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Next Generation Satellite Systems for Aeronautical Communications

by Ozgur Ercetin, Michael O. Ball, Leandros Tassiulas

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Next Generation Satellite Systems for Aeronautical Communications

Özgür Erçetin[*]
Institute for Systems Research and Electrical and Computer Engineering Department,
University of Maryland,
College Park, MD 20742.
Tel: (301) 405-6558.
ercetin@isr.umd.edu
[*]***Corresponding author***

Michael O. Ball
Institute for Systems Research and Robert H. Smith School of Business,
University of Maryland,
College Park, MD 20742.
Tel: (301) 405-2227.
mball@rhsmith.umd.edu

Leandros Tassiulas
Institute for Systems Research and Electrical and Computer Engineering Department,
University of Maryland,
College Park, MD 20742.
Tel: (301) 405-6620
leandros@isr.umd.edu

Abstract: *The US airspace is reaching its capacity with the current Air Traffic Control system and a number of flights that is constantly rising, and estimated to be over 54 million per year by 2002. The FAA has undertaken several projects to modernize the National Airspace System (NAS) to ensure the safety of the increasing number of flights. Of special importance is the modernization of the Air-Ground (A/G) Communications infrastructure, which is the heart of the air traffic control (ATC). The current plan in the modernization of the A/G communications is to migrate from analog voice only system to integrated digital voice and data system. The next generation satellite systems can be an alternative to the terrestrial A/G systems by their low propagation and transmission delays, global coverage, high capacity, and free flight suitable characteristics. In this paper, we give an overview of the current and the future ATC architectures, describe the systems and the communications issues in these systems, and develop a framework in which LEO/MEO next generation satellite systems can be integrated to the future ATC systems.*

1 Introduction

Air travel has become an integral part of our lives. Every year over 48 million flights take place in US alone including commercial, military and general aviation flights. As air traffic volume has steadily increased, assuring the safety and efficiency of the US National Airspace System (NAS) and the broader world-wide airspace system has become one of the foremost systems engineering challenges of the 21st Century. The various national organizations responsible for air traffic management work together through the International Civil Aviation Organization (ICAO) to develop global air traffic regulations and standards. In the US, the Federal Aviation Administration (FAA) has responsibility for developing, operating and maintaining a safe, productive and efficient air traffic management system. The traditional

NAS includes navigation tools such as VOR (VHF omni-directional Radio) and TACAN (Tactical Air Navigation) for flight routing and surveillance via RADAR, weather observation systems such as AWOS/ASOS (Automated Weather/ Surface Observation System) for timely delivery of important weather changes and air/ground, ground/ground communications systems for air traffic control communications between pilots and controllers. Advanced navigation and surveillance systems are now emerging based on technologies such as GPS (Global Positioning System) and ADS (Automated Dependent Surveillance).

While aviation technological issues are extremely challenging, the political and economic issues may be equally (and some would argue more) difficult. Airspace users include three diverse constituencies: commercial airlines, general aviation and the military. Any technological innovation requires varying degrees of coordination among several players, including the airlines, manufacturers of airframes, avionics equipment and communications, navigation and surveillance devices and national and international aviation authorities. A fundamental issue that underlies nearly all innovation in aviation is the over-riding concern with safety. The manner in which safety is insured and the catastrophic consequences of any safety compromises pervade all aviation-related decision making.

The safe separation of aircraft during flight is the essential task performed by air traffic control (ATC). Currently ATC services depend on air/ground (A/G) voice communication between pilots and the air traffic controllers established principally via ground based VHF and UHF radios. These links support all phases of flight including ground movements; departures and arrivals; and en route. Furthermore, A/G communications are used to transmit instructions and clearances, provide weather services and pilot reports.

The US air traffic control is considered to be one of the safest in the world, because of strict regulations, and the extensive coverage of the system. However air travel is continuing to increase, with more passengers, flights, and aircraft. The FAA estimates that with the current increase rate, there will be over 54 million flights annually by 2002. The current communications infrastructure is inadequate to service such a capacity with its outdated technology. In fact the system has changed so little in the past 30 years that the FAA was the largest buyer of the vacuum tubes in the US in 1996 (a $19 million annual expenditure). [1]

The FAA is developing modernization programs to update equipment and to improve efficiency [2]. These programs focus not only on A/G communications, but also on all aspects of the NAS including navigation, surveillance, and weather observations. Reliable, efficient and robust communications is an integral part of all of these programs. There is an inherent inefficiency in the NAS that is principally due to limitations of the technology currently in use: there is heavy reliance of air traffic controllers and flights adhere to a fixed route structure. The aviation community generally has strong agreement that future air traffic systems should incorporate some form of *free flight* and free flight has become the guiding concept behind the next generation of the National Airspace System (NAS). Under the present (pre-Free Flight) paradigm, air traffic controllers direct or approve all but the most sudden of aircraft movements and aircraft are restricted to air routes defined based on terrestrial surveillance and navigation aids. Free flight calls for the NAS to move to a distributed command-and-control system that allows aircraft systems to share responsibility for detecting and avoiding potential conflicts. Such a distributed architecture together with satellite-based navigation mechanisms will allow aircraft to follow the most efficient and economical flight paths, which typically would not be restricted to a fixed route structure. Satellite-based communications systems also play a major role in enabling free flight, in that the terrestrial communications infrastructure places restrictions on the structure of present air route system.

It seems clear that a goal for future air traffic systems should be the support of new applications, global connectivity, seamless integration and interoperability, rapid reconfigurability and flexibility for future growth. Satellite communications is an enabling technology well positioned to meet this aim. In this paper, we investigate the use of *Next Generation Satellite Systems (NGSS)* (focusing on LEO/MEO satellite systems) for aeronautical communications, with special emphasis on Air Traffic Control and Traffic Flow Management communications.

Initial studies have shown that such systems are *feasible* for aeronautical communications. In this report, we classify a few issues that should be further investigated before such systems are *accepted* for aeronautical use. We also develop an evolution strategy for the introduction of such systems into the NAS. Specifically, we develop a chronological timetable such that NGSS can be used in the NAS starting with some near-term applications (very few users have the necessary equipage) and finally reaching to the longer-term more sophisticated applications (most of the users have the necessary equipage).

The structure of this report is as follows: In section 2, we give a brief overview of the current air traffic control procedures. We discuss the current air-to-ground communications, and their requirements and deficiencies in section 3. Current activities to improve the NAS architecture are also discussed in this section. In the following section, we give a brief overview of next generation satellite systems. In sections 5, and 6 we develop the model for our NGSS study, and discuss the several research problems, that may arise in aeronautical NGSS communications.

