Feasibility of a Networked Air Traffic Infrastructure Validation Environment for Advanced NextGen Concepts

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Abstract—**Next Generation Air Transportation System (NextGen) applications reliant upon aircraft data links such as Automatic Dependent Surveillance-Broadcast (ADS-B) offer a sweeping modernization of the National Airspace System (NAS), but the aviation stakeholder community has not yet established a positive business case for equipage and message content standards remain in flux. It is necessary to transition promising Air Traffic Management (ATM) Concepts of Operations (ConOps) from simulation environments to full-scale flight tests in order to validate user benefits and solidify message standards. However, flight tests are prohibitively expensive and message standards for Commercial-off-the-Shelf (COTS) systems cannot support many advanced ConOps. It is therefore proposed to simulate future aircraft surveillance and communications equipage and employ an existing commercial data link to exchange data during dedicated flight tests. This capability, referred to as the Networked Air Traffic Infrastructure Validation Environment (NATIVE), would emulate aircraft data links such as ADS-B using in-flight Internet and easily-installed test equipment. By utilizing low-cost equipment that is easy to install and certify for testing, advanced ATM ConOps can be validated, message content standards can be solidified, and new standards can be established through full-scale flight trials without necessary or expensive equipage or extensive flight test preparation. This paper presents results of a feasibility study of the NATIVE concept. To determine requirements, six NATIVE design configurations were developed for two NASA ConOps that rely on ADS-B. The performance characteristics of three existing in-flight Internet services were investigated to determine whether performance is adequate to support the concept. Next, a study of requisite hardware and software was conducted to examine whether and how the NATIVE concept might be realized. Finally, to determine a business case, economic factors were evaluated and a preliminary cost-benefit analysis was performed.**

I. INTRODUCTION

Air Traffic Management (ATM) Concepts of Operation (ConOps) that rely on advanced technologies such Automatic Dependent Surveillance-Broadcast (ADS-B), Controller/Pilot Data Link Communications (CPDLC), airborne and ground-based automation, and advanced controller and pilot interfaces have been developed and investigated by NASA, the Federal Aviation Administration (FAA), and others over recent decades. Research and development to date for concepts that rely on the exchange of data between aircraft or between ground systems and aircraft have almost exclusively been conducted using modeling, analysis, and Human-in-the-Loop (HITL) simulation. To continue progress toward implementation of these advanced ConOps as future elements of the National Airspace System (NAS), extensive validation and refinement must occur in the environments of their ultimate use.

Due to their high cost, flight activities associated with ATM concepts have often been limited to isolated demonstrations of capability. For many advanced concepts, extensive validation involving multiple field tests is required. The enabling technologies, their performance and interoperability standards, and their design requirements will require updates based on results of the in-flight concept validation and refinement. However, equipping many aircraft with the new systems and supporting avionics often requires a resource-intensive multi-year commitment to in-flight validation for a single flight test. Reducing these cost and time factors may be critical in meeting modernization expectations for the ConOps and their enabling technologies.

In addition, commercially available systems comply with existing standards, such as the Minimum Operational Performance Standards for ADS-B (currently RTCA DO-260B for the 1090 MHz ES standard). These standards do not include some of the message content proposed to support many advanced ConOps that may be necessary to provide acceptable returns-on-investment (ROI) demanded by airspace users to justify the expense of equipping their fleets. In addition, some ConOps may rely on the surveillance of very large numbers of targets. ADS-B In is currently limited to surveillance of 127 aircraft. [1] Because these advanced concepts cannot be validated using currently-available ADS-B systems, there may be no way to validate these concepts in flight, and therefore, no way to justify the expense of extending the standards. Currently-available production systems may have limited value to owners of aircraft, so they have little incentive to equip and participate as partners in flight tests. Another approach is needed for in-flight evaluation of concepts that rely on ADS-B, CPDLC, and other advanced communications and surveillance concepts or technologies.

It is proposed to conduct in-flight validation using a two-way data link that connects simulations of future airborne surveillance and communications equipage on each participating aircraft in lieu of actual equipment. A new capability, referred to as the Networked Air Traffic Infrastructure Validation Environment (NATIVE), emulates aircraft data links such as ADS-B using easily-installed test equipment and a small ground-based system of computers. NATIVE would be used in dedicated flight tests using either test aircraft or aircraft that are removed from revenue service for the test. A deployed NATIVE system would provide equipage and software that emulates an end-state system that relies on current and potential future ADS-B functions, CPDLC functions, and other functions for air-to-air and air/ground data exchange. The airborne NATIVE equipment would be installed and flown in an experimental certification. NATIVE may be able to utilize existing in-flight Internet systems and existing real-time simulations of the advanced data links, thereby keeping its development and implementation costs low.

If NATIVE is adopted as a flight test method, airlines and other aircraft providers would be able to participate in NASA/FAA *in situ* validation trials and experiments by allowing NATIVE equipage to be installed on their aircraft on a temporary basis. In one potential use strategy, NASA would provide computing platforms to be installed in each participating aircraft as well as the ground-based component. In addition to the data link simulations, the airborne equipage would contain pre-installed and pre-tested NASA automation and display technologies. The ground-based component would be connected to existing FAA automation systems such as En Route Automation Modernization (ERAM), to other information services, and to platforms containing advanced ground-based technologies that support the ConOps under evaluation.

This paper presents results of a feasibility study of the NATIVE concept. To determine requirements, six NATIVE design configurations were evaluated for two NASA ConOps that rely on ADS-B and other data links. The performance characteristics of three existing in-flight Internet Service Providers (ISP) were investigated to determine whether existing performance is sufficient to support the concept. Next, a study of requisite hardware and software was conducted to examine whether and how the NATIVE concept may be realized. Finally, to determine a business case, economic factors were evaluated and a preliminary cost-benefit analysis was performed.

