welcome_LAX.aspx?id=806</a>	Haendel
LAX Departures	2013	Scheduled departure Times	<a href="http://www.airport-la.com/lax/departures?t=1">http://www.airport-la.com/lax/departures?t=1</a>	Haendel
VDL Mode 4	2011		<a href="http://www.eurocontrol.int/services/vhf-digital-mode-4">http://www.eurocontrol.int/services/vhf-digital-mode-4</a>	Haendel
VDL/4 ADS-B	1999	Overview by AAT Ltd	<a href="http://www.aatl.net/publications/implementing ADS-B.htm">http://www.aatl.net/publications/implementing ADS-B.htm</a>	Haendel
VDL/4 presentation	2000	J. Nilsson Swedish Aviation Authority	<a href="http://staffwww.itn.liu.se/~annli/JN-art2.pdf">http://staffwww.itn.liu.se/~annli/JN-art2.pdf</a>	Haendel
VDL Mode 4 Concerns	2000	R. Jones, B. Phillips AMCP WG-C	<i>legacy.icao.int/anb/pansels/acp/WG/M/M1wp/WP/M1-WP25.doc</i>	Haendel

### 11.3 Appendix 3 – Air Transport – Domestic Business Case Analysis

Table 11-8: Air Transport – Domestic Business Case Analysis

Air Transport – Domestic Business Case Analysis									
Future Architecture						Current Architecture			
Future Architecture Components	Future Architecture Includes	Notes	Future Architecture LRU Cost	Future Architecture - 400 A/C Fleet Cost	Future Architecture Fleet Spares Cost/Discount	Current Architecture Components	Current Architecture LRU List Price	Current Architecture - 400 A/C Fleet Cost	Current Architecture Spares
VHF BBSDR / DM (Primary)	VHF / DM LRU; Dual SDR, Dual TX (50W), All VHF voice and VDL, LAAS	DM integrated into VHF BBSDR LRU; will perform all current CMU and DMU functions	\$10,000	\$2,800,000	\$140,000	CMU	\$ 72,000	\$ 20,160,000	\$ 2,016,000
			\$0	\$0	\$0	DMU (Redundancy Included)	\$ 85,000	\$ 23,800,000	\$ 2,380,000
			\$0	\$0	\$0	VHF Comm 1	\$ 40,000	\$ 11,200,000	\$ 373,333
		A single VHF BBSDR will provide dual VHF voice LRU capabilities; Backup VHF BBSDR provides equivalent of Comm 3 and a 4th VHF LRU not in current architecture	\$0	\$0	\$0	VHF Comm 2	\$ 40,000	\$ 11,200,000	\$ 373,333
			\$0	\$0	\$0	VDL-2 #1	\$ 40,000	\$ 11,200,000	\$ 560,000
			\$0	\$0	\$0	VOR / ILS / GS - 1	\$ 36,000	\$ 10,080,000	\$ 504,000
VHF BBSDR / DM (Backup)	VHF / DM LRU; Dual SDR, Dual TX (50W), All VHF voice and VDL, LAAS	VHF functions will be important enough to require AT redundancy	\$10,000	\$2,800,000	\$140,000	VDL-2 # 2	\$ 40,000	\$ 11,200,000	\$ 560,000
			\$0	\$0	\$0	VOR / ILS / GS 2	\$ 36,000	\$ 10,080,000	\$ 504,000
			\$0	\$0	\$0	VHF Comm 3	\$ 40,000	\$ 11,200,000	\$ 373,333
L-Band BBSDR	L-BBBSDR; Quad SDR, Dual TX (300W), All L-Band - ADS-B-NEXT, AeroWAN, GNSS, DME, SDARS, Legacy TCAS	Note that if a third backup DM is required it will be embedded into L-Band BBSDR	\$60,000	\$16,800,000	\$560,000	GPS / All GNSS	\$ 65,000	\$ 18,200,000	\$ 910,000
				\$0	\$0	DME 1	\$ 55,000	\$ 15,400,000	\$ 770,000
				\$0	\$0	DME 2	\$ 55,000	\$ 15,400,000	\$ 770,000
				\$0	\$0	SDARS		\$ -	
				\$0	\$0	Transponder 1	\$ 66,000	\$ 18,480,000	\$ 924,000
				\$0	\$0	TCAS	\$ 100,000	\$ 28,000,000	\$ 2,800,000
L-Band BBSDR Backup	L-Band BBSDR #2		\$60,000	\$16,800,000	\$560,000	GPS 2 / MMR 2	\$ 65,000	\$ 18,200,000	\$ 910,000
L-B BBSDR # 3	L-Band BBSDR #3	3 L-Band BBSDRs required for AT due to broad range of important functions included	\$60,000	\$16,800,000	\$560,000	Transponder 2	\$ 66,000	\$ 18,480,000	\$ 924,000
AeroMACS 5 GHz BBSDR	AeroMACS / Radio Altimeter 5 GHz BBSDR	AeroMACS + Radio Altimeter; AeroMACS is software defined to facilitate future upgrades, added spectrum, etc.	\$10,000	\$2,800,000	\$140,000			\$ -	
AeroMACS BBSDR - Backup	AeroMACS / Radio Altimeter 5 GHz BBSDR (Backup)	Importance of AeroMACS for AT operations requires 2 LRUs	\$10,000	\$2,800,000	\$140,000	Radio Altimeter	\$ 80,000	\$ 22,400,000	\$ 1,120,000
Commercial Cellular Datalink	Cellular IFE System	For IFE service during non-oceanic flight segments	\$30,000	\$8,400,000	\$840,000	Cellular IFE System	\$ 40,000	\$ 11,200,000	\$ 1,120,000

Table 11-9: Air Transport – Domestic Business Case Analysis (Cont.)

<b>Air Transport - Domestic Business Case Analysis: Summary of Results</b>			
<b>Architecture Cost Comparison</b>			
<b>Future Architecture Cost</b>	<b>\$73,080,000</b>		
<b>Current Architecture Cost</b>	<b>\$303,772,000</b>		
<b>Future / Current Cost:</b>	<b>24%</b>		
<b>LRU Comparison:</b>			
	<b>Current</b>	<b>Future</b>	<b>%</b>
<b>Total LRU Count</b>	18	8	44%
<b>Total LRU Types</b>	11	4	36%
<b>Comparison by Future LRU Type</b>			
VHF Functions:	\$6,160,000	\$ 135,408,000	5%
L-Band Functions:	\$53,760,000	\$ 148,176,000	36%
5 GHz Functions:	\$6,160,000	\$ 24,640,000	25%
Commercial Cellular Functions:	\$9,240,000	\$ 12,320,000	75%