2 Overview of Air Traffic Control

The safety of air travel is ensured by many mechanisms working precisely and cooperatively. Aircraft use navigational equipment and aides and follow Visual Flight Rules and/or Instrument Flight Rules (VFR/IFR) to precisely follow their flight path. *Air Traffic Control* ensures that no two aircraft have conflicting flight paths. The FAA has established federal airways where the necessary air traffic control is provided for safe air travel. These federal airways consist of necessary ground navigational aids for precise navigation of the aircraft, flight service stations for weather advisories, and radio communication facilities for the air traffic controller-to-pilot communications. [3]

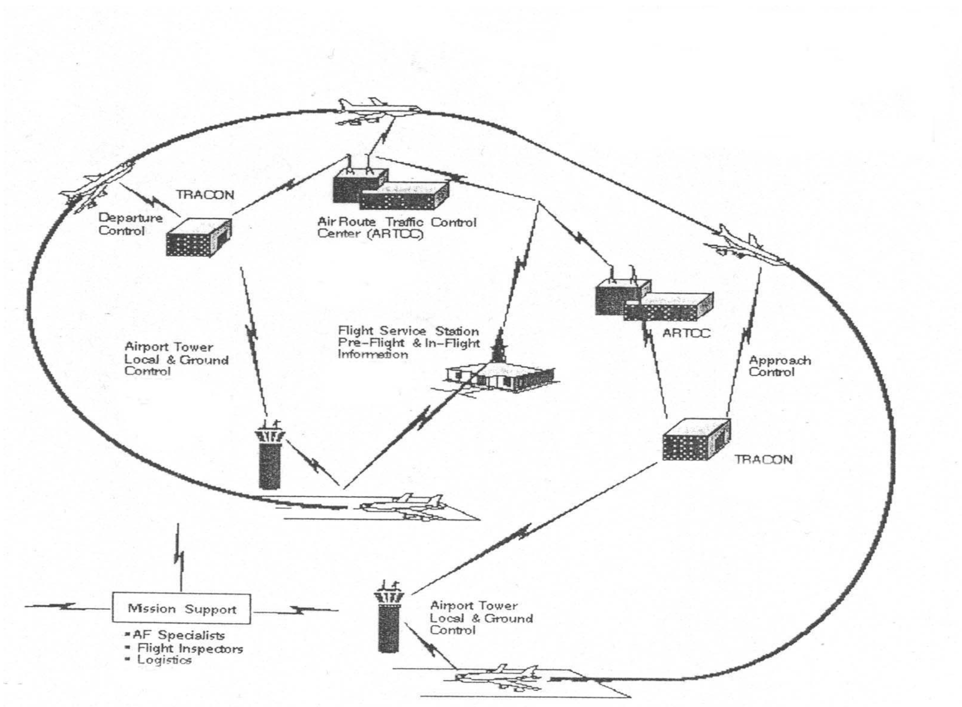

Figure 1-Present NAS Air Traffic Control Structure [2]

The FAA has established procedures to be followed in these federal airways for the accurate control of air traffic (Figure 1). Prior to a flight, the aircraft files a flight plan to its departure Air Route Traffic Control Center (ARTCC). The flight plan consists of the requested flight route, the duration of the flight, the requested altitude, etc. The local ARTCC gives clearance to the flight with possible amendments, and changes. When the flight is cleared, the departure of the airplane is controlled by the local airport tower. The tower is responsible for the safe landing and takeoff of the aircraft, as well as safe taxiing on the ground. The airport control tower is also responsible for safe separation of the aircraft within a 5-mile radius of the airport. When the airplane takes off, it communicates its flight information to the departure Terminal Radar Approach Control (TRACON), which relays this information to the local ARTCC. This information is further disseminated to other ARTCC 's that are en route of the airplane. The TRACON is responsible of safe separation of aircraft within a 50-miles radius of the airport (also called the *terminal area*). The air traffic control of an aircraft flying outside a 50-miles radius of its arrival and departure airports is the responsibility of the ARTCC 's.

Thus, the air traffic control of an aircraft is performed in three stages: Ground and departure control by Air Traffic Control Towers (ATCT), terminal area control by TRACON, and en-route control by ARTCC. There are 21 ARTCC 's covering the flight routes in the continental United States. Each ARTCC is responsible for a portion of the airspace. This airspace is further divided into subportions called *sectors*. There is a controller and fixed radio frequency assigned to each sector. The controllers communicate with the aircraft in their sector via this fixed multi access voice channel, and provide altitude, heading information to the pilots, as well as weather advisories for flight safety. The current communication system is an analog, voice-only system. Communication between the controller at the ARTCC and the pilot is relayed via Remote Communications Air/Ground (RCAG) stations located throughout the USA. As the aircraft flies on its path, it changes sectors (Figure 2). At every sector change the control of the aircraft is *handed over* to the receiving controller – the transferring controller provides the aircraft with the new frequency to be used for communication with the receiving controller. As the aircraft approaches its destination airport the transfer of responsibility is reversed, and the control of aircraft is first transferred to the destination TRACON and then to the airport control tower. [3]

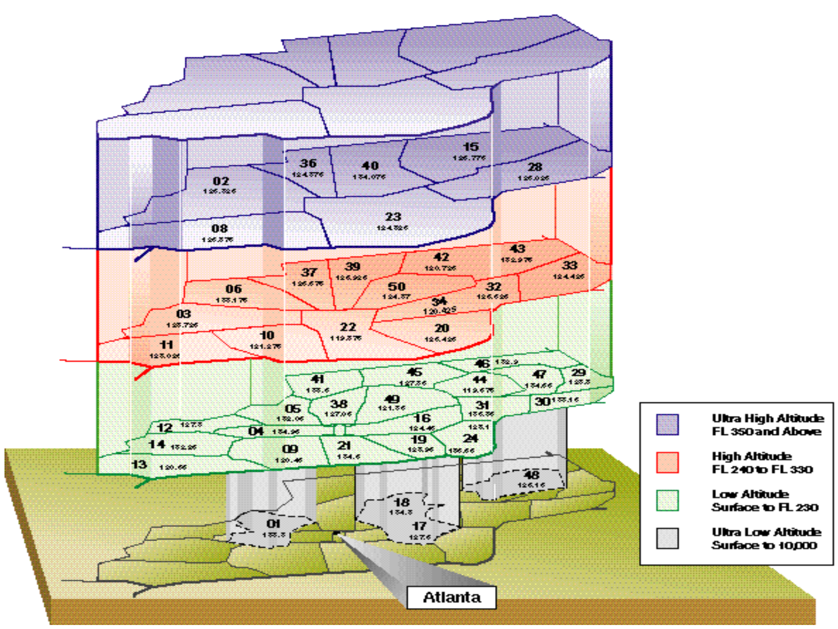

Figure 2: Sector Overview: Atlanta Center Airspace, 46 three-dimensional sectors. [4]

3 Overview of Air Ground Communications

3.1 Types of Communications

The NAS consists of both ground-to-ground and air-to-ground communication systems. Ground-to-ground communication systems interconnect all ground facilities to each other. Air-to-ground (A/G) communication systems provide pilot-to-controller (specialist) communications. In this paper, we focus on the A/G communication systems. The Air Ground Communications can be divided into two main categories: [2], [5]

SAFETY COMMUNICATIONS

- Air Traffic Services (ATS)

  Air traffic control, weather and flight information services

- Aeronautical Operational Control (AOC)

  Dispatch, flight planning, weather, maintenance communications involving safety and regularity of flight, and independent company communications required by federal aviation regulations.

NON-SAFETY COMMUNICATIONS

- Aeronautical Administrative Communications (AAC)

  Cabin provisioning, passenger-related and other company communications not directly associated with safety and regularity of flight.