II. ANTICIPATED BENEFITS

NATIVE may prove to bridge the gap between research and development and implementation of advanced ATM ConOps and their enabling communication and surveillance technologies. Anticipated benefits of NATIVE are:

- Costs of flight trials are mitigated for specific airborne functions that rely on advanced technologies or new standards for communication and surveillance. Cost reduction is achieved by reducing or eliminating the requirements to procure and permanently install certified equipment on aircraft to enable participation in the test.

- Flight trial preparation time is substantially reduced since aircraft are equipped with existing test hardware on a temporary basis, new functional capabilities are provided from outside the aircraft, and the new capabilities already exist in simulation laboratories in some instances. Test hardware would be designed for minimal aircraft recertification to participate in multiple flight trials.

- Because of the substantially-reduced costs, more aircraft are available to use a function during the flight trial, thereby allowing measurement of system benefits for concepts that rely on a large percentage of the aircraft being equipped and participating.

- Costs incurred by airline partners in NASA/FAA flight trials are reduced. This may increase the pool of airlines and other airspace users available to participate as partners in government flight validation activities.

- A virtual representation of communication and surveillance technology rather than reliance on actual hardware enables the exploration and validation of communication, navigation, and surveillance (CNS) requirements *in situ*. Simulations of future hardware are easily modifiable to explore and test potential new standards for message content and transfer rate. Test hardware will not become obsolete as a result of CNS standards changes, and the virtual environment will enable rapid update of the test system as standards evolve.

- Simulated aircraft may augment the actual aircraft in the test, thereby increasing complexity of test scenarios with a minimal increase in costs.

- Research algorithms and crew interface software stay on the research platforms on which they were developed and tested, thereby reducing costs, preparation time, and flight trial execution risk.

- If a research organization provides portable and easily site-adaptable system components, the components can be reused many times at many sites. Test planning, coordination, and set-up times could be reduced to the level where the rate of testing is several times greater than the rate achievable if certified flight hardware is employed.

III. NATIVE ARCITECHTURE

As envisioned, NATIVE would utilize Commercial-off-the-Shelf (COTS) hardware as well as specifically-developed software components to emulate future surveillance and communication equipage for experimental flight tests.

A. Hardware

NATIVE hardware includes laptop or tablet computers installed on participating aircraft, ground-based computers with Internet access, and an in-flight Internet system. The airborne hardware would host displays and user input capabilities that support the ConOps under evaluation, and would be operated by the pilot or the flight test engineer. This equipment provides connectivity to the airborne Internet data link and hosts advanced ConOps algorithms, the associated aircraft data interfaces, and special processing functions as needed. An Electronic Flight Bag (EFB) may be used as the host platform. Modern aircraft that are compliant with ARINC Characteristic 702A Revision 1, such as the Boeing 737NG, make Flight Management System (FMS) information available to the ARINC 429 data bus. This information is sufficient to investigate many proposed ConOps, and is accessed through the use of an EFB data concentrator or data concentrator

emulation software. The information will only be received from aircraft systems; providing data from the advanced technology back to the aircraft systems is not a part of the envisioned NATIVE use. Flight crews will fly manually based on the NATIVE display guidance or will enter the displayed information into aircraft systems manually.

In-flight Internet transmits and receives emulated aircraft surveillance and communication data between all participating aircraft and the NATIVE ground system. The ground system aggregates and processes traffic and weather information and, in some cases, hosts the advanced ATM technologies.

Figure 1 illustrates a NATIVE test configuration for a future concept that makes use of ADS-B for airborne surveillance. Airborne and ground-based technologies are hosted by NATIVE to enable *in situ* evaluation of an integrated air/ground traffic management concept. ADS-B surveillance is simulated. The airborne NATIVE component of each participating aircraft constructs the simulated ADS-B Out message and sends it over the Internet downlink to the NATIVE ground component. The ground component receives simulated ADS-B broadcast messages from all participating aircraft and assembles a continuously-updated traffic surveillance data base. It can also accept traffic information from existing FAA traffic automation systems such as ERAM and from traffic simulators that generate virtual traffic. The ground-based component then provides traffic information to both the ground-based NASA automation technology and the airborne technologies.
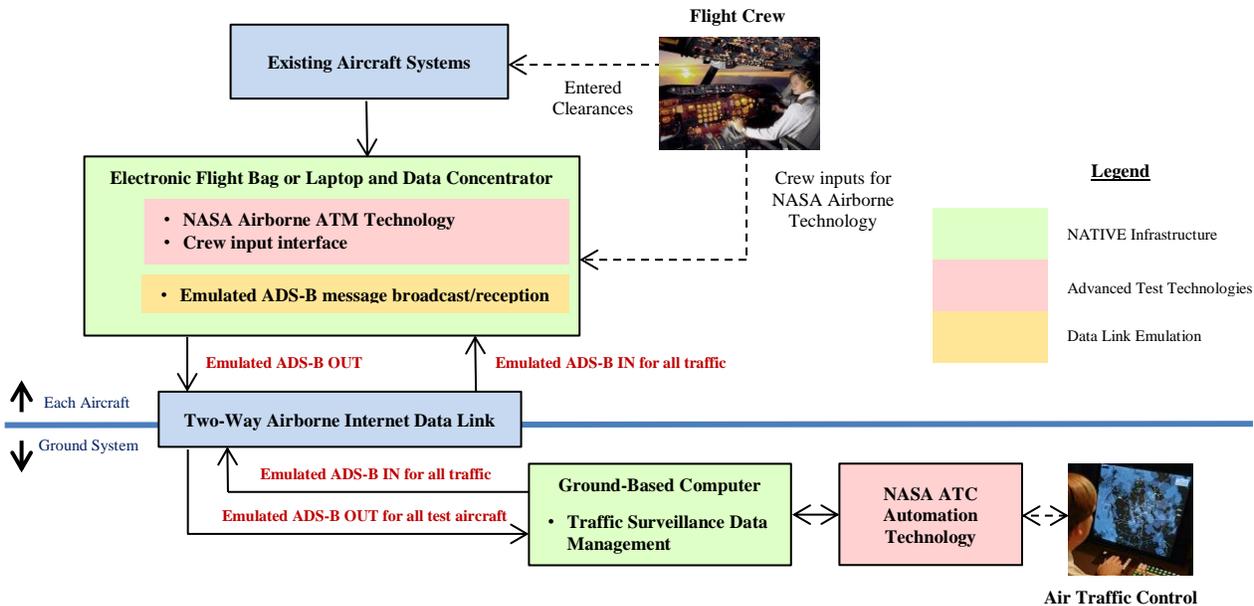