## 11.4 Appendix 4 – Air Transport – Oceanic Business Case Analysis

Table 11-10: Air Transport – Oceanic Business Case Analysis

Air Transport - Oceanic Business Case Analysis									
Future Architecture						Current Architecture			
Future Architecture Components	Future Architecture Includes	Notes	Future Architecture LRU Cost	Future Architecture - 300 A/C Fleet Cost	Future Architecture Fleet Spares Cost/Discount	Current Architecture Components	Current Architecture LRU List Price	Current Architecture - 300 A/C Fleet Cost	Current Architecture Spares
VHF BBSDR / DM (Primary)	VHF / DM LRU; Dual SDR, Dual TX (50W), All VHF voice and VDL, LAAS	DM integrated into vHF BBSDR LRU; will perform all current CMU and DMU functions	\$10,000	\$2,100,000	\$105,000	CMU	\$ 72,000	\$ 15,120,000	\$ 1,512,000
			\$0	\$0	\$0	DMU (Redundancy Included)	\$ 85,000	\$ 17,850,000	\$ 1,785,000
			\$0	\$0	\$0	VHF Comm 1	\$ 40,000	\$ 8,400,000	\$ 280,000
		A single VHF BBSDR will provide dual VHF voice LRU capabilities; Backup VHF BBSDR provides equivalent of Comm 3 and a 4th VHF LRU not in current architecture	\$0	\$0	\$0	VHF Comm 2	\$ 40,000	\$ 8,400,000	\$ 280,000
			\$0	\$0	\$0	VDL-2 #1	\$ 40,000	\$ 8,400,000	\$ 420,000
			\$0	\$0	\$0	VOR / ILS / GS - 1	\$ 36,000	\$ 7,560,000	\$ 378,000
VHF BBSDR / DM (Backup)	VHF / DM LRU; Dual SDR, Dual TX (50W), All VHF voice and VDL, LAAS	VHF functions will be important enough to require AT redundancy	\$10,000	\$2,100,000	\$105,000	VDL-2 # 2	\$ 40,000	\$ 8,400,000	\$ 420,000
			\$0	\$0	\$0	VOR / ILS / GS 2	\$ 36,000	\$ 7,560,000	\$ 378,000
			\$0	\$0	\$0	VHF Comm 3	\$ 40,000	\$ 8,400,000	\$ 280,000
L-Band BBSDR	L-BBBSDR, Quad SDR, Dual TX (400W), All L-Band - ADS-B-NEXT, AeroWAN, GNSS, DME, SDARS, Legacy TCAS	Narrow Body 2, Widebody 3; Note that if a third backup DM is required it will be embedded into L-Band BBSDR	\$60,000	\$12,600,000	\$420,000	GPS / All GNSS	\$ 65,000	\$ 13,650,000	\$ 682,500
				\$0	\$0	DME 1	\$ 55,000	\$ 11,550,000	\$ 577,500
				\$0	\$0	DME 2	\$ 55,000	\$ 11,550,000	\$ 577,500
				\$0	\$0	SDARS	\$ -	\$ -	\$ -
				\$0	\$0	Transponder 1	\$ 66,000	\$ 13,860,000	\$ 693,000
	TCAS Function embedded in L-Band BBSDR ADS-B Next			\$0	\$0	TCAS	\$ 100,000	\$ 21,000,000	\$ 2,100,000
	Iridium-NEXT LEO L-Band (No LRU Required - integral to L-Band BBSDR)	Polar & Oceanic data / vox comm for ATC & AOC		\$0	\$0	Iridium LEO L-Band Comm	\$ 35,000	\$ 7,350,000	\$ 367,500
	Space-Based ADS-B (NO LRU required)	Oceanic surveillance		\$0	\$0	HF Radio / SATCOM	\$ 100,000	\$ 21,000,000	\$ 1,050,000
L-Band BBSDR - Backup	L-Band BBSDR #2		\$60,000	\$12,600,000	\$420,000	GPS 2 / MMR 2	\$ 55,000	\$ 11,550,000	\$ 577,500
L-B BBSDR # 3	L-Band BBSDR #3	3 L-Band BBSDRs required for AT due to broad range of important functions included	\$60,000	\$12,600,000	\$420,000	Transponder 2	\$ 35,000	\$ 7,350,000	\$ 367,500
AeroMACS 5 GHz BBSDR	AeroMACS / Radio Altimeter 5 GHz BBSDR	AeroMACS + Radio Altimeter; AeroMACS is software defined to facilitate future upgrades, added spectrum, etc.	\$10,000	\$2,100,000	\$105,000	No Equivalent Link	\$ -	\$ -	\$ -
AeroMACS BBSDR - Backup	AeroMACS / Radio Altimeter 5 GHz BBSDR (Backup)	Importance of AeroMACS for AT operations requires 2 LRUs	\$10,000	\$2,100,000	\$105,000	Radio Altimeter	\$ 80,000	\$ 16,800,000	\$ 840,000
Ku- or Ka-Band BBSDR	Simultaneous multiple channel capability; single beam-steered antenna or future LEO Ku/Ka satellite system	ATC & AOC Datacom, IFE; BBSDR allows multiple channel operations with single LRU, but may not address antenna steering issues	\$20,000	\$4,200,000	\$420,000	Ku-Band or INMARSAT	\$ 200,000	\$ 42,000,000	\$ 2,100,000
Commercial Cellular Datalink	Cellular IFE System		\$30,000	\$6,300,000	\$630,000	Cellular IFE System	\$ 40,000	\$ 8,400,000	\$ 840,000

Table 11-11: Air Transport – Oceanic Business Case Analysis (Cont.)

<b>Air Transport - Oceanic Business Case Analysis: Summary of Results</b>			
<b>Architecture Cost Comparison</b>			
Future Architecture Cost	<b>\$59,430,000</b>		
Current Architecture Cost	<b>\$292,656,000</b>		
Future / Current Cost:	<b>20%</b>		
<b>LRU Comparison:</b>			
	<b>Current</b>	<b>Future</b>	<b>%</b>
<b>Total LRU Count</b>	21	9	43%
<b>Total LRU Types</b>	14	5	36%
<b>Comparison by Future LRU Type</b>			
VHF Functions:	\$4,620,000	\$101,556,000	5%
L-Band Functions:	\$40,320,000	\$132,846,000	30%
5 GHz Functions:	\$4,620,000	\$18,480,000	25%
Ku/Ka-Band Functions:	\$5,145,000	\$ 47,040,000	11%
Commercial Cellular Functions:	\$6,930,000	\$ 9,240,000	75%

## 11.5 Appendix 5 – General Aviation Business Case Analysis

Table 11-12: – General Aviation Business Case Analysis

General Aviation Business Case Analysis						
Future Architecture				Current Architecture		
Future Architecture Components	Future LRU Includes	Notes	Future LRU COST	Current Architecture Components	Notes	Current Architecture: Cost of LRU (Light Twin)
VHF BBSDR	VHF BBSDR: Dual SDR, Dual TX (10 W); all VHF, LAAS	Single LRU includes all functions of current dual VHF Nav/Com, and VDL	\$5,000	VHF Nav/Comm/VOR/ILS 1	No VDL capability today	\$5,500
		Only 1 GA VHF BBSDR required; performs current functions of 2 (or more) VHF Nav/Coms with single LRU, L-Band BBSDR serves as failure backup		VHF Nav/Comm/VOR/ILS 2		\$5,500
L-Band BBSDR / DM #1	L-BBSDR; Dual SDR, Dual TX (100W), ADS-B NEXT, GNSS, AeroWAN, DME, SDARS	2 redundant LRUs required for GNSS, ADS-B, & VHF Backup; For GA, DM is built into the necessarily redundant LRU – the L-Band BBSDR.	\$12,000	GPS	GPS / All GNSS	\$8,000
		Expect DME becoming obsolete in 50 years, but FAA GNSS backup plan is based on DME/DME, so software-defined legacy capability included		DME	(Note: although FAA GNSS backup plans include use of DME/DME navigation, few GA aircraft currently are DME equipped, and very few new OEM products are available, so no current cost is included)	
		Provider subscription control provisions in generic BBSDR – similar to SIM Card		SDARS	XM/Sirius	\$15,000
		AeroWAN performs very wide range of functions and backups for others			No Current Equivalent	
		Re-architected 1030/1090 is integral part of L-BBSDR		Mode S Transponder	Most GA A/C not fully ADS-B equipped today	\$3,500
		UAT becomes obsolete with new 1030/1090 ADS-B		UAT	Cost analysis used Mode S TXPDR	
		AeroWAN will be capable of providing digital audio backup to VDL (or primary) as needed		VHF Comm –(Backup)	Typically no third comm backup today unless handheld	
L-Band BBSDR / DM - #2 (Backup)		Identical to Unit #1	\$12,000	GPS 2 / VOR-2 / DME/DME Substitute for sole means navigation	No current equivalent for GNSS sole means; estimated cost for compliance	\$5,000
				ILS-2 Substitute (GNSS)	No Current Equivalent	
AeroMACS BBSDR	5GHz BBSDR, AeroMACS, Integral Radio Altimeter	AeroMACS includes ground-ground datalink; Radio Altimeter function provides vertical approach guidance for additional precision approach capability	\$5,000		No Current Equivalent	
Commercial Cellular Datalink		Too many variables about future spectrum allocations to speculate on integration into other BBSDR units – analyze as separate unit	\$1,000	Handheld Cellular WX Service		\$1,700

Table 11-13: – General Aviation Business Case Analysis (Cont.)

