DEVELOPMENT AND DEMONSTRATION OF THE NASA SMALL AIRCRAFT TRANSPORTATION SYSTEM (SATS) AIRBORNE INTERNET (AI)

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Abstract

The NASA the Small Aircraft Transportation System (SATS) Airborne Internet (AI) is a key enabling technology that must successfully contribute to the scheduled SATS Technology Demonstrations in 2003-5 and to the future SATS flight operations. The development of the SATS AI Testbed is the first step to supporting the NASA GRC Airborne Internet initiative. It will allow numerous Communications, Navigation, and Surveillance (CNS) technologies to be evaluated. Future growth of the SATS AI Testbed capabilities is a practical option as other communication means are evaluated, or as new communications capabilities are introduced.

The initial SATS AI Testbed has been developed using the VHF Data Link (VDL) Mode SATS radio and application emulators. Early Proof of Concept tests and evaluations have proven that the AI is a viable concept. The promise of the SATS AI Testbed is in the ability to establish temporary network connections with SATS development teams. These connections can provide the necessary active connection interface development and testing capability to realistically exercise and prove the SATS AI concept while supporting the development and integration of the SATS airborne technology.

The goal of the research program is to define and develop the Airborne Internet (AI) architecture to support the SATS flight experiments in 2003-5. The work effort involved research and experiments necessary to define the AI architecture. The areas of investigation were:

- An assessment of the impact of the AI architecture on the National Airspace System (NAS) infrastructure.
- The identification and evaluation of the available CNS that could provide the most robust yet realistic SATS system proof-of-concept evaluation in 2005.
- The definition of the CNS requirements that the AI would support.
- The definition and evaluation of candidate AI architectures leading to the selection of a single architecture for the 2003 flight experiments.

This paper reports the results of the architecture work and the testbed studies.

Background

The National Aeronautics and Space Administration (NASA), in partnership with the Federal Aviation Administration (FAA) and State and local aviation development organizations, has initiated a research and development program focused on maturing enabling technologies for the Small Aircraft Transportation System (SATS). The program will initially focus on intermodal transportation systems engineering to develop an overall design for SATS that is complimentary to existing air and ground transportation systems.

SATS is envisioned to take advantage of technology advances in aircraft engines, avionics, airframes, navigation equipment, communications, and pilot training to make it the new generation of general aviation (GA) that will let people travel from small airports. SATS not only will help to break the gridlock at large commercial airports by diverting traffic to non-hub small airports, it also can generate new air traffic demand as it can reduce the door-to-door time for travels from or to a place close to a small airport. With high-speed aircraft, numerous airports, an affordable cost, and easy pilot training, SATS can provide better door-to-

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door travel time, enhance mobility, and stimulate business activity [1].

NASA is identifying technologies for the SATS that could play a major role in helping to relieve large airport congestion and provide reliable, convenient, safe environmentally compatible air transportation service to rural and outlining communities, as well as revolutionizing the national transportation system. The Advanced General Aviation Transport Experiments (AGATE) and General Aviation Propulsion (GAP) programs have taken a quantum step in this process through the development of affordable, easy to use, environmentally friendly aircraft and propulsion systems. This investment is already benefiting the flying public through more affordable, informative and readable avionics systems. To bring the SATS vision to its full potential of a personal transportation alternative, however, will require major technology enhancements to the National Air Space (NAS) system, and order of magnitude advancements in affordability and performance for aircraft systems.

SATS Objective

The objective of the SATS program is to conduct integrated flight demonstrations of four new operating capabilities that are currently not possible today [2]. These operating capabilities are:

- Higher Volume Operations at Non-Towered/Non-Radar Airports. Simultaneous operations by multiple aircraft in non-radar airspace at and around small non-towered airports in near all-weather conditions through the use of vehicle-to-vehicle collaborative sequencing and self separation algorithms and automated air traffic management systems. Meeting this objective has the potential to safely expand the capacity of the NAS.
- Lower Landing Minimums at Minimally Equipped Landing Facilities. Precision approach and landing guidance, through the use of graphical flight path guidance and artificial vision, to any touchdown zone at any landing facility while avoiding land acquisition and approach lighting costs. Meeting this objective has the potential to safely reduce the cost for increasing accessibility to small airports.
- Increase Single Crew Safety and Mission Reliability to Two-Crew Levels. Increased safety and mission completion through the use of human-centered automation, intuitive and easy to follow flight path guidance, software enabled flight controls, and onboard flight planning/management systems. Meeting this objective has the potential to safely increase the throughput of the NAS.
- En Route Procedures and Systems for Integrated Fleet Operations. Integration of SATS equipped aircraft into the higher en route air traffic flows and controlled terminal airspace through the use of automated air traffic management systems designed to facilitate operations at non-towered airports and in non-radar airspace. Meeting this objective has the potential to safely reduce the need for ground holds.