- Aeronautical Public Correspondence (APC)

  Public correspondence, personal communications by/for passengers and crew.

A new type of communications need that is emerging, and should be considered separately, is communication for *Air Traffic Flow Management*. In the future NAS architecture, airlines will be given much more flexibility relative to the control of their aircraft. At the same time, the amount of air traffic will increase. To simultaneously accommodate greater airline control and increased traffic, new traffic flow management mechanisms are being developed based on Collaborative Decision Making (CDM) [6]. Under CDM, traffic levels will be monitored very closely in real time and accurate predictions of future traffic levels will be formulated based on intent information obtained from the airlines and aircraft. This traffic information will be disseminated to the airlines, and as appropriate, to individual aircraft. In order for an airline to achieve the most efficient routes for its fleet, including real-time rerouting to avoid points of congestion, new information exchanges among the airline operational control centers (AOCs), the aircraft and the FAA will be required. This class of communications represents an emerging, yet-to-be-defined demand for aeronautical communications.

3.2 The Current A/G Communication System

3.2.1 A/G voice and data communications

Every controller is responsible for the separation of the aircraft in his/her *sector*. The controller of a sector is assigned a fixed 25 kHz AM Double Side Band voice channel for the air traffic control communications with the pilots of the aircraft in his/her sector. The communications between the controller and the pilot of an aircraft is carried out in a party-line/broadcast mode so that all the aircraft in the same sector can monitor all controller-to-pilot communications in that sector. The controllers are located in the ARTCCs. The A/G communication between the controllers and the pilots is accomplished by over 40,000 radios located at 2,500 different sites. The spectrum that is reserved for air traffic communications is VHF 117.975MHz-137MHz for civilian applications and UHF 225MHz-400MHz for military applications.

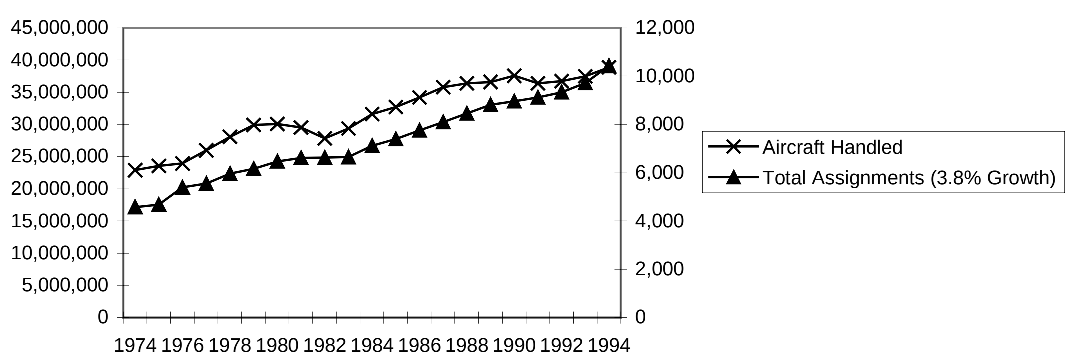

Figure 3- The increase in air traffic [7]

From 1974 through 1995, the NAS has experienced an annualized growth rate of approximately 3.8% in the number of flights. Due to this growth, the flight levels are reaching the current NAS radio communication capacity limits, especially in the terminal areas. Historically, one approach in obtaining new radio channels has been to reduce the channel bandwidths. The A/G voice channel bandwidth has been reduced in time from 100 kHz to 50 kHz and finally to 25 kHz. The increase in the number of channels by reducing the bandwidth has come with its cost – channel interference has increased. Due to the current growth projections with large increase in channel requirements for the NAS modernization, the FAA ruled out further reduction in channel bandwidth. However, the European aviation administrations are still considering some plans to increase the number of channels by reducing the channel bandwidth to 8.33 kHz. [2]

The channel assignments over the continental USA are all interrelated. In order to provide a few new A/G radio channels to one location, a considerable number of channel reassignments have to be made. For example, it is determined that 22 frequency reassignments are required in order to provide 3 new radio channels to the Chicago TRACON. [7]

Currently, the FAA does not own the necessary equipment to provide an en-route Aeronautical Data Link (ADL) service. The FAA leases data link services from ARINC, Inc., to provide Pre-Departure Clearances (PDCs) at over 30 airports. These services are based on the twenty-year-old analog ACARS [8] data link technology, and are generally considered outdated and spectrally inefficient. They do not provide message priority-preemption-precedence, and thus are not suitable for time critical ATC communications. Currently the data link services are primarily used for internal airlines applications such as, providing gate or schedule information for connecting flights. ARINC currently provides data link services to over 5,400 aircraft, with almost 100% coverage of the federal airways in the continental USA. They have also established infrastructure in Europe, and provide an HF Data Link service over the oceans, and the North Pole. ARINC also provides the GLOBALink® Satellite Service for aircraft with satellite communications equipment. [8]

The current use of satellites for ATC communications is quite limited due to the high round-trip delay and the high on-board equipment (purchase and certification) costs to use GEO satellite systems, which are the primary satellite systems of today. Satellite Communications (SATCOM) is primarily used for emergency communications by equipped aircraft (especially true for the transoceanic flights). Today pilots makes use of SATCOM by placing a phone call to the appropriate controller. The FAA has also developed FAATSAT program [2], to interconnect some radio sites to ARTCCs via satellites for communication diversity. Currently, there are also studies underway on connecting certain remote radio sites (especially those in Alaska) via IRIDIUM.

The inefficient use of the current radio resources is one of the main reasons for the insufficiency of the current NAS communication system capacity. The inefficiency is caused by both the spectrum inefficiency of the AM system, and the inefficiencies in the operation of this system. In the current voice-only analog system, all airborne and ground users share the same channel. Thus, as the number of users grows, voice congestion increases. Furthermore, the channel may become completely unusable by channel blockage, a problem caused by "stuck microphone" (the switch on the speaker of the radio is left on). The 25 kHz AM-DSB channel is also susceptible to interference, which may cause difficulties for the pilots and the controllers to understand each other. User addressing is verbal through the use of the flight's call sign. Thus, continuous pilot monitoring is required to identify transmissions directed to the cockpit. The communication structure is also inefficient; for example 1 in 7 ATC messages are hand-off messages exchanged during the change of sectors. All of these problems result in low system message throughput. The AM radio equipment is outdated, and requires high maintenance. The reliability of the overall communications *system* is high – however, this is mainly due to high redundancy in a system made up of failure-prone components. The high redundancies and maintenance requirements, result in a significant financial burden on the part of the FAA, just to keep the system running.

3.2.2 Present Air/Ground Communication Infrastructure

NAS A/G communications is supported by [9] (see Figure 4):

- 21 Air Route Traffic Control Centers (ARTCC) and 3 Center Radar Approach Controls (CERAP) supported by 793 Remote Communication A/G Facilities (RCAG) and 720 Back-Up Emergency Communication (BUEC).
- 14 Flight Service Stations (FSS) and 61 Automated Flight Service Stations (AFSS) supported by 1854 Remote Communication Outlets.
- 57 Tower Data Link Services (TDLS) air traffic control towers supported by 393 Remote Transmitter Receivers (RTRs).
- 289 non-TDLS air traffic control towers supported by 1029 RTRs.