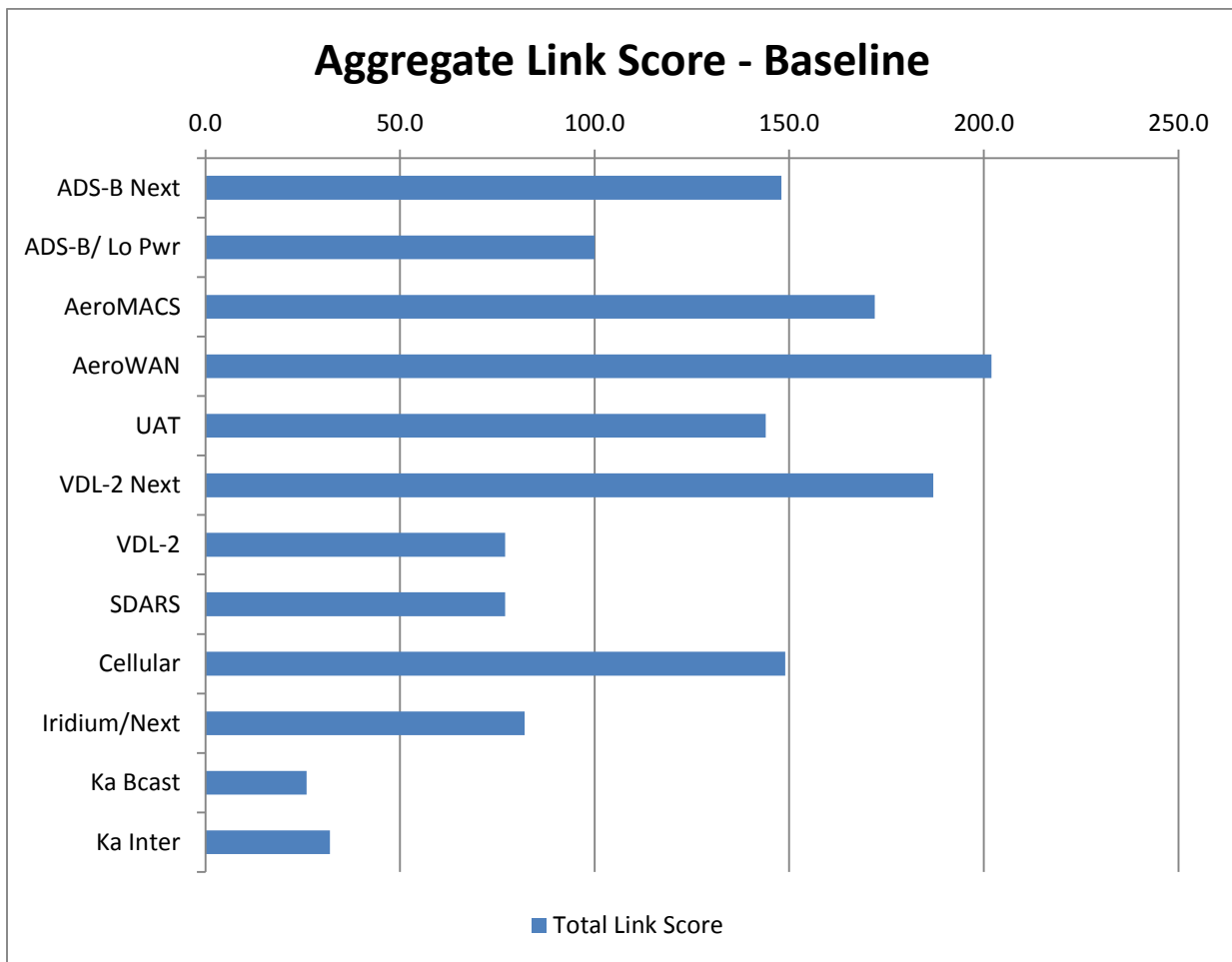
<b>General Aviation Business Case Analysis: Summary of Results</b>			
<b>Architecture Cost Comparison</b>			
Future Architecture Cost		<b>\$35,000</b>	
Current Architecture Cost		<b>\$44,200</b>	
Future / Current Cost:		<b>79%</b>	
<b>LRU Comparison:</b>			
	<b>Current</b>	<b>Future</b>	<b>%</b>
<b>Total LRU Count</b>	7	5	71%
<b>Total LRU Types</b>	6	4	67%
<b>Comparison by Future LRU Type</b>			
VHF Functions:	\$5,000	\$11,000	45%
L-Band Functions:	\$24,000	\$31,500	76%
5 GHz Functions:	\$5,000	\$ -	N/A
Commercial Cellular Functions:	\$1,000	\$ 1,700	59%