The initial 5-year objective (2001-2005), SATSLAB, will address the President's and Congress' charge to NASA and the FAA to "prove that SATS works." SATSLAB is focused on demonstrating technologies to enable the use of existing small community and neighborhood airports, without requiring control towers, radar, and more land use for added runway protection zones. The key to such a system is a robust, extremely reliable automated communications system. Such a system must be capable of passing large amounts of data between aircraft and various ground systems as well as between neighboring aircraft in a reliable fashion [2].

To this end, NASA Glenn Research Center, through its partnership with NASA Langley Research Center, is pursuing a key enabling technology area: the Airborne Internet (AI). The Airborne Internet will leverage open standards and protocols for a client-server network system architecture that are in development in the telecommunications industry for increased bandwidth for mobile applications. SATS research will leverage the developments in NASA and FAA Airspace System Capacity (ASC) research on Distributed Air/Ground Traffic Management

(DAG-TM) collaborative decision-making. SATS research will focus on defining the functional allocations between clients and servers for all navigation, communications, and surveillance information necessary for aircraft operations including sequencing, separation, and conflict resolution [3]. A conceptual drawing of the SATS AI is shown in Figure 1.

The NASA SATS AI must successfully contribute to the scheduled SATS Technology Demonstrations in 2003-5 and to the future SATS flight operations. The development of the SATS AI Testbed is one of the first steps in supporting the NASA GRC Airborne Internet initiative. It will allow numerous communications technologies to be evaluated. Future growth of the SATS AI Testbed capabilities is a practical option as other communication means are evaluated, or as new communications capabilities are introduced.

The goal of the research program is to define and develop the Airborne Internet (AI) architecture to support the SATS flight experiments in 2003-5. The work effort involves research and experiments necessary to define the AI architecture. The areas of investigation are:

- The definition of the CNS requirements that the AI would support.
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- The identification and evaluation of the available CNS technologies that could provide the most robust yet realistic SATS system proof-of-concept evaluation in 2005.
- The definition and evaluation of candidate AI architectures leading to the selection of a single architecture for the 2003 flight experiments.

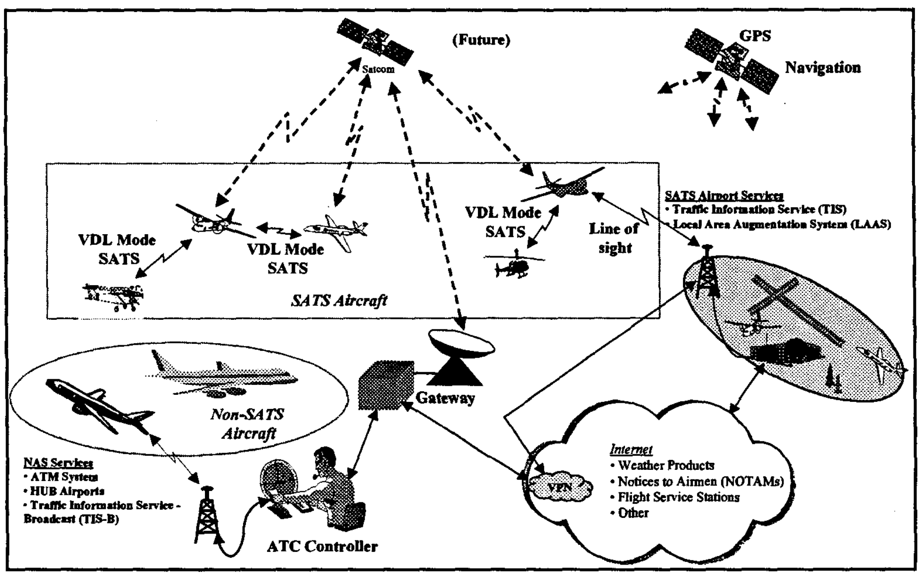

Figure 1. Airborne Internet - A Key Enabling Technology to Realize the SATS Vision