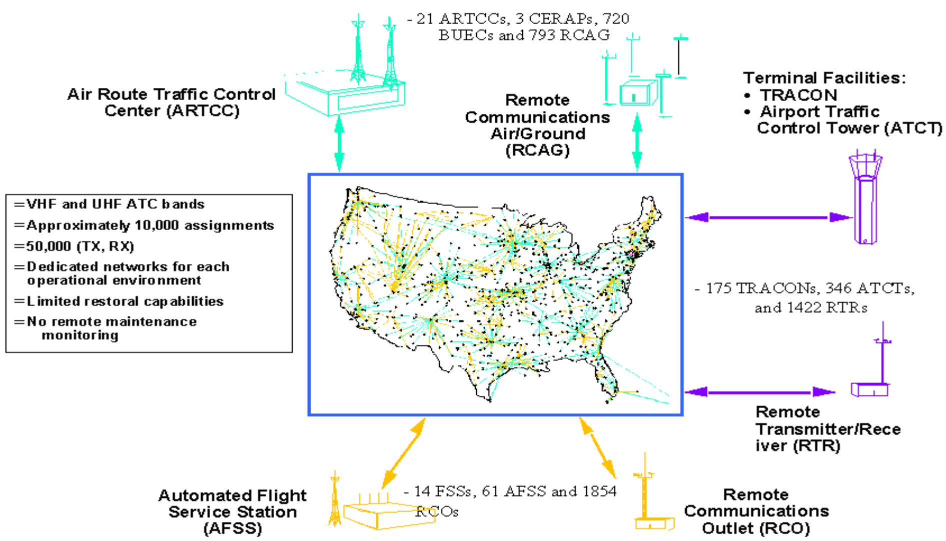

Figure 4-Present NAS Air/Ground Communications Infrastructure

The en-route air traffic controllers are located at the ARTCCs, and communicate with the aircraft in their sector via RCAGs and possibly via BUECs. The NAS employs approximately 46,000 DSB-AM radios. Telecommunications between existing sites are performed by 1,158 FAA owned circuits, and

5,601 leased circuits. Among these, 2,885 circuits are used for en route communication. The FAA leases 2,030 of these en-route communication circuits. [9]

Currently, there is almost one-to-one correspondence between BUEC and RCAG sites. BUEC sites provide backup to protect against the failure of all radios (primary and backup) at an RCAG station. BUECs are not co-located with RCAGs, in order to provide communication diversity to the primary sites. The primary radio sites, RCAGs, are located on the air traffic routes. However, in time some of these routes have changed. For this reason, at several locations, BUEC sites are used under non-failure conditions, since they can provide better communications quality compared to their RCAG counterparts.

3.3 Near Term Plans for Improving ATC A/G Communications

In order to solve the inefficiencies of the current A/G communication system, the FAA is pursuing a modernization program [9]. Under the proposed communications system, ATC A/G communications will evolve from primarily voice to primarily data. Aeronautical VHF radio systems will transition to digital modulation to improve voice quality and to increase channel capacity. VHF resources will be networked to make more efficient use of the resources and to support new capabilities, such as intrinsic backup. Voice communications will continue to be used for some communications such as, emergency or non-routine messages, and for those aircraft that are not data-equipped; AM voice will continue to be supported during the transition period.

3.3.1 Air-to-Ground Data Link

The data link is currently envisioned as an extension of the current voice communication system, with applications imitating their voice communication counterparts. The future Air Traffic Systems could be much different from today’s systems, and new applications that increase the benefits of the data link considerably may evolve.

Multiple data link standards have been developed: *VDL Mode S*, *VDL Mode 2*, and *VDL Mode 3*.

- VDL Mode S can provide two-way, domestic ATC communications, cooperative surveillance, and Automatic Dependent Surveillance Broadcasts (ADS-B). ADS is the latest surveillance technology being developed by the FAA that can provide accurate surveillance using a simple and relatively inexpensive cooperative system. Every participating aircraft periodically broadcasts surveillance data such as position, altitude, identification, and velocity. The system relies on a GPS global navigation system to determine the position and the velocity. [10]

- ARINC is updating its ACARS network to meet VHF Data link (VDL) Mode 2 [21], [13]. VDL Mode 2 uses a Carrier Sense Multi Access (CSMA) 25 kHz channel with 31.5Kbps differential 8-bit Phase Shift Keying (PSK). The capacity of a VDL Mode 2 channel is 2400 bps. This is almost ten times the capacity provided by the current ACARS data link. The planned ARINC VDL 2 network will have almost 300 sites over the continental US providing almost 100% en-route coverage by year 2000. The FAA will lease VDL Mode 2 data link services from ARINC, to provide Controller-to-Pilot Data Link Communications (CPDLC). CPDLC will take over the routine communications between the controller and the pilots, and thus will emulate the current voice communications. The VDL Mode 2 standard does not provide priority-preemption-precedence, and can not guarantee the timely delivery of the message. For these reasons time critical ATC communications can not be carried over VDL Mode 2.
- The FAA plans to use digital NEXCOM radios for both voice and data [9]. The data link standard for these radios is VDL Mode 3. The system is capable of reorganizing transfer queues so that high-priority traffic is sent before lower-priority traffic. The *Medium Access Control* sublayer of the VDL Mode 3 is different from VDL Mode 2, which is Time-Division-Multiple-Access (TDMA). VDL Mode 3 is designed to carry time-critical safety ATS communications.

3.3.2 NEXCOM Project

The FAA plans to replace all aging VHF AM radios with digital NEXCOM radios to increase the radio spectrum efficiency [9]. NEXCOM radios are based on 25KHz Time-Division-Multi-Access channels that use differential 31.5 kbps 8-bit PSK. The same frequency is used for both uplink and downlink. 3 or 4 time slot schemes may be used, where 3 slot provides long-range interference free communication (up to 609 nmi), and 4 slot provides short range interference-free communication (up to 200 nmi). The NEXCOM radios are designed to work both in analog AM and digital TDMA modes. The four time slot scheme may be used both for data and voice in 2 Voice – 2 Data (2V2D), 3V1D, 4V formats. Voice has 4.8 kbps encoding with 250 ms end-to-end propagation delay. Data can be used functionally simultaneously with voice. NEXCOM radios provide priority-preemption-precedence, for both voice and data communications. A ground controller's voice messages would always preempt the current airborne communication. Voice communication can be provided by push-to-talk action and data communication is done via reservation schemes.

The initial operation of this system is slated to be in 2002 in the form of AM voice communication over new NEXCOM radios. In 2008, digital voice will be in service for en-route communications. By 2010, data link services will be implemented at all ARTCCs. It is expected that the NEXCOM project will be completed by year 2020 with a total facilities and equipment cost of $794.9 million [9]. The length and the cost of the project may motivate the FAA to look for new systems that can be integrated with the NEXCOM system to reduce the total cost of the modernization while still supporting the projected applications. The LEO satellite systems have the potential to meet this aim.