Figure 1: A potential NATIVE test configuration for a concept that uses ADS-B for airborne surveillance.

B. Software

NATIVE software components include data link reception and broadcast simulations, and software that amalgamates traffic and weather data from the participating aircraft and any other sources required for a given test. The NATIVE hardware may also host the advanced ConOps algorithms and any associated operator interfaces for both flight deck and ground-based applications. If needed for the test scenario, virtual traffic generators, traffic filtering, and data fusion algorithms can also be hosted by the NATIVE system.

ADS-B reception and broadcast models developed by NASA for use in real-time simulation may be used to package, transfer, and receive information over the Internet. Similar models also exist for data links such as CPDLC. The ADS-B Out model uses data from the hosting aircraft's systems, constructs an ADS-B broadcast message, and transfers it over the Internet. The ADS-B In model receives emulated ADS-B Out data over the Internet for all aircraft. It then determines whether each actual ADS-B message would have been received based on the originating aircraft's range and transmit power, and whether interference would have prevented reception [2]. ADS-B message standards are still in flux, so content and format remain subject to change. The NASA real-time ADS-B simulation can support additional messages as well as the standard ADS-B message set currently defined by RTCA DO-260B [3]. The ability to perform flight tests with non-standard ADS-B messages enables updated ADS-B report structures to be instituted, alleviating the issue of attempting to test ADS-B avionics based on a nonexistent standard.

Several applications have been developed by NASA and others that make use of ADS-B In. They have been investigated extensively using HITL and fast-time simulations. One example is Pair-Dependent Speed (PDS) guidance, which uses a trajectory-based spacing algorithm called Airborne Spacing for Terminal Arrival Routes (ASTAR) in the Flight Deck-based Interval Management (FIM) ConOps. Another is the Traffic Aware Planner (TAP) application which generates and displays an optimized flight path to flight crews within the Traffic Aware Strategic Aircrew Requests (TASAR) ConOps. Use cases for these two ConOps are provided in Section IV.

Flight crew interfaces for TASAR and FIM have been developed and tested at NASA. The display presents visual outputs of applications to the flight crew and will exist on the on-board NATIVE hardware. The FIM ConOps requires a display be mounted to the glare shield in the pilot's line of vision. A research prototype version of this additional display can be provided as part of the NATIVE installation.

The NATIVE system may contain special elements depending on configuration and specific needs of the ConOps being tested. A CPDLC model could be utilized for some configurations of NATIVE in conjunction with emulated ADS-B. A virtual traffic generator may simulate traffic scenarios to enable more experimental control without exposing aircraft to unnecessary risk. In many instances, test aircraft may have access to an Internet traffic feed as well as ADS-B In data. A data fusion algorithm known as a scenario filter will enable control over the source of traffic information when choices are available. Some NATIVE configurations may also utilize software that gathers additional traffic information and/or weather information. Traffic information may be obtained either from FAA data feeds or from an Aircraft Situation Display to Industry (ASDI) data stream. Weather data may be gathered from National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh or elsewhere.

IV. USE CASES AND SYSTEM CONFIGURATIONS

Two advanced NASA ConOps that require ADS-B In — FIM and TASAR — offer use cases to investigate the feasibility of the NATIVE concept.

FIM is a concept that allows pilots to efficiently space aircraft along Standard Terminal Arrival Routes (STAR) to optimize runway throughput [4]. Aircraft are given a target aircraft behind which to fly with a designated separation measured in time or distance. The desired separation interval is sent to the ASTAR algorithm from ATC, and the pilot makes throttle adjustments throughout the STAR until the final approach fix in order to match an interval requirement provided by a cockpit display of speed guidance [4]. The benefits of utilizing FIM in integrated airborne and ground-based arrival management ConOps include relieving traffic congestion at airports, increasing runway throughput, reducing flight delays, and mitigating environmental effects such as noise and air pollution around airports.

TASAR is a concept that enables the flight crew to perform in-flight replanning based on airline optimization preferences and generate flight plan changes that are approvable by air traffic controllers. TASAR's Traffic Aware Planner (TAP) is an EFB-based application that uses traffic, weather, winds-aloft, and restricted airspace information to advise the pilot of possible trajectory changes that would be beneficial to the flight, such as to optimize fuel efficiency or flight time [5]. Potential benefits to users of TASAR are reduced fuel cost per flight, fewer in-flight miles, improved schedule compliance, less environmental impact, and increased passenger comfort.