Task Methodology

Figure 2 presents the overall task plan and relationships for the activities associated with the definition of the AI. There are basically four major tasks involved:

- AI Requirements
- NAS Infrastructure Assessment
- Technology Assessment
- AI Architecture Development and Evaluation (Testbed)

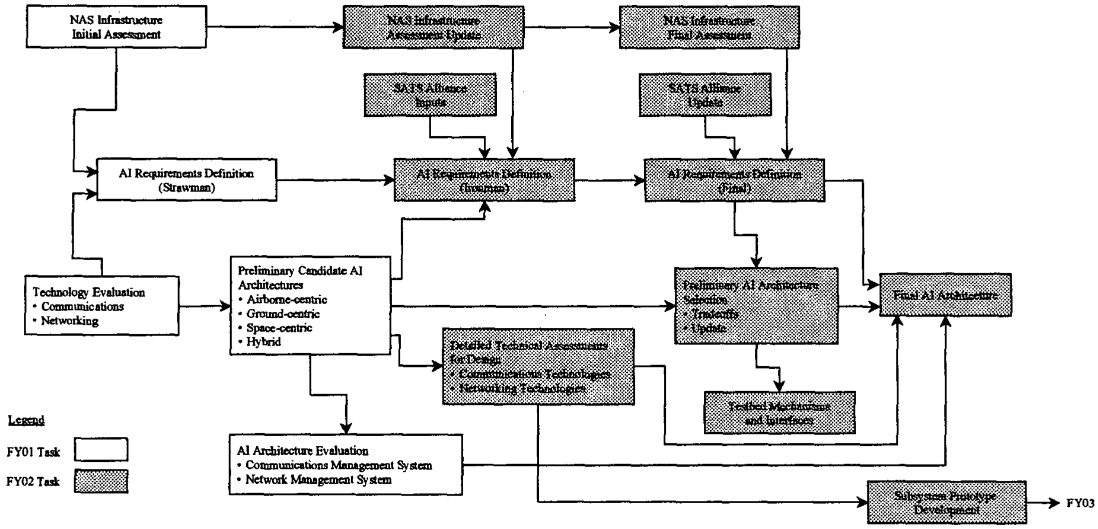

Figure 2. Task Flow Diagram

AI Requirements Definition Process

The process of defining the AI requirements (Figure 3) started with the development of a set of operational concepts for the SATS aircraft [4].

These concepts describe the SATS operational environment. Next, operational services were defined based upon the forecast concepts and a set of information exchange objects was defined to support this exchange. Reference models were also developed to show the entities with which a SATS user would communicate.

Reference Models

The development of reference models aided in understanding the information (data) exchange environment. The SATS reference model is shown in Figure 4.

The SATS aircraft is at the center of the model universe. Each of the entities is shown in a rectangle and the interface between them identified with a letter.

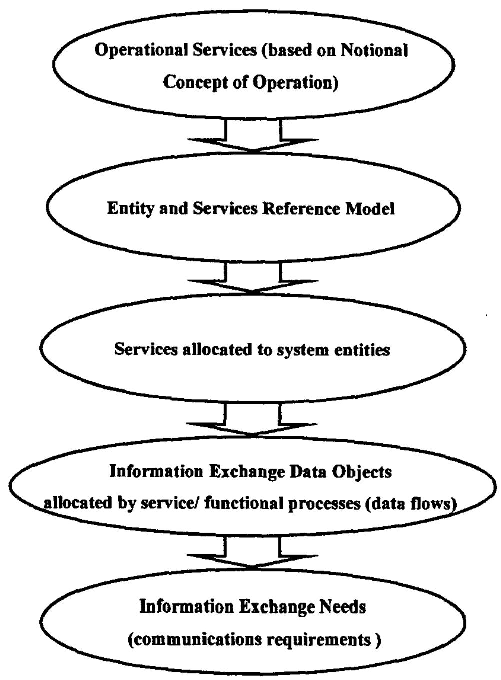

Figure 3. AI Requirements Identification Methodology

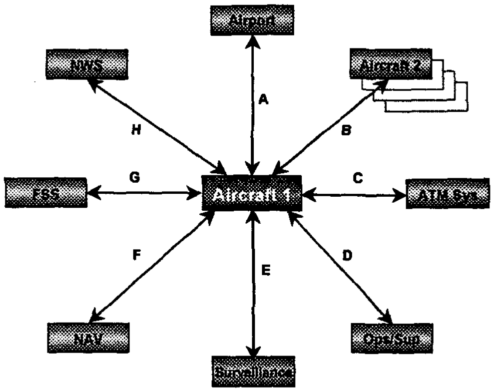

Figure 4. SATS Reference Model

The entities are:

- Airport represents the Fixed Base Operator (FBO).
- Aircraft 2 is one or more SATS equipped aircraft.
- ATM Sys represents the FAA's Air Traffic Management System.
- Ops/Sup stands for the operators/owners of SATS aircraft (e.g., aircraft rental agencies, flying clubs, etc.) plus other suppliers that would be involved with the SATS aircraft. It also represents suppliers associated with the SATS "doorstep to destination" concept such as rental car agencies.
- Surveillance is the ground-based system that broadcasts positional data for all aircraft within a specified region.
- NAV represents the system that is broadcasting navigation information in reference to a location. The only NAV system considered viable to use the AI as its transport mechanism is the Local Area Augmentation System (LAAS).
- FSS represents the Flight Service Stations. Many of them currently provide services (e.g., weather, NOTAMs, etc.) through web sites. The FSS supports pilot recorded flight plans via telephone today, and is expected to support flight plans filed by email in the near future. These sites could be accessed if a SATS gateway into the Internet is available.
- NWS is the National Weather Service. It too provides weather data including graphical NEXRAD reports via its web site.

The services available to a SATS user require that information be exchanged between the user (pilot, aircraft, and passengers) and the external entities (other aircraft and ground-based systems). For purposes of modeling, information exchange objects were defined, which are described in Table 1. Next was the development of the parameters that are associated with the transmission of each of the information exchange objects. The objects and their parameters were used in developing the data communications load associated with a typical 2-hour flight by a SATS aircraft. The results from modeling the communications requirements of a single SATS aircraft were analyzed and adjusted to describe the communications load to be supported by the AI for all aircraft within a 50 mile radius of a SATS airfield.

Operational Services/Entity Match

Providing operational services to the SATS user involves all of the entities shown in the reference models. Insight into communications requirements can be achieved by matching the operational services with the entities that will support those services. An example is shown in Table 2.

Operational Services/Information Exchange Object Match

Additional insight into the communications requirements associated with SATS operational services can be gained by matching the services with the information exchange objects that are involved. An example of this matching is shown in Table 3.

Table 1. Information Exchange Objects

FPU:	Flight Planning and Use: Submission and processing of original or revised flight plans.
WX:	Weather: Collection and exchange of weather data both forecast and current (FIS-B like)
AS:	Airspace Situation: Information to enable a common situational awareness (ADS-B /TIS-B like).
MC:	Maneuver & Control: Near real time exchange of data to direct or implement the maneuvering of an aircraft (CPDLC like).
NAV:	Navigation Information: Information to provide airborne and surface navigation guidance.
ASI:	Aviation System Information: Information regarding the current status, use or readiness of the system entities.
PAE:	Pilot/Aircraft Information Exchange: Pilot-to-pilot or aircraft-to-aircraft exchange of flight information.
AT:	Aircraft & Travel: Exchange of aircraft status and other travel related information.
PIE:	Public Information Exchanges: Passengers use of email and other Internet-based services.

Table 2. Operational Services and Entities

Flight Services		A/C 1	A/C 2	A/P	ATM Sys	Ops/ Sup	Surv	NAV	FSS
<u>Purpose</u> Provide a lost comm separation plan. Provide SAR information .	<u>Functions</u> File flight plans and amendments. Process flight plans and amendments. Provide information for flight plans. Obtain in-flight or pre-flight weather and NAS status (NOTAMs) advisories. (*Near real time and forecast, tactical and strategic*) Obtain in-flight or pre-flight traffic advisories. (*Existing tactical and strategic*) Obtain in-flight NAS status advisories – current and scheduled.	X			X				X