## 11.6 Appendix 6 – Candidate Comparison Detail

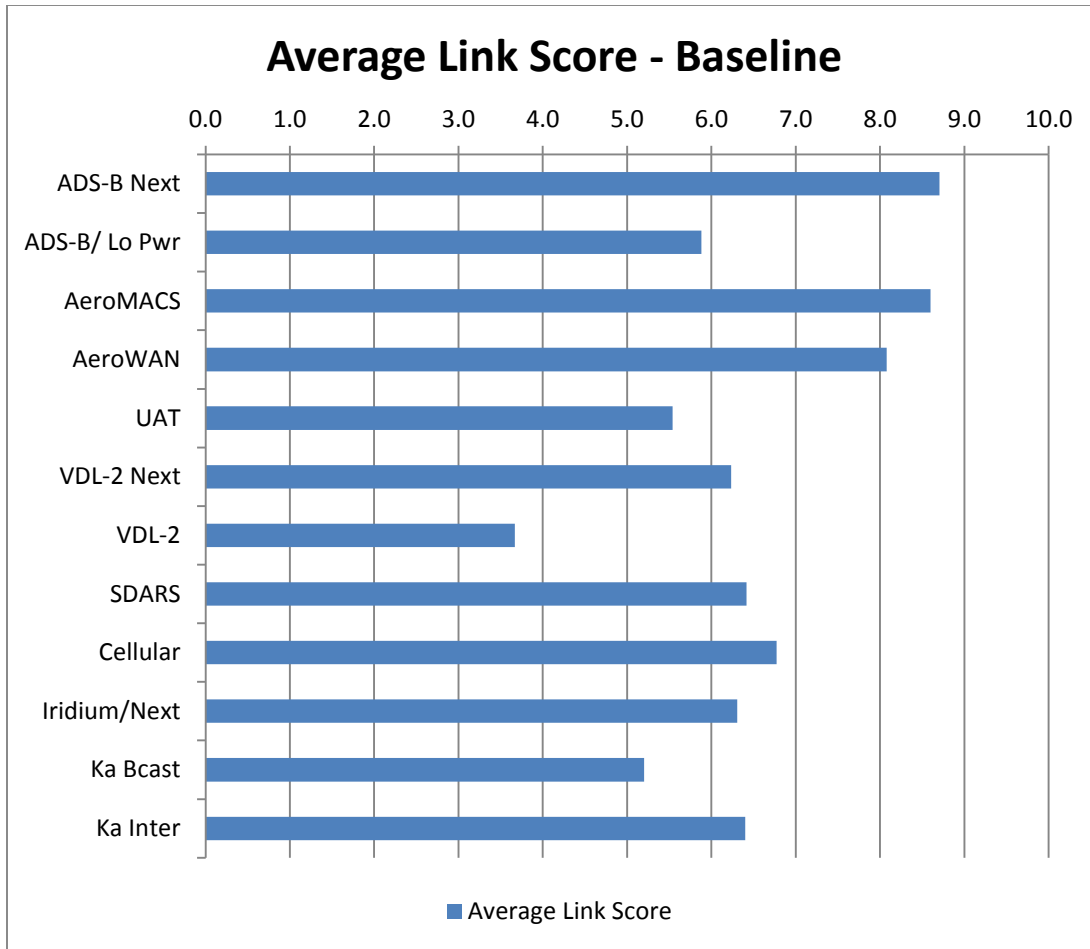
### 11.6.1 Baseline Analysis Results

The Baseline Analysis step employed a numerical analysis of the initial suitability ratings for each link, by function, for both the aggregate and average scores, using as input the ratings summarized in Appendix 2. Results are shown in Figs. 1 and 2 below.



**Figure 11-1: Aggregate Link Scores - Baseline**

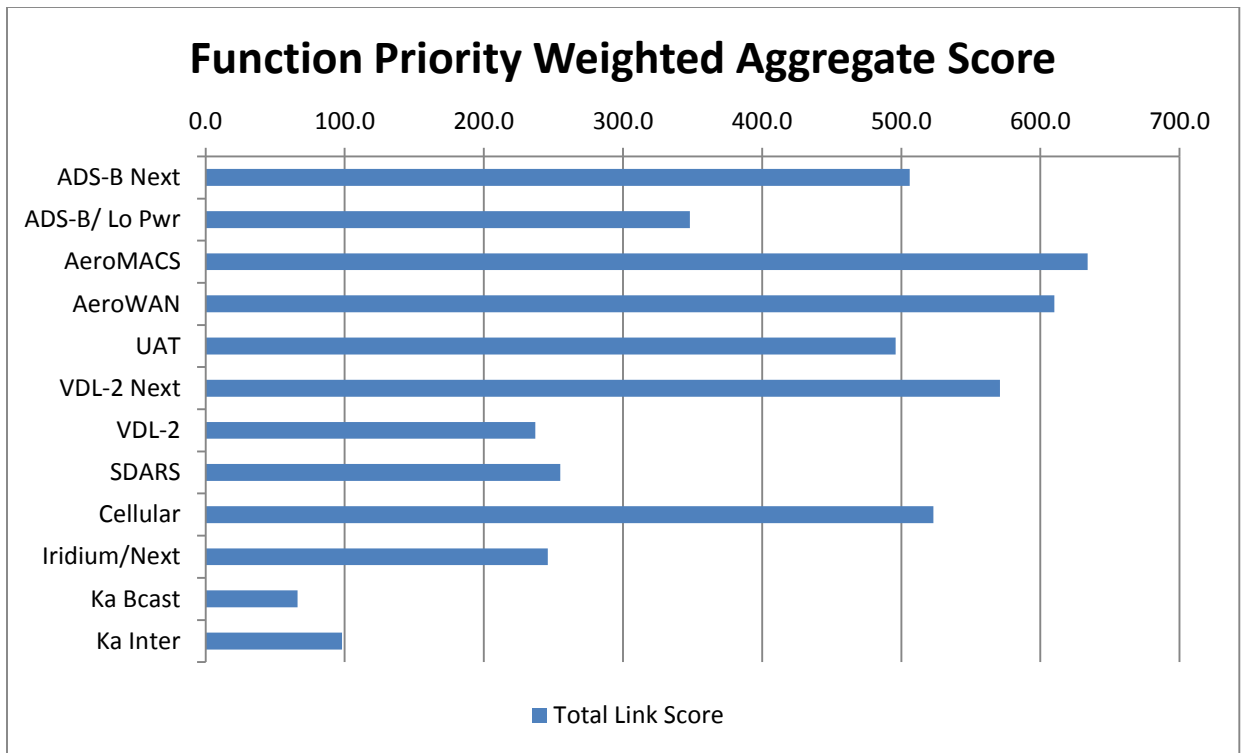
The aggregate scores highlight those links that would be suitable for a wider range of functions, with higher scores due on part to having been scored for more functions. This is particularly true for AeroWAN and AeroMACS, whose mobile network capabilities are compatible with many different tasks. VDL-2 Next and Cellular also feature applicability to a variety of functions. The average scores (Fig. 2) show a different perspective, with systems optimized for a specific type of function, and only scored for those functions, ranking higher than their aggregate scores. ADS-B Next has the highest score, essentially because it is intended to do one very important type of job, and does it well.



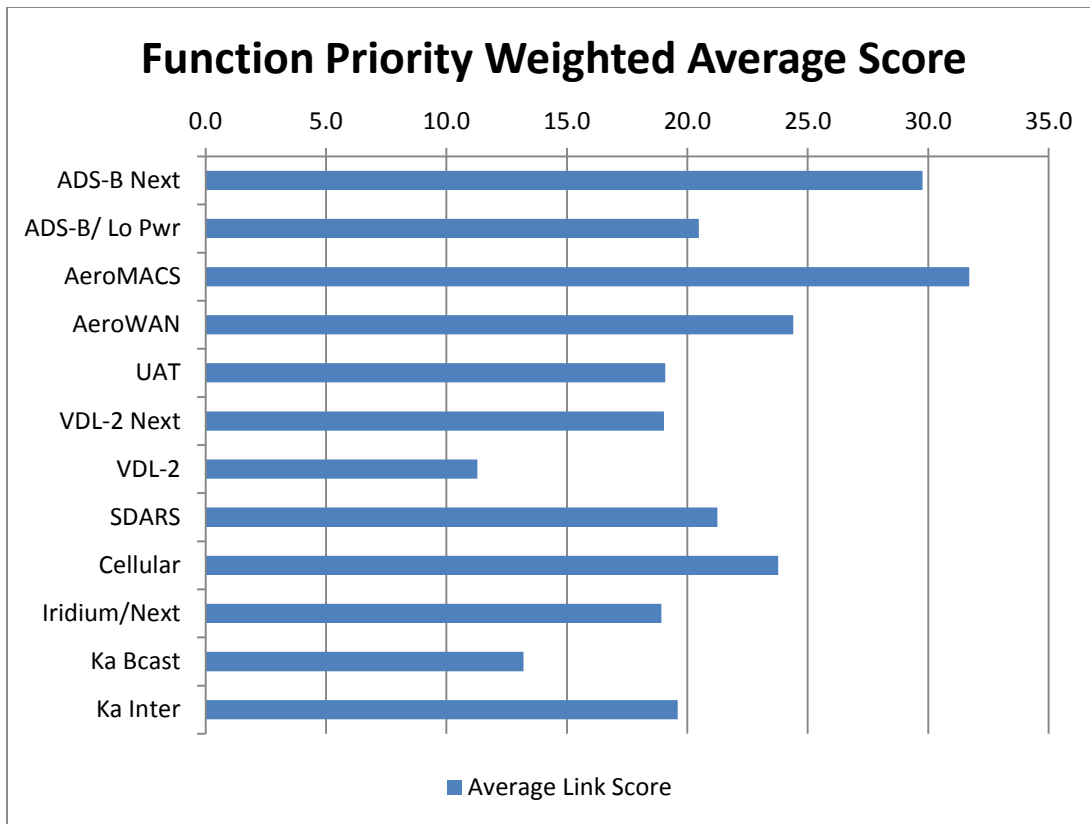
**Figure 11-2: Average Link Scores - Baseline**