For both FIM and TASAR, three NATIVE architectural configurations were developed and analyzed for bandwidth, latency, computational load, and practicality. Figures 2 and 3 summarize the principal data flow of the NATIVE system in each of the following FIM and TASAR configurations, respectively. NATIVE components are outlined in gray.

A. FIM Configurations

In FIM Configuration 1, the majority of the computing occurs on the flight deck. The NASA-developed PDS guidance application, the flight crew interface, and the ADS-B In and Out models are located on an airborne NATIVE computer. The necessary speed to maintain an interval will be displayed on the airborne NATIVE computer or separate display. A complete traffic picture is sent from the ground system to each aircraft, where it is then filtered by the ADS-B In reception model. Since all traffic information relevant to the test is uplinked to each participating aircraft, this configuration was expected to require high Internet throughput relative to other configurations.

In FIM Configuration 2, the ASTAR and PDS algorithms are located on the airborne NATIVE computer, and traffic data

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management occurs on the ground, as with FIM-1. In FIM-2, the ADS-B In model resides on the ground, filtering the traffic data to determine which ADS-B transmissions would be received by each participating aircraft. A specific set of traffic information is then uplinked to each participating aircraft. This reduces required bandwidth for the in-flight uplink portion of the Internet system, but bandwidth requirements and computational loads for the ground system are increased. The increased computations could introduce latencies since traffic information would be sent to all participating aircraft after all traffic computations are complete for the surveillance update interval.
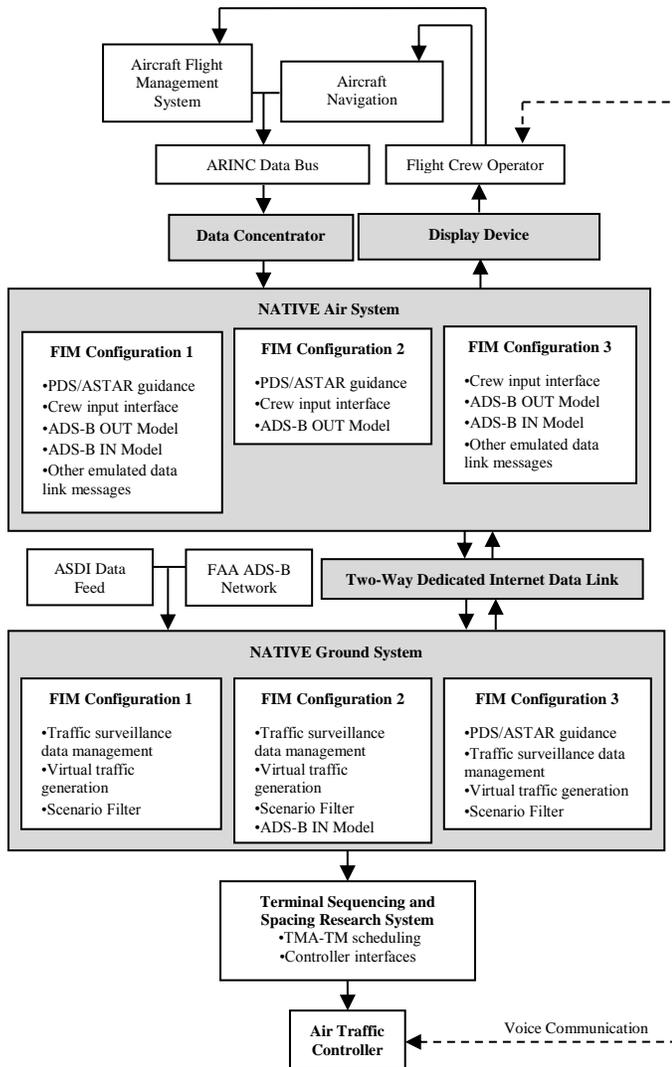

Figure 2: FIM Block Diagrams.

FIM Configuration 3 manages the traffic picture on the ground. The ASTAR algorithm, ADS-B In model, and traffic integration software are also ground-based, requiring only a speed guidance message to be sent to each aircraft as an emulated CPDLC message. In this design, in-flight Internet throughput requirements are decreased considerably, yet latencies may exist because speed guidance is sent to each participating aircraft. Table 1 summarizes the three FIM use case configurations.

TABLE 1. FIM NATIVE CONFIGURATION COMPARISONS

	Traffic Sent to Aircraft	Algorithm Location	ADS-B In Model Location	ATG[a] Data	GTA[b] Data
1	All	Air	Air	Emulated ADS-B	Emulated ADS-B or CPDLC
2	Partial	Air	Ground	Emulated ADS-B	Emulated ADS-B
3	None	Ground	Air	Emulated ADS-B	Emulated CPDLC

a. Air-to-Ground
b. Ground-to-Air

B. TASAR Configurations

NASA plans to conduct an in-flight assessment of the TASAR concept to accelerate readiness and make TASAR operations available to the aviation community for near-term operational use. The objective of the flight trial is to identify operational factors unique to the in-flight environment that may affect TASAR functionality, data requirements, interface requirements, and procedures. These early findings will help refine the TAP application and the TASAR concept.