Table 3. Operational Services and Information Exchange Objects

Flight Services		FPU	WX	AS	MC	NAV	ASI	PAE	AT	PIE
Purpose Provide a lost comm separation plan. Provide SAR information.	Functions File flight plans and amendments. Process flight plans and amendments. Provide information for flight plans. Obtain in-flight or pre-flight weather and NAS status (NOTAMs) advisories. (*Near real time and forecast, tactical and strategic*) Obtain in-flight or pre-flight traffic advisories. (*Existing tactical and strategic*) Obtain in-flight NAS status advisories – current and scheduled.	X	X	X			X			

Aircraft Communications Load Model

The operational services/information exchange object matrix shows all of the objects associated with each service. Since the same object supports multiple services, the matrix cannot be used directly to gain insight into the communications load experienced by a SATS aircraft in flight. A spreadsheet model was created to gain insight into the communications load experienced by a single SATS aircraft. The model was based upon a two-hour flight with the following segments: departure - 15 minutes, en route - 85 minutes, and arrival - 20 minutes.

The model was based upon 250 aircraft being within a 50-mile radius of a SATS airfield. The number of aircraft in the area is significant because it is the basis for the size of the airspace situation (AS) message. The AS broadcast (analogous to Traffic Information Service – Broadcast (TIS-B)) contains data generated by the ground-based surveillance system. More aircraft in the area results in a larger message.

The FPU, MC, ASI, AT and PAE objects were assumed to be transmitted via addressed messages. The AS, WX and NAV objects used a broadcast transmission scheme. Protocol overhead was added to each message that was transmitted.

The messages associated with the objects were grouped into either a human and system message category. A human message is one that has to be processed by a person. Processing can be preparing the message, reading it, or just acknowledging it. A system message is one that is generated or processed by systems on board the aircraft.

A graphical depiction of the flight profile is shown in Figure 5. Figure 6 shows the communications load by type for a single aircraft throughout its flight. It is clear from looking at Figure 6 that the vast majority of the communications load is attributed to system messages. The average communications load attributed to system messages is almost 300 times that of human messages (171.8 Kb/min vs. 0.6 Kb/min). The average communications load attributed to a single SATS aircraft is 172 Kb/min.

The modeling activities yielded the communications load attributed to a single SATS aircraft. One goal of the AI effort is to reduce the number of transmission mediums needed to support the SATS aircraft. Achieving this goal should reduce the number of radios and antennas needed aboard the aircraft, but the bandwidth must be sufficient to support all of the aircraft that are using it.

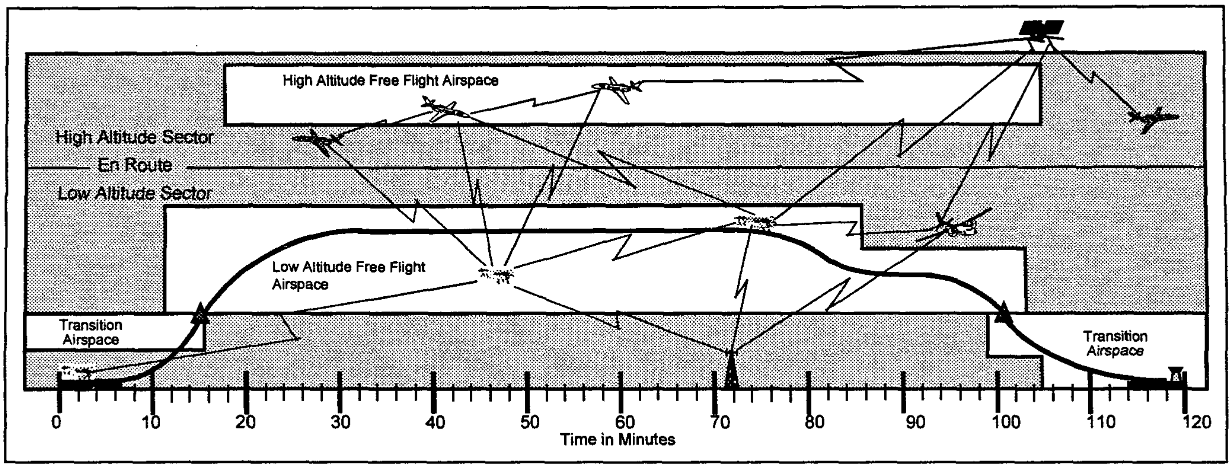

Figure 5. Typical Flight Profile

Airborne Internet Air/Ground Messages	Human	System	Total
Total Load (Kb)	70	20,611	20,681
Average Message Size (Kb)	1.3	2.7	2.0
Average Load/Minute (Kb/min)	0.6	171.8	172.3
Total # Messages	55	7,671	7,726
Average # Messages/Minute	0.5	63.9	64.4

Figure 6. Communications Load by Type

There are two areas where the single aircraft model results have to be adjusted. Although SATS aircraft #1 will only use the Local Area Augmentation System (LAAS) as an aid to navigation during departure and arrival, other aircraft in the vicinity will be using it while aircraft #1 is in the en route segment of its flight. Thus, the bandwidth must accommodate the continuous use of the LAAS.