**11.6.2 Function Priority Weighted Analysis Results**

Each future NAS function was identified early in this research effort, and its datalink-related characteristics defined. One parameter defined for each function is its relative priority, defined in terms of “Must Have, Highly Desirable, or Nice-to-Have”. These priorities were used in the next analysis step, to establish weighting factors for each candidate link based on the priority of each function that it serves. A 5-point scale was used, with weightings of 1, 3 and 5 respectively for each increasing level of priority. This helps to differentiate those candidates which potentially contribute the most to the conduct of flight. Fig. 3 shows the aggregated scores, which also illustrate broadest range of functions served, and shows that AeroMACS and AeroWAN not only serve a range of functions, but of high priority functions as well.



**Figure 11-3: Function Priority Weighted Aggregate Scores**



**Figure 11-4: Function Priority Weighted Average Scores**

Fig. 4 considers the function priority in the context only of each candidate’s level of service to those functions it enables. Results are similar to the Baseline average in that ADS-B Next still scores well, as a system focused on a specific and important job. AeroMACS also scores well, in part because of its potential application as an alternative to ADS-B Next for ground operations.

**11.6.3 Weighted Scores with Obsolescence**

Adding the consideration of potential obsolescence to the preceding analysis steps required developing ratings for each candidate link’s susceptibility or resistance to obsolescence going forward from the 50-year future reference time point. It should be noted that this area of consideration has both technical and business case elements; this report is focused on the technical aspects of candidate comparison, with business case analysis to follow in the next phase of this research. Accordingly, the team approached the analysis of potential obsolescence as a transition point, with primary focus on technical considerations but including some preliminary assessment of related business factors as well. A number of factors were applied by the team to assign obsolescence ratings, 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)

Ratings assigned were:

ADS-B Next	5
ADS-B	2
AeroMACS	4
AeroWAN	5
UAT	2
VDL-2 Next	4
VDL-2	1
SDARS	3
Cellular	4
Iridium	4
Ka-Band Broadcast	5
Ka-Band Interactive	5

As discussed previously in Section 4.8, the application of SDR technology to the overall architecture of the future system enhances the resistance of all candidate links to potential obsolescence, but to varying degrees in some cases. Current links such as VDL-2 and ADS-B were evaluated without any benefit of SDR technology; the future versions proposed in this research (e.g., ADS-B Next, VDL-2 Next) are in part defined by that specific difference. Conversely, the AeroWAN concept is an entirely new link, with SDR and DM as integral elements of its architecture, and can be expected to derive maximum benefit from those technologies as a result. Other candidates fall in between.

In general, the SDR architecture for any given avionics unit applies to a group of contiguous frequencies, such as the entire L-Band, but not to more disparate frequency ranges such as L-Band (nominally 1 GHz) versus the 5 GHz range where AeroMACS currently resides. For this reason AeroMACS is rated slightly lower than AeroWAN due to its location in the former MLS

band, where there is a limited scope of other aviation services or link types within SDR range, whereas AeroWAN resides in the L-Band along with many other aviation-related services. Thus an L-Band SDR could potentially be adapted and used for many more future functions than an SDR designed for AeroMACS.

It is anticipated that bandwidth demand will continue to escalate beyond the 50-year reference point, and links whose capability to adapt as needed in order to access additional bandwidth will be more susceptible to obsolescence. Current VDL-2 is limited by its available bandwidth and channel structure, and its modulation, and offers limited resistance to future obsolescence in its current form. With the implementation of SDR and DM technology in the future, VDL (or other VHF band avionics) will allow restructuring of many of those limiting factors, greatly increasing capabilities and allowing various future enhancements and functions. Since this is the underlying premise of the VDL-2 Next candidate proposed as part of this research versus current VDL-2, VDL-2 Next is scored much higher in its resistance to obsolescence. However, as a VHF system, with its growth presumably limited to the scope of the currently defined VHF aviation band, its potential for growth is more limited than some other candidates and was scored at less than maximum rating as a result.

The same rationale applies to current ADS-B relative to the ADS-B Next candidate proposed as part of the current research. Current ADS-B's inherent purpose-built hardware and single-channel spectral structure place firm constraints on both its bandwidth expansion and adaptability to future architectures. In contrast, ADS-B Next has inherent SDR architecture and access to additional spectrum for future growth, and a straightforward path to implementing enhancements on a configuration-based or software-only basis using the same hardware.

UAT has similar limits to those of current ADS-B, with single-purpose hardware and a single, firmly defined bandwidth for current and future needs. The research team opted not to propose a "UAT-Next" candidate; the proposed ADS-B Next system has ample bandwidth and expansion capacity to accommodate all potential ADS-B user segments, without the need for segregated solutions for different types of users. Merging the General Aviation and low-altitude users into the overall ADS-B community increases interoperability, standardization, production volumes, and efficiency of bandwidth use, while simplifying system architecture and removing the need for an external infrastructure to relay ADS-B data between the different systems. As a result, UAT was scored lower than ADS-B Next in Obsolescence susceptibility.

SDARS is a commercial system designed for a very different purpose, and capitalized by a very different core subscriber base, than its current aviation users. This "piggyback" model for serving aviation is more difficult to predict going forward, particularly over long periods of time. If the market dynamics of the much larger core use base change, niche users such as