TASAR Configuration 1 represents a possible NATIVE use case for the planned TASAR flight trial. Flight trial goals could be expanded with NATIVE to increase the value of the trial. Some experiment goals may be achievable without the need for ADS-B on the test aircraft, so some cost reduction may also be possible, depending on the final choice of experiment objectives. For this configuration, only uplink capability is utilized. Traffic data provided by ASDI are uplinked to participating aircraft to either augment or replace information provided by on-board ADS-B. Convective weather and winds-aloft data from NOAA Rapid Refresh or elsewhere may also be uplinked. A NATIVE ground system is needed to collect and process these data feeds and format the data for uplink. Data processing may include polygonization of convective weather regions. On the test aircraft, a separate NATIVE laptop may be required to augment the data processing load of the EFB. This computer would receive ADS-B In inputs and compare them with ASDI data received via uplink. Duplicate targets would be removed by the scenario filter that would construct a traffic surveillance data set for use by TAP. Duplicate targets may also be used by this function to estimate latencies for data received through the uplink. If direct ADS-B In latencies are assumed to be insignificant, the availability of duplicate target information enables comparisons of the two sources of data, and the time of applicability for the uplinked targets may be adjusted for use in extrapolations of current target states. Depending on test objectives, the airborne NATIVE component may also host an ADS-B In emulation, which would filter uplinked ASDI traffic data and remove targets that would not have been received by an actual ADS-B system. High Internet bandwidth may be required for this configuration, and depending on the number of participating aircraft, latencies may also be high.
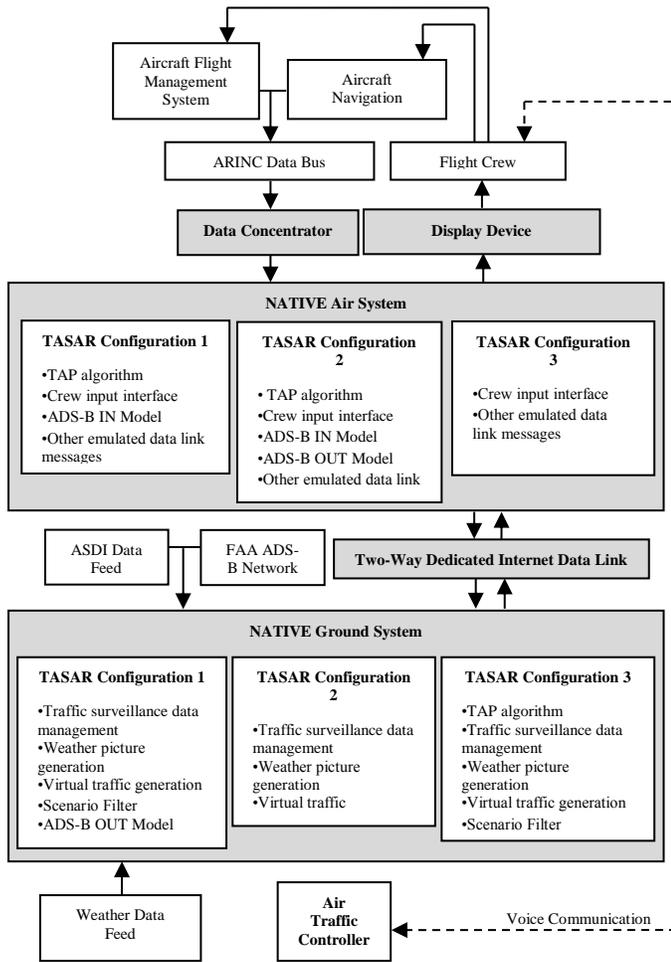
Figure 3: TASAR Block Diagrams.

TASAR Configuration 2 emulates ADS-B surveillance so participating aircraft need not equip with ADS-B hardware. This configuration may be used for tests involving traffic aircraft that would be accounted for in the test aircraft's in-flight replanning. Computational workload is distributed between the airborne component and the ground system. As in TASAR-1, the airborne component hosts the TAP algorithm, interface, and the ADS-B models. Additional traffic and weather are localized on the ground system and uplinked to the aircraft. Emulated ADS-B data is sent between aircraft, but in this configuration, NATIVE can utilize ADS-B as well.

TASAR Configuration 3 represents a hypothesized ATM cloud-computing scenario where the specialized TAP flight replanning and optimization functions are supported by a ground-based computer rather than a computer on the flight deck. In such a scenario, only a pilot interface exists on the EFB. The pilot would query a stand-alone TAP algorithm engine hosted by the NATIVE ground system. Crew optimization preferences are entered through the interface and downlinked to the TAP engine. The active flight plan, flight plan modifications, and all relevant aircraft-specific information are also downlinked. The TAP algorithm engine utilizes traffic and weather data feeds on the ground, and flight plan alternatives are uplinked via emulated CPDLC. Flight plan modification advisories are anticipated to be offered no more

than once per minute. This configuration minimizes the amount of Internet throughput required, but latencies are still expected. Table 2 summarizes the three TASAR use case configurations.

TABLE 2.   TASAR NATIVE CONFIGURATION COMPARISONS

	Traffic Sent to Aircraft	Algorithm Location	ADS-B IN Model Location	ADS-B System	ATG[a] Data	GTA[b] Data
1	All	Air	Air	Optional	N/A	Emulated ADS-B + Weather
2	Partial	Air	Air	No	Emulated ADS-B	Emulated ADS-B + Weather
3	None	Ground	None	No	Emulated ADS-B	Emulated CPDLC + Weather

a. Air-to-Ground

b. Ground-to-Air

V.   TECHNICAL FEASIBILITY

Internet bandwidth and latency requirements were considered for the architectural configurations of the aforementioned NATIVE use cases. The capabilities of three existing in-flight Internet systems were then estimated based on measurements obtained during commercial flights and consultation with the ISPs. The estimated capabilities were then compared with requirements to determine feasibility. An Internet latency impact assessment test was performed, and other factors and risks were also investigated.