A second adjustment is associated with weather data that is transmitted by the aircraft. The bandwidth must accommodate multiple aircraft transmitting weather data. The assumption used was that 25% of the aircraft would transmit weather data from its sensor.

Finally, the bandwidth must accommodate addressed communications from each aircraft in the area. Thus, the single aircraft requirement is multiplied by the number of aircraft in the region.

The resulting bandwidth requirements are shown in Table 4. The table also shows the communications load requirements by addressed and broadcast transmission scheme. Based on 250 aircraft, the AI bandwidth requirement is 11.8 Kbps.

Table 4. Model Results

All Messages	FPU	MC	ASI	AT	PAE	AS	WX	NAV	Total
Message Load - Flight (Kb)	3,250	10,000	900	3,300	18,000	15,984	13,192	20,304	84,930
Average Message Load (Kbps)	0.45	1.39	0.13	0.46	2.50	2.22	1.83	2.82	11.80
Addressed Messages	FPU	MC	ASI	AT	PAE	AS	WX	NAV	Total
Message Load - Flight (Kb)	3,250	10,000	900	3,300	18,000				35,450
Average Message Load (Kbps)	0.45	1.39	0.13	0.46	2.50				4.92
Broadcast Messages	FPU	MC	ASI	AT	PAE	AS	WX	NAV	Total
Message Load - Flight (Kb)						15,984	13,192	20,304	49,480
Average Message Load (Kbps)						2.22	1.83	2.82	6.87

NAS Infrastructure Assessment

The purpose of the NAS infrastructure assessment was to identify, assess and tradeoff the various issues and concepts involved in the SATS relationship with the NAS Infrastructure. Information about the programmatic and technical aspects of the NAS infrastructure as they relate to communications, navigation and surveillance functions were gathered and evaluated. Methods for interfacing the communications and networking technologies with the NAS infrastructure were also evaluated [5]. Activities performed in this task included:

- Assessing today's NAS for its ability to accommodate the SATS objectives in context of the Airborne Internet development and implementation.
- Identification of NAS interface services
- Assessing the modernization plans of the NAS for their ability to accommodate the SATS objectives in the context of the Airborne Internet development and implementation.
- Identification of Interface Concepts and Issues
- Identification of candidate interfaces
- Performance of an assessment and trade-off analysis of the candidate interfaces
- Identification of communications spectrum utilization as it relates to airborne operations

SATS aircraft use of the NAS will include operations in virtually all classes of airspace. Some SATS flights will originate in uncontrolled airspace, then transition into controlled airspace at flight plan coordinated fixes and times. SATS aircraft may transit the NAS at virtually any altitude, but will likely operate at altitudes between the Minimum En Route Altitude and Flight Level (FL) 220. SATS flights in controlled airspace will comply with the operational requirements of the airspace in use. Arrival and landing operations will be conducted at all levels of control, from TRACON airspace to uncontrolled approaches and landings at non-towered airfields.

In the current NAS, the focus is on sustaining essential air traffic control services and delivering early user benefits. Today Flight Service Stations (FSS) provide accurate and timely aviation weather, aeronautical information, and flight planning assistance to commercial and general aviation. This information is obtained directly from an FSS via telephone or by using a personal computer to access the FSS via the Internet. Current pre-flight and in-flight service functions include:

- Filing instrument flight rule (IFR) and visual flight rules (VFR) flight plans.
- Providing VFR flight following.
- Providing broadcast messages.

- Providing user access to weather briefings.
- Disseminating NOTAMs
- Processing and disseminating pilot reports (PIREPs)
- Providing emergency services.
- Providing other services as needed.

Computer Networks & Software, Inc. developed a SATS Operational Concepts document, which identified a set of services that will be provided by the NAS and used by the SATS [4]. This set of services is used to assess various interface approaches. The FAA is deploying a number of technologies and systems to implement these NAS services. The services are summarized in Table 5. The table also indicates the feasibility of providing these services to SATS aircraft via a Mode SATS or SATCOM AI.