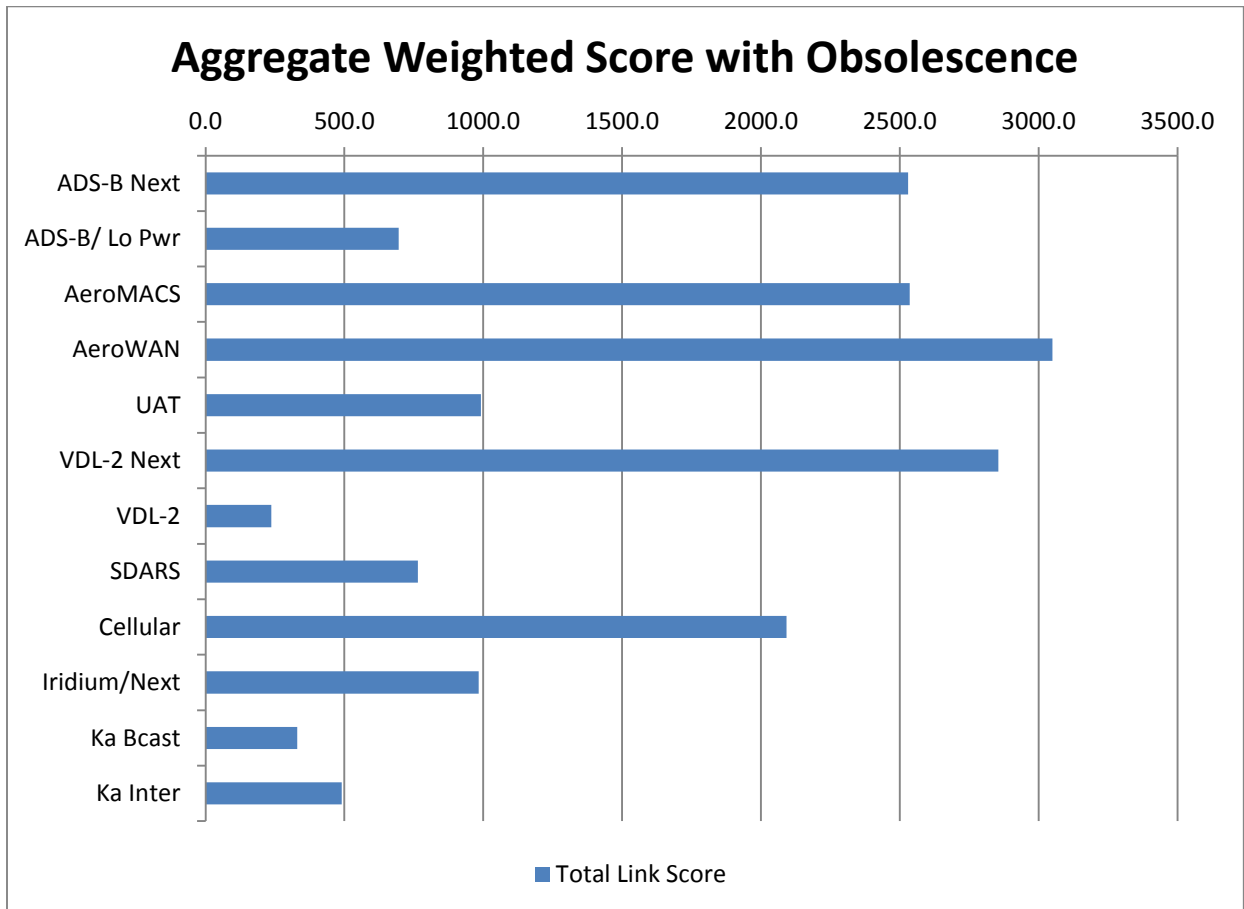
aviation have little control over the future of the link, be it technically or financially. As a result, SDARS was assigned a lower rating than some candidates based in part on this uncertainty. In addition, its commercial architecture allocates limited bandwidth to special applications such as aviation. If the current commercial business model does remain stable, there is a likelihood that limited additional bandwidth will be allocated away from other competing user functions to aviation. In that event its ability to keep pace with anticipated increasing aviation bandwidth needs becomes a form of obsolescence in itself.

In general, it is anticipated that cellular systems will continue to thrive and progress for the foreseeable future, both technically and commercially. What is less certain is the evolution of the commercial business model in relation to the relatively small aviation user base. The aviation base is expected to grow over time, but whether it will grow in relation to the ground-based revenue segments competing for bandwidth and capital for infrastructure adaptations is much less clear. As discussed previously, this report is focused on technical considerations, with business case aspects the subject of the next phase of research, and obsolescence is an area that relates to both areas. For the purpose of this report, cellular candidates were given a relatively high score on technical grounds, but reduced by one point based on the uncertainties of bandwidth access and other expansion and adaptation prospects.

The obsolescence prospects of Iridium and similar future systems was based on the assumption that the planned Iridium/Next system will be fully implemented as planned over the next 10 years, including the planned space-based ADS-B capability. Although Iridium is fundamentally a commercial system being used in part by aviation applications, the advent of space-based ADS-B increases the likelihood of long-term access to bandwidth and adaptation by aviation users. Conversely, the prospects for allocation of significant additional spectrum to such services are questionable based on the current climate, which could limit this candidate's long-term bandwidth growth access. For these reasons a relatively high rating was assigned, but not the highest possible rating.

Both Ka-band systems (broadcast and interactive) were considered primarily in the context of services to larger aircraft in oceanic regions, where they offer the strongest benefits. Due to considerations of antenna size limitations on smaller aircraft, and weather induced signal attenuation at low altitudes, their obsolescence potential was based primarily on air transport applications. In this user segment Ka-band candidates were deemed to have strong long-term potential for availability, as well as potential bandwidth growth through both spectrum access and various technical enhancements. With these caveats, both were assigned high ratings. It should be noted that satellite systems will also benefit from the application of SDR technology, and those requiring steerable antennas can be expected to benefit less SDR than other candidates.

Fig. 5 shows the aggregate scores for all candidates with obsolescence taken into account. This may provide the clearest “investment case” perspective of which candidates merit the most investment in research and development to realize the maximum future benefit. It can be seen that the highest ranking candidates, in order, 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.



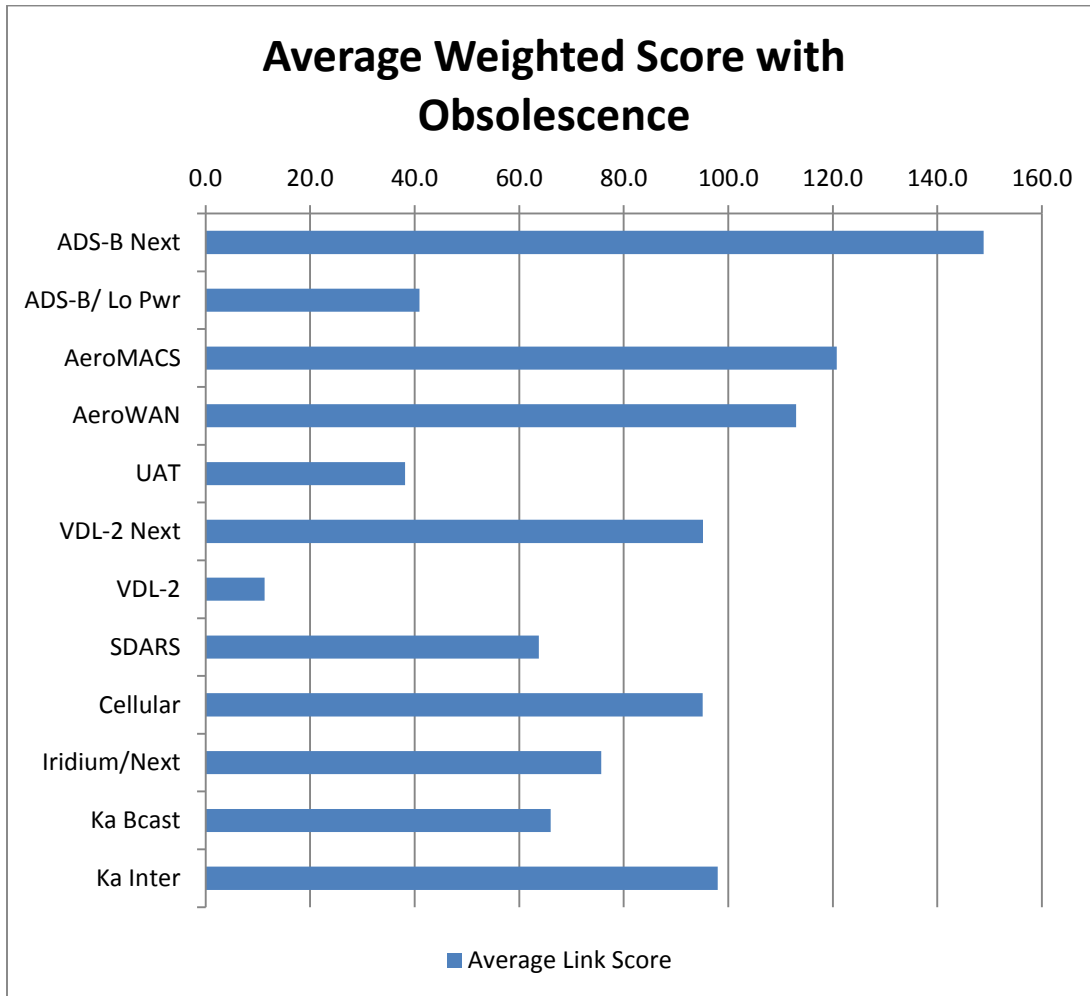
**Figure 11-5: Aggregate Weighted Score with Obsolescence**

The average scores with obsolescence considered, shown below in Fig. 6, show a somewhat different order of the same four top candidates, with ADS-B Next scoring highest in its performance within its more limited areas of application, followed by AeroMACS, AeroWAN, and VDL-2 Next. Note that both cellular and interactive Ka-band also score well.