3.3.3 Aeronautical Telecommunications Network (ATN)

The aviation community has generally agreed that all data sources and sinks (airborne or ground) should be interconnected via an Aeronautical Telecommunication Network (ATN). ATN is an internetwork of data networks that allows users to exchange data link messages between different subnetworks and data link systems without regard for which system is being used. The ATN is a point-to-point ISO/OSI packet mode data traffic network [11]. The ATN will choose the best links in terms of operating environment, technology, timeliness and integrity of the application to deliver the messages reliably. ATN will automatically route messages through the best networks and data links available, and will free both the user and the provider to implement the data link systems that they desire. The system requires both an airborne and a ground communication router, which connects the end-user systems with the different air-ground links and ensures reliable message delivery. Both in the air and on the ground, ATN is designed to guarantee the integrity and priority of the messages sent between airborne and ground users

4 Next Generation Satellite Systems

4.1 Overview of NGSS

The Next Generation Satellite Systems (NGSS) have evolved from analog transmission modes to using digital messaging techniques for communication. They use such sophisticated techniques as spot-beams, frequency reuse, inter-satellite links, on-board processing, TDMA and Code Division Multiple Access (CDMA) techniques and their constellations lie not only in geosynchronous orbits but also in low and medium earth orbits.

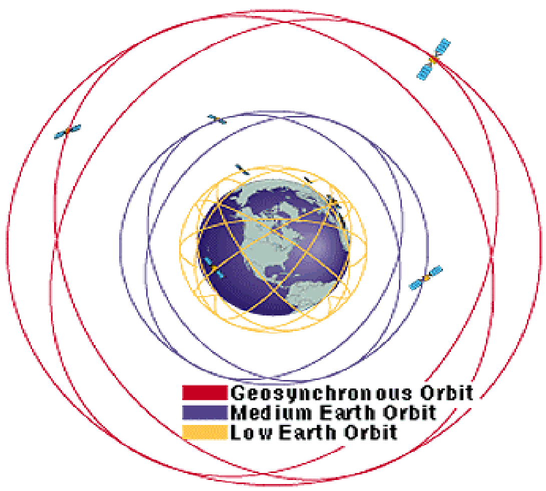

Figure 5-The description of Low-, Medium-, Geosynchronous- Earth Orbits.

A Low Earth Orbit (LEO) is any Earth orbit up to approximately 1,500 kilometers in altitude. A Medium Earth Orbit (MEO) is a few thousand kilometers in altitude. LEO satellite systems offer significant advantages over geosynchronous (GEO) systems for the delivery of mobile satellite services. These advantages result from an orbit selection that enhances the quality of services to low-power mobile hand-held and vehicle-mounted user equipment. GEO satellite systems, located at an altitude of 35,800 kilometers above the Earth, are best suited for their missions of high-speed data, television transmission and other broadcast applications and various broadband applications.

The expected advantages of the Next Generation Satellite Systems for aeronautical communications include:

- Global coverage (including polar areas for some constellations such as Iridium).
- High communication capacity.
- Low message propagation delay.
- The potential for universal equipage, i.e. an aircraft could use a single communications mechanism worldwide.
- Suitability to *Free Flight* concepts, i.e. aircraft need not be restricted to air routes covered by terrestrial communications facilities.
- Economic benefits.

4.2 Summary of Specifications of Current and Next Generation Satellite Systems

In this section we discuss various existing or planned satellite systems and their potential use for aeronautical communications.

- **INMARSAT-3** [12]**:** Until now Inmarsat has handled the vast majority of satellite-based civil aeronautical traffic, with its four satellites (plus spares) in geostationary orbit around the equator providing the Aero-H, Aero-I and Aero-L range of services. Inmarsat's equatorial satellite system does not provide polar coverage. Aero-H has 9.6 Kbps, Aero-H+ has 4.8Kbps, and Aero-I has 4.8Kbps RF channel capacity. User data rates of 160-500 bps can be attained for data transfer [13]. TDMA and FDMA multi-access schemes are used for low-rate data communications and high-rate data communications respectively. The cost of the aeronautical Inmarsat equipment exceeds $200,000, and has a calling charge of $5/min. Inmarsat can support 1100 circuits with global beam coverage and 4300 circuits with spot beam coverage.

- **BOEING** [12]**:** The plans for this system call for a 16-satellite MEO constellation that can provide 100% coverage. The developers have announced that the system will provide service with latencies lower than 200 ms and user data rates of 1200bps. The multi-access scheme to be employed will be CDMA. The redundancy of the system is high, with two satellites in view 100% of the time. The system is capable of augmenting GPS and Boeing has announced its plans for aeronautical communication support. The proposed aeronautical support includes CPDLC, ADS, accessing weather data and airline dispatch and maintenance.
- **ICO** [12]**:** The planned ICO satellite system will have a 10-satellite MEO constellation. The construction of the first ICO satellite has been completed in June 1999, and expected to be launched in early 2000. The constellation is on two orthogonal planes each inclined at 45° to the equator. It can provide continuous 100% coverage. This system can also provide aeronautical services. The developers have announced that they will support user data rates up to 9600bps. The redundancy of this system is high, with 2 satellites in view 90% of the time. The multi access scheme is TDMA, while the mobility management and user identification is performed according to GSM standards. It is stated that 4500 full duplex circuits can be maintained per satellite. ICO Global Communications filed for Chapter 11 bankruptcy on Aug 27, 1999, after failing to secure $600 million in financing commitments it was seeking. Thus, it is expected that the planned rollout of service will be delayed.
- **ORBCOMM** [14]**:** ORBCOMM offers global low bandwidth data and messaging services by its 28 satellite LEO constellation orbiting at altitude of 825 km. ORBCOMM system uses 137-138MHz and 400MHz for downlink, and 148-150MHz for uplink transmissions. In ORBCOMM system, satellites are relays that forward small data packets from sensors in vehicles, vessels or remote fixed sites to a tracking Earth station. These packets are then forwarded to a local gateway, which has the responsibility of delivering the packets to the final addressee via e-mail, dedicated phone line or facsimile.

- **IRIDIUM** [12]**:** IRIDIUM is the first operational LEO system providing narrow-band phone services. It employs a 66 satellite constellation, that can provide 100% coverage. It can provide user data rates of 2400bps without any overhead [13]. IRIDIUM has plans to provide aeronautical service. It has contracted with AlliedSignal for the production of aeronautical terminal equipment, called AIRSAT for large body planes and with Edmo for aeronautical terminal equipment, called SatTalk, which is more suitable for general aviation. The equipment ($3,995 for SatTalk) and the per-minute usage costs (half of Inmarsat as announced by IRIDIUM) are much lower than the current satellite communications equipment. IRIDIUM complies with ICAO AMSS specifications. On August 13th, 1999, IRIDIUM filed for Chapter 11 bankruptcy, since it has failed to promote sales of its satellite phones. Since then, it has been undergoing financial restructuring, and according to these restructuring plans has reduced substantially the price of handsets (from $3500 to $1800) and calls (from $3/min to $2/min).
- **GLOBALSTAR** [12]**:** Globalstar is the second operational LEO system providing narrow-band phone services. It has officially launched service on October 13th, 1999. Globalstar satellite system has a 48-satellite LEO constellation. The satellites are of bent-pipe type, so global coverage can only be possible with a sufficient number of earth stations. Support for data rates of 9600 bps has been announced. This system has one of the cheapest announced satellite call rates: $0.35/min. The price of terminal equipment for personal users is also quite low: $750. The satellites are not as sophisticated as those of other systems; they do not have on-board processing or inter-satellite links. The call set up delay of Globalstar phones may be as high as 1-2 minutes. It is also stated that, this system can maintain 2000-3000 full duplex circuits per satellite using CDMA. However, Globalstar has not yet announced plans for aeronautical services.
- **TELEDESIC** [15]**:** This system is probably the most ambitious one among many other planned satellite systems, with plans calling for 288 satellites in a LEO constellation. The Teledesic system is principally designed for broadband data communications, and publicized as the 'internet-in-the-sky'. The constellation has a geodesic design, that is, each satellite can communicate with the satellites on