A. Bandwidth Requirements.

Internet bandwidth required to support NATIVE-based FIM and TASAR ConOps during flight trials is derived from assumed upper bounds. A breakdown is given in Table 3 and ceilings for FIM and TASAR configurations are listed in Table 4. When considering the bandwidth required to transmit ownship data or traffic information, it has been assumed that messages are sent in compliance with DO-260B. The ADS-B reception range of each aircraft has been estimated as a circle with a 90nmi radius with the ownship at the center. Overall NAS traffic density has been assumed from the LA Basin 2020 scenario, where there are 2694 aircraft within 400nmi of the center [6]. The density has been applied over the approximate area of the contiguous United States [7].

In FIM-3, speed guidance information sent to the aircraft was conservatively assumed to be a 64-bit floating point number, sent twice per second. In the case that ASDI traffic data is being used, the analysis assumed that each aircraft's track information is contained in a 36-byte message and updated once per minute [8]. Weather data was assumed to come from the NEXRAD mosaic at its uncompressed size of approximately 7MB over an update time of 5 minutes. In practice, the NEXRAD mosaic can be compressed to around 300 kB [9] [10]. For TASAR-3, ownship data is assumed to be 293 bits broadcast at 2Hz [11]. When transmitting intent data, the aircraft flight plan was conservatively assumed to consist of 100 waypoints [11]. Lastly, a 60-byte packet header over an IPv4 network has been assumed. This header is the largest in the IPv4 standard, which is the most common protocol for data

transmission over the Internet. Packet sizes are assumed to be 68 bytes, which is the lower bound of this protocol and hence requires the transmission of more packets and therefore more headers, using more bandwidth.

TABLE 3. BANDWIDTH REQUIREMENT BREAKDOWN

Data	Bandwidth (kbps)
Ownship ADS-B	0.68
All US NAS ADS-B	7300
ADS-B within 90nmi range	720
Speed guidance	0.13
National NEXRAD Mosaic	190
Ownship TASAR-required	5.2
Intent (100 waypoints)	3.9
All US NAS ASDI track	52

TABLE 4. SUMMARY OF BANDWIDTH REQUIREMENTS FOR FIM AND TASAR CONFIGURATIONS

	Downlink (kbps)	Uplink (kbps) Upper Limit
FIM 1	1.7	7300
FIM 2	1.7	720
FIM 3	1.7	0.61
TASAR 1	0	460
TASAR 2	1.7	1000
TASAR 3	10	7.8

B. Data Link Specifications

Major providers of commercial in-flight Internet service utilize cellular or Ku-band satellite technology. Two in-flight ISPs—Gogo and Row44—were examined to determine NATIVE's feasibility for both Internet data exchange technologies.

Gogo provides a ground-based cellular network within the continental United States and advertises a peak uplink bandwidth of 3.1 Mbps over their ATG-3 system. Gogo is currently installing ATG-4 with an advertised throughput of 9.8Mbps [12] [13]. A test of the ATG-3 system measured latency and throughput characteristics on a Boeing 757 during the cruise phase of a single routine five-hour commercial cross-country passenger flight to obtain a limited sample of system performance. Connectivity to the aircraft's Internet system was shared among paid passengers throughout the entirety of the trip, so the test results may not be indicative of the expected performance capabilities for a NATIVE implementation. Using speedtest.net at five-minute intervals to obtain averages based on cellular tower location and potential temporal spikes in shared bandwidth usage, median uplink throughput of 100kbps, median downlink throughput of 82kbps, and a median latency of 560ms, were found.

Row 44 provides Ku-band satellite Internet connectivity and claims a peak throughput of 11Mbps per aircraft [14] [15]. A test of Row 44's Internet system measured latency and throughput characteristics on a Boeing 737 during the cruise phase of a single routine five-hour commercial cross-country passenger flight to obtain a limited sample of system performance. Connectivity was shared among paid passengers

throughout the trip, so again, the test results may not be indicative of the expected performance capabilities for a NATIVE implementation. Using speedtest.net at five-minute intervals to obtain averages based on satellite coverage and temporal spikes in shared bandwidth usage, median uplink throughput of 340kbps, median downlink throughput of 72kbps, and a median latency near 1200ms were found. Data for Gogo and Row44 are presented in Figure 4.
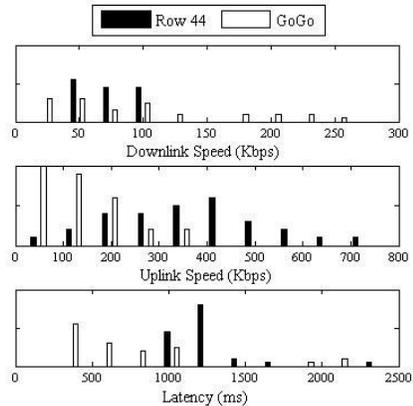

Figure 4: In-flight Internet Flight Test Results.

C. Internet Latency Impact Assessment

Several experiments were performed at Langley Research Center that investigated the impact of Internet latencies on FIM in a high-fidelity simulation environment with a three-aircraft stream comprised of a Boeing 757 in the lead, a Boeing 777 first in trail and equipped with NATIVE, and Boeing 737 second in trail and equipped with ADS-B. In these experiments, the three aircraft begin at 15, 21, and 26 nautical miles from a runway threshold at Dallas/Fort Worth International Airport, respectively. The NATIVE-equipped B777 is designated a 93s time interval behind the lead aircraft, and the B737 is given a 122s interval behind the B777. The experiments showed that the NATIVE-borne FIM algorithm withstood 25s ±50% mean Internet latency and is unaffected by up to 2% dropped packets. Results of this study are presented in detail in [16].

D. Other Technical Feasibilty Concerns

Although the transmission of flight-critical data is not envisioned for flight tests, security should be addressed in the context of utilizing the Internet as a data link. It should be noted that ADS-B is currently an unsecured data link [17]. The Internet, on the other hand, offers many methods of encrypting sensitive information.