ADS-B Next, AeroMACS, and interactive Ka-Band all score well in part because they are purposely designed to address specific needs in specific areas rather than broad-based links for many applications. AeroMACS only serves ground-based users in close proximity to airports, Ka-Band serves large aircraft at cruise altitudes in oceanic areas, and ADS-B Next is purposely



limited to proximate aircraft awareness functions. Cellular candidates also score well for similar reasons, being primarily applicable to ground-based uses not unlike AeroMACS.

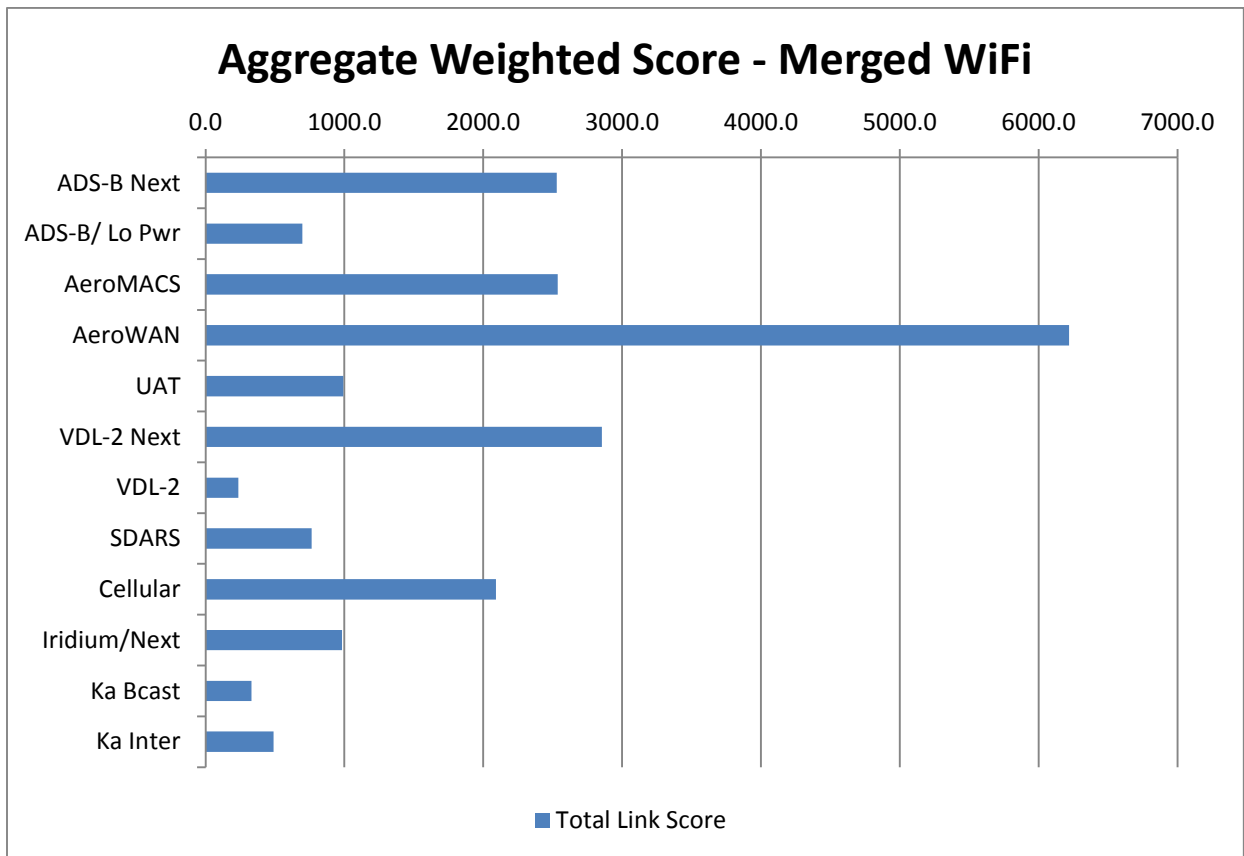


**Figure 11-6: Average Weighted Score with Obsolescence**

#### 11.6.4 Merged AeroWAN and AeroMACS Rankings

One special case was also analyzed by the team. AeroWAN and AeroMACS, as currently defined, are based on similar technology and operate in similar ways, but serve two disparate operational contexts using two relatively divergent frequency bands. As a result, each scores very well in its own area: AeroWAN in airborne functions only, and AeroMACS in ground functions only. If these two systems could be merged over the 50 year research period, a number of advantages would be gained, including commonality of both ground and airborne equipment, potentially one less avionics device needed, and increased coverage by using airport systems to also serve as AeroWAN ground stations and vice versa.

The team opted to model a merged system in the AeroWAN L-Band spectrum primarily due to the broader applications of an L-Band SDR; however, more detailed technical analysis would be needed to formulate a considered recommendation. The aggregate scores under this scenario are shown in Fig. 7 below. It can be seen that the “Merged WiFi” system outscores all other candidates by a significant margin, due to its broad-based range of functions served coupled with its high bandwidth and other strong performance rankings. This suggests that, of all the candidates analyzed, such a merged AeroWAN/AeroMACS system would serve the most users and functions, across all user segments, of any single link studied.



**Figure 11-7: Aggregate Weighted Scoring Showing Merged AeroWAN / AeroMACS Score**

**11.6.5 Aggregate versus Average Rankings**

The Gap Analysis input downselect 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. This indicates that suitable performance can be obtained for each function from two or more candidates. As a result, while the Average rankings provide an interesting look at optimum options, which may be useful in choosing between two qualified candidates, in general the team concluded that the Aggregate Rankings provide a more compelling measure of overall candidate merit, particularly in the context of defining development priorities going forward.

A link candidate that provides suitable service for many functions may well support a better business case for development investment than one that provides somewhat better service for a small number of functions. Using the *Aggregate Weighted Score with Obsolescence* analysis results, as shown in Fig. 5, the highest-ranking candidates are AeroWAN, VDL-2 Next, ADS-B Next, and AeroMACS.