Table 5. NAS Infrastructure vs. SATS User Services

SATS User Services	NAS Systems	NAS Data Link Medium	SATS AI Medium
Flight Service	FIS-B, DUATS, OASIS, AFSS, TWIP, D-ATIS, TAMDAR	VHF Broadcast, VHF to Internet, SATCOM to Internet, VDL M2, UAT, Mode S (1090 MHz) VDL M4	VHF Mode SATS, SATCOM
Air Traffic Service	TIS, TIS-B, CPDLC	UAT, Mode S (1090 MHz) VDL M2, VDL M3	VHF Mode SATS, SATCOM
Emergency and Alerting Service	TIS-B, CPDLC	UAT, Mode S (1090 MHz) VDL M2, VDL M3	VHF Mode SATS, SATCOM
Self-Separation and Sequencing Service	TIS, TIS-B	UAT, Mode S (1090 MHz)	VHF Mode SATS, SATCOM
Navigation Service	LAAS	VHF	VHF Mode SATS
Pilot/Aircraft Information Service	Voice	VHF	VHF Mode SATS
Aircraft and Travel Service	Internet	VHF to Internet, SATCOM to Internet	VHF Mode SATS, SATCOM
Public Information Exchange Service	Internet	VHF to Internet, SATCOM to Internet	VHF Mode SATS, SATCOM

Technology Evaluation

A mock AI architecture was used as the basis for broadly identifying areas of relevant AI-related technology. This aided the investigators in narrowing the scope of the search range required to inventory the known and emerging technology [3].

A survey of the potential technologies that could be of possible use to satisfy requirements of the AI was conducted. The term technology is defined in the broadest terms of techniques, components, systems, and services. The inventory task produced a list of the technologies and reference identifications for further information.

The investigators developed a set of top-level criteria to use in screening the identified technologies. The filter elements include such factors as:

- Performance
- Cost
- Availability to support the AI Development Milestones
- Scalability

Using these criteria an assessment of the identified technologies was performed, where applicable. A list of the technologies was then identified for further assessment. The technologies selected are shown in Figures 7 and 8.

Tool Kit	Technologies
1 / Wireless	VDL M2-B, VDL M4, VDL M3, UAT
2 / SATCOM	Inmarsat INM 3 & 4, GlobalStar/ Qualcom
3 / Cellular	3GPP, UMTS, Aircell
4 / LAN	802.11, ARINC 664
5 / Protocols	ATN, IPv4, IPv6, VoIP, IPSec, Mobile IP, QoS, Multicast, Self Organizing MANET, P-P, CDMA, IP Over M2, M3, M4
6 / Navigation	LAAS, WAAS
7 / Surveillance	ADS-B, TIS-B, TIS

Figure 7. Near-term Technologies

Tool Kit	Technology	Comments
Wireless	VDL Mode 4 - Like	Wider bandwidth
SATCOM	Packet Mode - C Band	Wider bandwidth
	K Band	Weight, size, and power
	Motient	Collect Information
	Inmarsat 3 & 4 - MPDS	Collect Information
Cellular	UMTS for ATC	U.S. ATC suitability

Figure 8. Technologies for Further Research

AI Architecture Development and Evaluation (Testbed)

The AI System testbed is intended to simulate a real world SATS environment. It provides a "hands-on" technical platform to assess the principles and design of the Airborne Internet concept. In addition, the SATS AI testbed provides an affordable platform using commercial-off-the-shelf products and an excellent base for additional technology insertion.

Installed technology includes VHF Data Link (Mode SATS), TCP/IP, and peer-to-peer connectivity. The testbed demonstrated the use of real communications applications, including Automatic Dependent Surveillance – Broadcast (ADS-B), Aeronautical Telecommunications network (ATN)-compliant Context Management (CM) and Controller Pilot Data Link Communications (CPDLC), Flight Information Service – Broadcast (FIS-B) graphical weather products, pilot-to-aircraft information exchange, and email.