Reliability is also an issue that must be addressed. For example, coverage gaps in mountainous regions and legal constraints below 10,000 feet inhibit Gogo's cellular signal at low altitudes; however, Gogo can temporarily install cellular towers near airports that would allow unfettered access for testing purposes. In the case where this will be necessary, software updates will be required for participating aircraft [13]. Also, because Row44 employs Ku-band satellite technology, rain fade is a practical concern. At roughly one inch of rain per hour, Ku-band satellite transmission is attenuated on the order of 5dB [18].

Message transmission integrity is another concern. The figures shown in Table 3 above are based on an assumption that TCP/IP will be the preferred data transfer protocol for the test arena. If the data link is reliable, TCP/IP ensures packet integrity. On the other hand, User Datagram Protocol (UDP) is a lighter and faster transmission protocol than TCP/IP; however, packet loss is a practical concern.

E. Analysis Results and Conclusions

An analysis of the technical feasibility of NATIVE has presented no major roadblocks with respect to throughput, latency, security, reliability, or integrity.

Throughput characteristics of current cellular and satellite in-flight Internet systems can support NATIVE for FIM and TASAR. As shown in Table 4, the most substantial required throughput is roughly 7.3 Mbps for FIM-1; however, this value is based on the assumption that over one-thousand aircraft would take part in a test. Realistically, no more than 100 aircraft would be involved in a test, so throughput requirements will likely not exceed 100kbps. The measurements of cellular and satellite Internet described in Section A above were taken during a typical revenue flight with at least 150 paid passengers, any number of whom may have been sharing the aircraft Internet system as well. Therefore, results from the throughput and latency tests likely reflect a low estimate of per-aircraft bandwidth capability. However, the uplink throughput for both experiments was measured to be at least 100kbps. Therefore, it can be concluded that throughput constraints will not hamper NATIVE's feasibility. In the absolute worst case, where over one-thousand aircraft would take part in a FIM-1 test, in-flight Internet service providers still advertise the capability to support even the throughput requirement specified in Table 4, with the exception of Gogo ATG-3, which cannot support the worst-case FIM-1 and FIM-2 configurations; however, at 9.8Mbps, Gogo ATG-4, as advertised, will support the worst case FIM-1 and FIM-2 cases.

Measured latencies will not affect timely execution of ConOps. While simulator experiments perform inadequately after 25s, measured latencies of Gogo and Row44 were on the order of one second. Latency will thus not present a limiting factor.

Security should also pose no concern. While ADS-B is inherently an unsecure data link, an Internet data exchange offers many methods of encrypting sensitive information. For this reason, NATIVE will be sufficiently secured for a flight test arena.

Signal reliability must be carefully considered. In the event that full-scale flight tests will commence in extreme rain conditions, Ku-band satellite service should be avoided; however, precipitation levels that will significantly affect Ku-band transmission reliability would also likely jeopardize flight test objectives. Therefore, rain fade is a minor concern. Coverage gaps below 10,000ft or in mountainous regions will hamper the reliability of Gogo's cellular signal, but this can be solved with additional localized towers, albeit at increased cost. Reliability will not negatively affect feasibility.

Assuming TCP/IP is the chosen data transfer protocol, integrity will be sufficient for NATIVE flight tests. Because of TCP/IP's error-correction schema, integrity is guaranteed. However, should the test environment utilize UDP, integrity must be further examined.

VI. PRELIMINARY COST-BENEFIT ANALYSIS

A preliminary analysis was performed to examine the potential for cost savings through the NATIVE approach. Costs of a sample flight test using NATIVE were compared to those of a test that utilizes ADS-B in a traffic computer installation. A FIM test scenario with 15 participating aircraft was used for the analysis. FIM-1 was chosen because its data link bandwidth requirement was the greatest of the six use case configurations in Table 4.

In a permanent configuration to be used in revenue service, FIM requires a traffic computer as specified in ARINC Characteristic 735B-1. The FIM ASTAR and PDS guidance algorithms reside inside the traffic computer, and crew interfaces are provided by a Class 3 EFB and the primary field-of-view Configurable Glass Display (CGD). All equipment and software are certified for revenue operation. Because NATIVE is intended to support flight validation of the concept rather than preparing for revenue service, the analysis compared two potential configurations suitable only for concept validation.

For the NATIVE configuration, ADS-B equipage is emulated with on-board simulations of ADS-B and an in-flight Internet capability. FIM guidance algorithms and the ADS-B In/Out simulations reside on an EFB. All crew interfaces reside on the EFB and on an emulation of a CGD using a small computer attached to the glare shield. For the ADS-B equipage configuration, a traffic computer is installed, and the guidance algorithms reside on an EFB and the CGD is emulated as for the NATIVE configuration. Traffic information available to the EFB-based algorithms is limited to Display Traffic Information File (DTIF) data feeds from the traffic computer.