## 11.7 Appendix 7 – SDR and DM Conceptual Architecture

### Software Defined Radio (SDR) Receiver Architecture - Direct Conversion

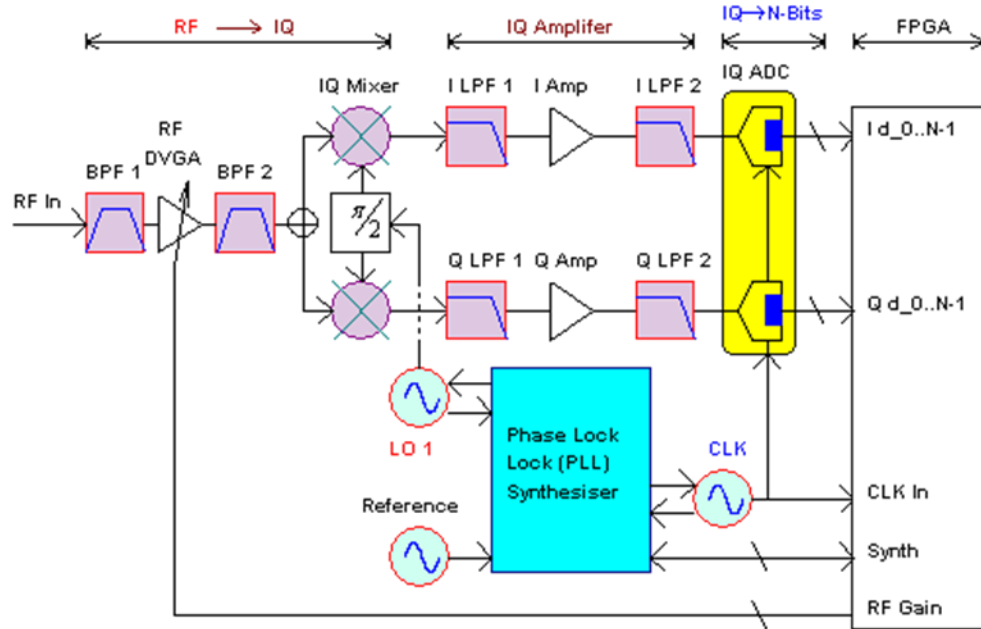


Figure 11-8: Conceptual Architecture of Delivery Manager and BBSDR in Aircraft Systems

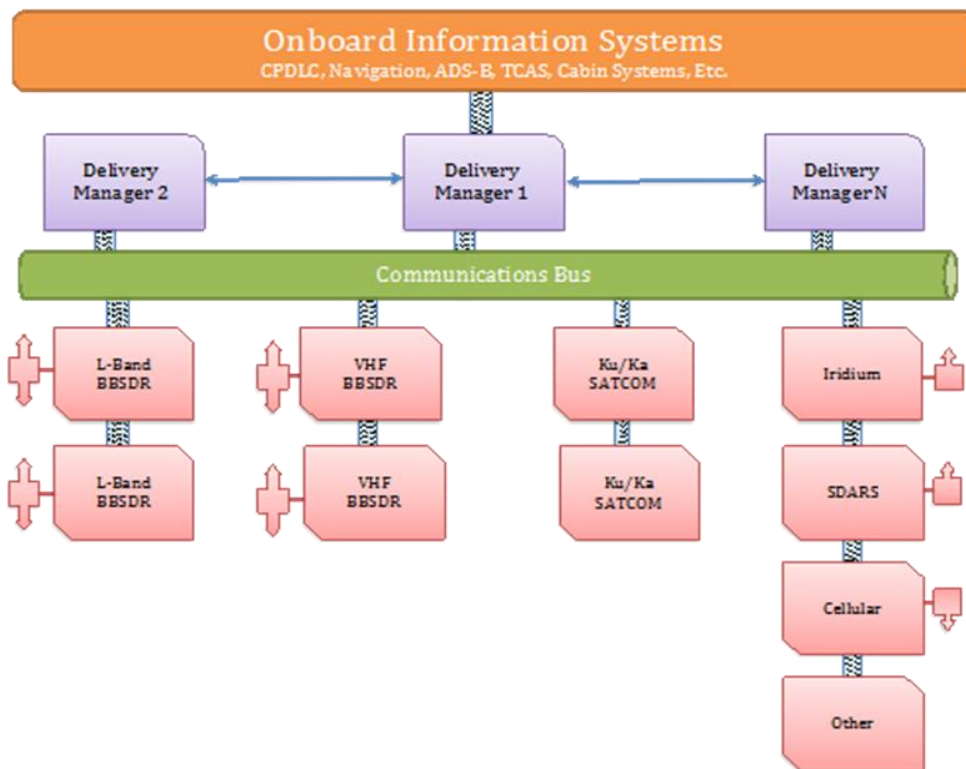


Figure 11-9: Conceptual Architecture of Delivery Manager and BBSDR in Aircraft Systems (Cont.)

## 11.8 Appendix 8 – Acronyms and Terms

**Table 11-14: Acronyms and Terms**

4G LTE	Fourth Generation, Long-Term Evolution
AAC	Airline Administrative Communications
AAI	Aircraft Airborne, Inbound communications
AAO	Aircraft Airborne, Outbound communications
ACARS	Aircraft Communications Addressing and Reporting System
ACK/NAC	Acknowledge / No Acknowledgement
A/D	Analog to Digital
ADS-B	Automatic Dependent Surveillance – Broadcast
AeroMACS	Aeronautical Mobile Airport Communication System
AeroWAN	Aeronautical Wide Area Network
AGATE	Advanced General Aviation Transport Experiment
AGI	Aircraft on Ground, Inbound communications
AGO	Aircraft on Ground, Outbound communications
ALOHA	Protocol: precursor to Ethernet
AM	Amplitude Modulation
AMDAR	Aircraft Meteorological DATA Relay
ANSP	Air Navigation Service Provider
AOC	Airline Operational Communications
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
BBSDR	Broad Band Software Defined Radio
CMU	Communication Management Unit
CO-I	Co-Investigator
CPDLC	Controller Pilot Data Link Communications
DBA	Doing Business As
DM	Delivery Manager
DME	Distance Measuring Equipment
DMU	Data Management Unit
DSP	Digital Signal Processor
FAMS	Federal Air Marshall Service
FCC	Federal Communication Commission
FEC	Forward Error Correction
FIS-B	Flight Information Services - Broadcast
FOQA	Flight Operations Quality Assurance
GA	General Aviation
GEO	Geosynchronous Satellite
GHz	GigaHertz
GLS	GNSS Landing System

GNSS	Global Navigation Satellite System
GPS	Global Positioning System, a U.S. operated GNSS
HPA	High Power Amplifier
ICNS	International Communication, Navigation, and Surveillance conference
IFE	In Flight Entertainment
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IP	Internet Protocol
Ka-band	26.5–40 GHz
Km	Kilometers
KOM	Kick-Off Meeting
Ku-Band	12-18 GHz
LAAS	Local Area Augmentation System
LEO	Low Earth Orbit
LRU	Line Replaceable Unit
MLS	Microwave Landing System
MON	Minimum Operating Network
MSK	Minimum Shift Keying
MTBF	Mean Time Between Failures
MTTR	Mean Time To repair
NAS	National Airspace System
NIA	National Institute of Aerospace
NOTAM	NOtice To AirMen
OPD	Optimum Profile Descent
PI	Principle Investigator
PTM	Pair-wise Trajectory Management
PTT	Push-To-Talk
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RA	Radio Altimeter
RCP	Required Communication Performance
RF	Radio Frequency
RX	Receiver
SATCOM	Satellite Communication
SATS	Small Aircraft Transportation System
SDARS	Satellite Digital Audio Radio Systems
SDR	Software Defined Radio
SME	Subject Matter Expert
Squitter	Transponder Message Transmission
SSID	Service Set Identifier
SUAS, sUAS	Small Unmanned Aircraft System
SWAT	Special Weapons And Tactics team
TACAN	TACTical Air Navigation
TCAS	Traffic alert and Collision Avoidance System
TDMA	Time Division Multiple Access
TOC	Top Of Climb

TSA	Transportation Security Administration
TX	Transmitter
UAS	Unmanned Aerial System
UAT	(ADS-B) Universal Access Transceiver
UPR	User Preferred Routing
VDL- Mode 2	VHF Data Link – Mode 2
VFR	Visual Flight Rules
VHF	Very High Frequency
VLJ	Very Light Jet
WAN	Wide Area Network
Wi-Fi	Wireless Network Technology