VDL Mode SATS Subnet

The subnetwork plays a significant part in defining the SATS Airborne Internet Architecture. SATCOM and VDL Mode SATS, among others, offer potential for the AI. The SATS Testbed simulates the proposed Airborne Internet by emulating one of the candidate subnetworks, VDL Mode SATS

The AI Testbed employing the VDL Mode SATS subnetwork is shown in Figure 9. The testbed uses six VDL Mode SATS radios – one emulating the ground side and five emulating the aircraft side. The radios have the capacity for four separate 25 kHz channels, but only one was needed to handle the SATS communications load. As described in the section on the communications load model, the load imposed by 250 aircraft is within this single-channel capability. The radios transmit into dummy loads and attenuators. The ground and the aircraft workstations are connected by a common LAN to the test driver and data logger (residing in the ground workstation). The ground workstation can also contact the external Internet for weather-related data and other information.

VDL Mode SATS employs a Self-organizing Time Division Multiple Access (STDMA) scheme where all operators use the same set of frequencies to transmit and receive position and state vector messages (often called *sync bursts*). "Self Organizing" means that each user, rather than a central controller, evaluates the network traffic and assigns itself time slots. As part of its sync burst, each mobile user transmits a time slot reservation for its subsequent transmissions. All monitor the channel, track, and abide by this reservation information to prevent simultaneous use of the same time slot on a channel. When nearly all of the time slots are in use, there is a provision for two users to occupy the same time slot. In this way, reception range degrades gracefully as the number of users increases above the number of available time slots.

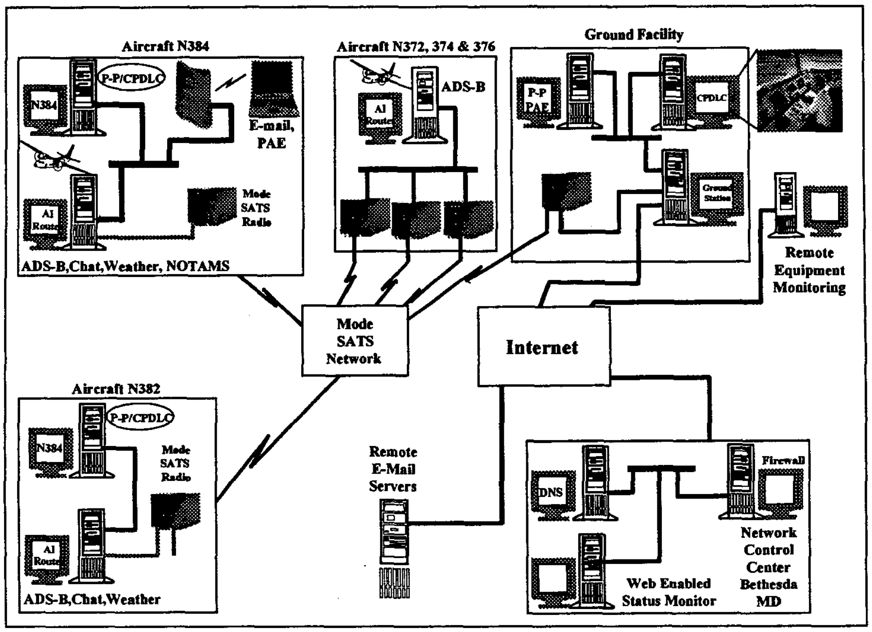

Figure 9. Mode SATS Testbed Architecture

Summary and Conclusions

The AI System testbed is intended to simulate a real world SATS environment. The initial SATS AI Testbed has been developed using the VDL Mode SATS radio and application emulators. The test bed demonstrated "all-in-one" connectivity, using a single radio for all applications, including Automatic Dependent Surveillance – Broadcast (ADS-B), Aeronautical Telecommunications network (ATN)-compliant Context Management (CM) and Controller Pilot Data Link Communications (CPDLC), Flight Information Service – Broadcast (FIS-B) graphical weather products, pilot-to-aircraft information exchange, and email. Installed technology includes VHF Data Link (Mode SATS), TCP/IP, and peer-to-peer connectivity. Hardware and software components from many suppliers were integrated into the testbed.

Early Proof of Concept tests and evaluations have proven that the AI is a viable concept. The promise of the SATS AI Testbed is in the ability to establish temporary network connections with SATS development teams. These connections can provide the necessary active connection interface development and testing capability to realistically exercise and prove the SATS AI concept while supporting the development and integration of the SATS airborne technology. This configuration and integration work represents a "one-of-a-kind" rapid prototype of the Airborne Internet.

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