the adjacent planes and with the satellites before and after itself on the same plane. For ground-to-satellite communications, Teledesic utilizes Ka band, which is very sensitive to shadowing and rain effects. For this reason, Teledesic satellites require high elevation angles (40° user elevation angle) for successful communications. Teledesic has 100% coverage of the Earth. Teledesic satellite network is a broadband packet mode communication network, but can provide voice communications as well. The proposed system can provide fiber-like bit error rates, bandwidth-on-demand, fiber-like availability (99.9% due to high elevation angle), and very low latency. The average round-trip-time will be less than 100 ms.

5 NGSS for Aeronautical Communications

5.1 Overview of Next Generation Satellite Systems for Aeronautical Communications

The International Civil Aviation Organization (ICAO) and the International Telecommunications Union (ITU) are investigating the use of satellites for two-way communications pertaining to flight safety and regularity on national or international civil air routes [16], [19]. This type of communications via satellite is designated Aeronautical Mobile-Satellite (On-Route) Service, abbreviated as AMS(R)S. The designator (R) indicates that the international spectrum allocation is intended for aeronautical communications and the equipment operating in this spectrum has been adapted for protection from interference. This spectrum is normally used for communications related to the safety and efficiency of flight, but non-safety communications is permitted on a non-interference basis, when priority and preemption can guarantee the precedence of the safety communications. In general, aeronautical communications of both safety and non-safety messages is referred to as Aeronautical Mobile Satellite Service (AMSS). The spectrum that is allocated for aeronautical communications in the L-band is 1616-1626.5 MHz. [16]

The requirements for AMSS are under development. One of the most important requirements is the priority of safety communications over non-safety administrative and passenger communications. Other requirements include compatibility and interoperability of such systems with ATN for data communications. The next generation satellite systems should be able to perform routing according to the 24-bit ICAO aircraft identification numbers [16].

The mobility of airborne users is quite high compared to ground mobile users. However, even aircraft mobility becomes negligible, when compared with the LEO/MEO satellites, which orbit the Earth as fast as 25,000 km/h. Thus, the design of the NGSSs do not have to be modified extensively to accommodate airborne users.

One important issue that should be investigated for the aeronautical safety communications via the NGSS SATCOM is the redundancy and/or availability of these systems. The current NAS architecture employs very high redundancy mainly due to the use of failure prone communications equipment. The higher costs of satellite equipment makes the maintenance of similar redundancy levels impractical for satellite networks. In fact, such redundancy may be unnecessary if system availability can be kept high using other means, such as in-orbit spares, inter-satellite links and the integration of the satellite network with the ground infrastructure whenever possible.

5.2 Perspectives of Various Players

The use of NGSS for future aeronautical communications will be influenced by the FAA, the airlines, the general aviation (GA) community and the satellite service providers. The current ATS communication system operated by the FAA is unable to handle increasing demands, provide new services and features such as graphical weather maps or support of *Free Flight*. Furthermore, the FAA has a huge ground infrastructure that is aged and inefficient. The maintenance and operations cost of this infrastructure is very high and continues to increase. The remote sites are connected to their respective centers via leased private lines and via microwave facilities owned by the FAA. The cost of the leased lines adds up to over $12 million a year [9]. The upgrade of the analog radios to digital NEXCOM radios represents a major capital investment, with the upgrade of a remote radio site projected to cost around $100,000 [9]. When considering these costs, one should keep in mind that each site contains fully redundant radio equipment and communications links and that the BUEC sites, themselves, are meant to be used only when a primary site fails. Thus, the movement to a next generation communications system is essential from the perspective of the FAA in order to keep up with increasing demand, to provide new services and to put a stop to escalating maintenance costs. At the same time, a system that mimics the current terrestrial architecture represents a major capital investment.

The US and world-wide airline industries are highly competitive which leads to extreme cost sensitivities. Any required changes in on-board communications equipment will represent a huge cost to the airlines both for the direct equipment and installation costs and the downtime of the aircraft required during installation. From the airlines' perspective, the benefits of installing new equipment must clearly outweigh the costs. That is, the installation of new equipment should be translated into increased revenues and cost reductions in other areas. The airlines are clearly concerned with potential saturation in channel capacity as well as other inefficiencies in NAS. It is estimated that the airlines lose over $5.5 billion annually due to NAS inefficiencies [17]. However, it must be clear that any new investments will lead to substantial reductions in these inefficiencies.

General aviation (GA) includes many privately owned smaller and perhaps shorter-range airplanes. These aircraft are used for general purpose, and in many cases their flight routes lie out of the federal airways (Gulf of Mexico, and Alaska are good examples for such cases). Contrary to common conception, GA represents almost 90% of all the flights in USA, and of all ATS/ATM communications generated, 50% belongs to GA. Thus, providing air traffic services to these aircraft is an important issue for the FAA. Using SATCOM to support GA in remote areas would seem to be a natural application.

When one looks at the business plans of the principal NGSS providers, it is clear that the principal revenue potential for aeronautical services to commercial aircraft (and possibly even for general aviation) does not come from the Air Traffic Services, but from the "back of plane" passenger communications. Typically ATS is bundled with a solution for passenger communications. It is clearly stated by the NGSS service providers that if too-stringent requirements for ATS are imposed by the FAA and/or other governing bodies, then the satellite companies may choose to provide only the passenger communications services [18].

5.3 Feasibility of NGSS for Aeronautical Communications

The Radio Technical Commission for Aeronautics (RTCA) published a report, [19], on the feasibility for the use of NGSS for AMS(R)S, following the fifth meeting of ICAO Aeronautical Mobile Communications Panel. RTCA is a private, not-for-profit organization that includes the FAA, airlines, and many communication service providers as members, and addresses requirements and technical concepts for aviation. The key considerations in this study were: Compliance with Aeronautical Mobile Satellite Systems (AMSS) Standards and Recommend Practices (SARPs), spectrum availability and interference protection, satellite coverage and capacity, service interoperability and economic viability.

The underlying RTCA study considered broad feasibility issues; the conclusions stated that the next generation satellite systems met certain criteria for satisfactory AMS(R)S. However, NGSS capabilities were only measured in comparison to the GEO AMSS. One would certainly hope that the NGSS's can support the use of much more sophisticated applications. In order to determine the exact capabilities of NGSS's, the future NAS architecture and related applications must also be considered. A more detailed study is needed to resolve several issues such as interoperability with ATN, and other satellite systems, availability and robustness of LEO/MEO satellite systems, and other voice and data communication requirements that may affect the performance, (such as call setup delay, transfer delay, etc.) as well as operational requirements for future systems.