Because the two configurations contain several common elements, several costs are identical and therefore not relevant to the comparison. These include supplemental type certificates (STC) and installation costs for Class 2 EFB hardware, costs of experimental certification, and costs to remove test equipment and perform regression testing to demonstrate original type certification. For the NATIVE configuration, participating aircraft were assumed to be pre-equipped with in-flight Internet services, and the costs to connect the in-flight Internet to the EFB were assumed to be negligible. Ground-based hardware costs and in-flight Internet subscription fees were included. Internet subscription fees were estimated from costs associated with a planned NASA TASAR flight test scheduled for 2013. The subscription requires a one-year contract that includes a limited amount of data usage, and additional fees are charged for supplementary data usage. [19] To determine uplink bandwidth requirements, traffic data were limited to 127 total traffic aircraft to allow direct comparison with the ADS-B equipage case. Internet data usage requirements assumed a flight test duration of ten hours using the FIM-1 configuration with the aforementioned traffic limitation of 127 targets. Using the calculated bandwidth requirement and assumed flight test time, the total amount of data transmitted and received does not exceed the data ceiling of the Internet subscription. Costs of NATIVE software development are not included. For the ADS-

B configuration, hardware costs, system integration costs, and STC costs were included and based on the ADS-B AIWP, and assumed an in-production retrofit installation of a digital narrow-body ADS-B In/Out system without a multi-mode receiver. [20]

The analysis shows that about $3.3M can be saved through the use of NATIVE for the example scenario. In light of necessary up-front infrastructure investments, a single NATIVE flight test may offer moderate savings, but significant savings may be obtained from repeated use because NATIVE-equipped test aircraft may be reused in future tests. Benefit mechanisms described in Section II should translate into significant savings for most tests.

The capability to validate advanced technologies on test platforms rather than on certified avionics systems may be the single greatest cost-reduction mechanism resulting from the use of NATIVE. The capability to validate candidate message standards may also provide a large benefit, and specifically for ADS-B, the use of NATIVE enables the exploration of future ConOps that may rely on the surveillance of more than 127 targets. Although these benefits may not translate directly into cost savings, they will enable early adoption of ADS-B in a timely manner by supporting maturation of ConOps that benefit users. Ultimately, NATIVE offers a bridge toward accelerated ADS-B standardization and validation of NextGen ConOps. Direct cost savings are achieved during standards maturation. More than one flight test will be necessary, and because airlines are hesitant to invest in them, a need exists to enable multiple reduced-cost flight tests.

TABLE 5. COMPARISON OF COST REQUIREMENTS BETWEEN NATIVE AND ADS-B IN A SIMILAR FLIGHT TEST

	ADS-B Test	NATIVE Test
Data Link Hardware	$235.39K per aircraft [20] *Assumptions*: Estimates from AIWP document for ADS-B In/Out; Equipment is digital narrow body without multi-mode receiver; Assumes retrofit to in-production aircraft.	$0 *Assumptions*: Aircraft utilizes pre-installed in-flight Internet system; EFB connection costs are negligible.
Ground-based Hardware and Software	$0 Not required for ADS-B test	$20K *Assumptions*: Rough Cost Estimate.
Internet Subscription Fee	$0 Not required for ADS-B concept	$17.5K per aircraft [19] *Assumptions*: Internet subscription cost based on planned NASA TASAR flight test.

VII. GROWTH POTENTIAL

By reducing costs and time required for flight trials that involve extensive air/ground data exchange, research and concept exploration may also be conducted for network concepts such as cloud computing applied to ATM. For these network-based concepts, the point of computation is not the same as the point of use, so new or updated available functions need not reside on the flight deck. This may significantly affect certification, equipage down time, and recurring costs of system functionality. An air/ground network infrastructure may facilitate fee-for-service capabilities and performance-based services that may prove to be critical enablers of benefits-driven airspace system modernization.

It may be possible for some services to be available in the near term if they do not adversely impact flight safety. TASAR-3 is an example of such a service. In this example, operators may choose to subscribe to an in-flight replanning optimization service. The service provider would receive specific information for the operator's aircraft as well as airline or flight crew preferences for optimization. The service provider would host the optimization function and use Internet uplink capability to provide flight plan modification alternatives to the crew. The crew would use the service through an EFB-based thin-client interface.

NAS delays amount to $8B/year in lost revenue, so an opportunity exists for cloud-computing entrepreneurial visions to utilize the NATIVE concept to increase NAS and airline efficiencies [21]. Fuel burn is hampering airline profit margins, so demand exists for methods to deliver increased efficiencies. In order to determine the cloud concepts' technical feasibility, a further study of the accuracy, integrity, and security of in-flight Internet must be undertaken.

Larger long-term opportunities afforded by the operational use of Internet to transfer flight data among aircraft and ground stations should also be considered. While congestion issues with 1090MHz hamper the expansion of the ADS-B message set, passengers aboard commercial flights use the Internet to send and receive data with no effective restrictions on content. Row44 is capable of increasing per-aircraft throughput and dedicating bandwidth in order to separate potential future flight application data exchange from retail passenger service on the flight deck [22]. Contingent upon availability, reliability, security, and integrity meeting application certification requirements, if an aircraft streamed data from the FMS and other aircraft systems to ground stations, applications not yet possible with currently envisioned data links may be possible and cost-effective through the use of the Internet.

VIII. CONCLUSION

It is feasible to employ NATIVE in flight trials to emulate data links such as ADS-B. Each of the in-flight ISPs can provide viable Internet access through which to validate NextGen ConOps and message content standards. Certification and installation of NATIVE components is cost-effective. Economic benefits provide a positive investment case for NATIVE, and preliminary findings suggest that NATIVE's value increases with the number of flight tests to be performed.

NATIVE may indeed accelerate the adoption of ADS-B In by enabling reduced-cost in-flight validation testing of air-to-air and air/ground data links, associated applications, and solidification of message content standards. NATIVE's scalability and adaptability enable evaluation of ConOps that are not supported by current avionics standards. NATIVE can inform discussions about the values intrinsic to alternative message sets. Airlines, application developers, and research organizations can develop test platforms for use with NATIVE to validate new ConOps and generate data that can be used to

estimate their benefits with high accuracy, without incurring expensive avionics costs and without limitations of currently available equipment.

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