6 Research Issues for Air/Ground Communications over NGSS

The future air-ground communication system must evolve with the overall NAS architecture. Although currently the risk of an aircraft accident is quite low, as air traffic continues to increase, the expected number of accidents could reach unacceptable levels even though the underlying accident risk remains constant. Worse yet, it is possible that as traffic levels increase, the accident risk also increases due to increased congestion. Thus, the underlying communication, navigation and surveillance systems, which support the future NAS, must provide for greater capacity, but at the same time satisfy stricter safety performance criteria. The Next Generation Satellite Systems have the potential to satisfy these stricter requirements with smaller costs compared to the other alternatives. However, several research issues must be addressed to validate this hypothesis.

6.1 Fundamental Assumptions

The studies conducted by the FAA have shown that the main congestion problem for air ground communications is experienced at the terminal areas. It is expected that the terminal area communications will continue to be voice communications oriented in the near to mid- term, because of the need for immediate response from the air traffic controllers to the conflicts that may be caused by anticipated small aircraft separation. Therefore, the need for new channel assignments will persist as the number of flights increase.

Although the biggest frequency congestion is at the terminal areas, the economic viability for NGSS will be driven by the en route communications. En route communications is currently supported by a very expensively maintained and geographically dispersed large ground infrastructure. The greatest potential for cost savings is associated with this infrastructure. It is important to note however, that terminal area communications capacity could be enhanced by a significant diversion of en route communications to NGSS. If this occurs some en-route spectrum could be freed up for use in the terminal areas.

Due to the large variety of the users with different needs, the ground VHF communication infrastructure will have to be supported for the foreseeable future. Therefore, any improvements in the NAS should consider hybrid communications architecture. In this report, hybrid system refers to VHF and satellite air-ground communications coexisting in the same architecture.

The primary users of the NAS (air traffic controllers and the pilots) will not accept rapid large-scale changes in the operations of the air traffic services. For this reason, it is expected that in the near- to medium-term, communications systems are going to emulate at least some portion of the operations of the current Air Traffic System. With this in mind, we expect that, for a possibly very long, transition period, A/G communications will be supported by a hybrid architecture that includes both SATCOM based components and terrestrial based components operating in concert. We now present several research questions that reflect this future vision and principally focus on systems issues related to such a future architecture. These questions are discussed in more detail in the following sections. The research questions are classified in chronological stages according to the different equipage levels of the users.

Near-term: In the near term, the applications enabling the use of the currently available, or soon to be available, NGSS products for air traffic systems should be investigated. For example, SATCOM can be used to provide Virtual Private Lines between the ARTCCs and RCAGs and BUECs. This application is almost immediately implementable, and requires no equipage updates by the airborne users. Another immediately implementable and important use of NGSS SATCOM is for oceanic/remote ATC coverage. The first users of this service will be the airlines and business jets with transoceanic routes. The possibility of full communication coverage for the polar routes by several NGSS providers should also be investigated.

Medium-term: There will be a hybrid architecture, which provides alternate communication links for data applications for the SATCOM equipped aircraft. The use of SATCOM data link will increase substantially. There may be a limited voice capability with NGSS SATCOM over the continental USA. However the *primary* means of communication is still the terrestrial infrastructure, and SATCOM is *secondary* means of communication.

Long-term: In the long term, it is expected that SATCOM and terrestrial A/G communications interchange roles: the terrestrial infrastructure is the *secondary* means of communication, while SATCOM is the *primary* communication mechanism. The ground infrastructure may be reduced, since there is significant number of aircraft with NGSS equipage. Both voice and data is supported via SATCOM, and the equipped aircraft operate under an advanced stage of free flight.

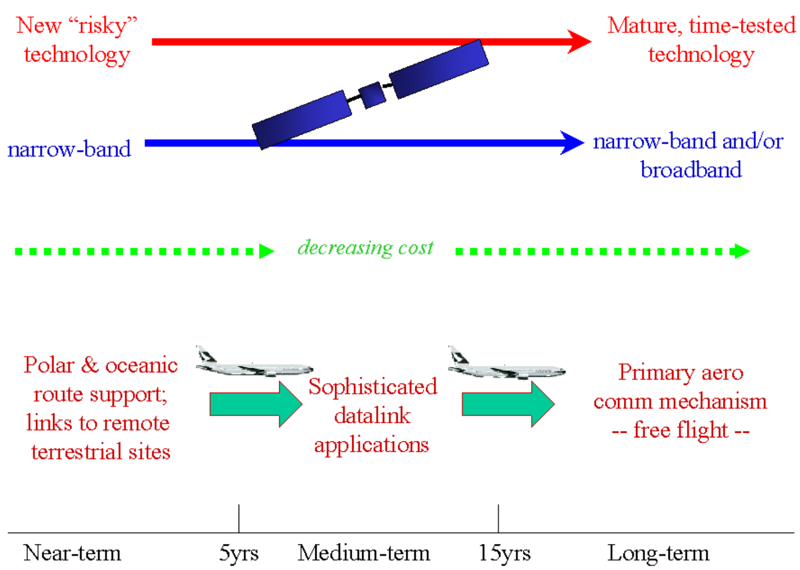

Figure 6: Vision for NGSS Evolution for Aeronautical Communications

6.2 Near-Term Applications

6.2.1 NGSS SATCOM as Virtual Private Lines

There are 793 RCAGs and 720 BUECs that provide remote connectivity between the controllers at the ARTCCs and the pilots. The remote sites are connected to their respective centers mainly via leased lines. Currently, the FAA is leasing 2030 circuits for its en-route communications connectivity. The cost of these leased private links to the FAA is more than $12 million per year. [9]

The BUEC sites are intended for emergency communications, when the aircraft can not use the assigned communication channel. The current rate of use of the communications links to BUEC sites is extremely low (excluding a few BUEC sites, less than 1% of air traffic control communications is completed via BUEC site) due to the existence of multiple redundant radios at each RCAG site. With the transition to NEXCOM, the rate of failure is expected to be much lower, since the NEXCOM system requires the Mean-Time-Between-Failure for ground radios to be greater than 3 years [9]. This should lead to even lower utilization on the links to the BUEC sites. Thus, instead of maintaining permanent private links for these sites, we propose that the FAA lease virtual private links from the NGSS service providers. That is, in case of a failure, a call may be placed between the ARTCC and the remote site via the NGSS SATCOM. This connection is only maintained until the failure at the main site is fixed.

Such an on-demand link may also be used for the maintenance communications between all remote radios and the related FAA facilities. Currently, the only way to check the status of the radios at the remote sites is by site visit, which is a strenuous task in many cases. Alaska represents a good operating environment for the application of such a system, where severe weather conditions limit the maintenance of permanent private lines, and the radio sites. The work is ongoing for a possible demonstration of the use of IRIDIUM system as a virtual private line in the Alaska region.

The implementation and operational costs and benefits of NGSS virtual private lines should be compared with those of the analog and digital permanent private lines. On the technical side, the operational concepts such as call set-up delay, call prioritization, channel capacity and the availability issues should be investigated.

6.2.2 Remote and Oceanic Coverage by NGSS SATCOM

Currently, there is very limited aeronautical communications to the airspace over remote terrestrial regions and over the oceans. In order to avoid conflicts in the oceanic airspace, aircraft are issued increased separation requirements compared to the aircraft on the continental routes. ARINC, Inc. provides HF band data link and SATCOM services for the oceanic aircraft. However, HF messaging is susceptible to interference and experiences large delays. Thus, the only suitable alternative for air traffic control communications over the oceanic airspace is SATCOM.

The current SATCOM systems, such as Inmarsat, experience high transfer delays, because of their GEO satellite constellations. The low transfer delay is essential for many critical ATC communications. The GEO satellite systems also require the users to employ large and expensive satellite transmitters and receivers. The non-GEO NGSS has the potential to provide communications with much smaller delays by smaller and cheaper equipment.

The following technical questions address the operational requirements and the acceptability of near-term NGSS SATCOM technology for ATC communications for remote and oceanic routes.

- In the near-term, voice will still be the principal medium of communication. Therefore, the proposed non-GEO NGSS should be able to emulate the current A/G communication system. Although the non-GEO NGSS experience lower transfer delays, the set-up time of a call is still quite long (IRIDIUM set-up delay is about 20 secs). Thus, the 'push-to-talk' capability can not be provided. Besides, there will be no inherent 'party-line' capability, since it is expected that, in the near-term, the calls between the controllers and the pilots can only be setup as point-to-point calls.
- The NGSS service providers are commercial companies, and their main business is from public communications. In fact, NGSS service providers expect significant amount of their revenue from the public communications, not from the ATS communications. However, in order to provide an acceptable level of ATC communications, the air traffic safety messaging should be given a higher priority than the public messaging. Any blocking and/or hard hand-off of a call may also be intolerable for the controllers and the pilots. NGSS should also guarantee the integrity and security of the ATC communication.
- The capacity of NGSS will most probably be sufficient for oceanic operations, because of the limited number of customers and calls over these regions.
- There are quite a few NGSS systems that are proposed, and none of these systems are designed to be interoperable with another. For the reliability/redundancy issues, the FAA may prefer to use multiple NGSS for ATC communications. The need to choose a single satellite service provider as an oceanic/remote communications service provider should be investigated. This may be necessary to achieve universal equipage on the planes. However, such a requirement may be unnecessary from the FAA point of view, as long as the user equipage conforms to specific standards. ARINC has announced it has built a communications interface that may route the information to any underlying physical layer [21]. By owning several different physical connections to different satellite service

providers at the oceanic ARTCCs, the FAA can provide ATC to differently equipped aircraft. The methods of providing ATC to differently equipped aircraft and the feasibility of these systems should be investigated.

- There is no ground radar surveillance over the oceans. In order to space the planes more closely over the oceanic routes, in addition to A/G communications, independent aircraft surveillance is also required. For this purpose, Automatic Dependence Surveillance (ADS) (which is expected to be implemented soon) can be used by an aircraft to identify the surrounding air traffic.

6.2.3 Polar Routes

Aside from remote and oceanic air traffic control, one area that might gather interest from both NGSS providers and airlines is the communications support over the North Pole. Due to the harsh climate conditions, building and operating ground stations for air traffic control close to the North Pole is unfeasible. Thus, necessitating other means of communications and surveillance. NGSS can provide necessary communications coverage over the poles without any need for ground stations.

Several operational and proposed NGSS, such as Iridium, ICO, Boeing, and Teledesic could provide polar coverage. The target markets of these NGSS are mainly developing countries, where the communications infrastructure is inadequate (for example China). The countries with good communication infrastructure such as USA are not the immediate target markets except for frequently traveling businessmen. However, by finding a niche use of their services, such as airline communications, NGSS companies would like to enter these markets as well. Moreover, since the polar regions are uninhabited, there will be very limited use of the capacity of the satellites for these regions. For these reasons, NGSS providers could support the idea of providing communication services for the airlines in the polar areas.

Technical issues for the acceptable ATC communications over the poles, includes general systems issues such as compatibility, satisfying the ATM SATCOM requirements, and reliability/redundancy. The question of reliability/redundancy appears to be the most important one, in determining the acceptability of NGSS for polar ATC communications, since there will be no other communication system capable of ATS communications, complimenting the NGSS SATCOM.

As an example, consider the Iridium system, which seems to be the only operational system with polar coverage, for at least a few more years. Iridium has polar orbit, which ensures multiple satellite coverage in the high latitudes. At these latitudes (over 70°) spot beams overlap substantially. Such multiple satellite and spot beam coverage of Iridium system may provide sufficient availability. A survivability analysis [20] has shown that even with only 45 percent of its satellites functioning (modeled with 36 failed Iridium satellites), the average packet delays were never greater than 178 milliseconds (ms), well within the real time packet delivery constraint of 400 ms.

Although NGSS can provide the necessary A/G communications coverage over the poles, independent aircraft surveillance is also required for the safe separation of aircraft. For this purpose, ADS can be used by an aircraft to identify the surrounding air traffic.

The polar routes will become a reality only if they are economically beneficial for the airlines. When the airlines make a commitment in technology, they expect a turn-around in profit in as little as 12-18 months. Such a turn-around is possible by a 1%-3% fuel savings. Therefore, for the realization of polar routes, the important question is whether the suggested savings are possible or not.

6.3 Medium-Term Applications

In the medium term as additional NGSS's become operational, we postulate that the SATCOM data link will become a viable option, due to lower prices of calls and NGSS equipment. For the medium term we expect a significant penetration level of SATCOM-equipped aircraft. SATCOM would be used to provide data link services to the equipped aircraft. It is hoped that the penetration level is significant enough that the spectrum from the ground-based system can be freed up to provide additional capacity, especially in the terminal areas.

6.3.1 SATCOM as an Additional Data Link

The need to use SATCOM for A/G air traffic communications arises not only from the need to improve the reliability/robustness, but also from the need for providing relief to the congested terrestrial-based A/G communications systems (especially in the terminal areas). The SATCOM equipped aircraft may use this additional link exclusively for all their communications needs (data and/or voice), or may use SATCOM for an appropriate subset of communications applications.

The information into and out of the aircraft can be partitioned, so that different types of information can be carried over different communication links such as NGSS SATCOM, VDL Mode 2, and VDL Mode 3. Current and future data link applications should be analyzed as to which data link is most appropriate for each.

While identifying these applications, we should also consider that the availability of a data link would induce the emergence of all new applications. Similar to what has happened in the evolution of the data networks (such as Internet); the demand for bandwidth will increase considerably in time due to new *killer* applications requiring more bandwidth to deliver large quantities of data (for example interactive graphical weather maps). These high bandwidth applications can not be delivered efficiently over VDL-2 or VDL-3. The high bandwidth broadcast oriented applications are the first candidates for the SATCOM data link. In general, by carrying non time-critical high bandwidth applications over the SATCOM, the channel capacity of the terrestrial radios can be relieved for time-critical communications.

6.3.2 Operational and Network Compatibility of NGSS SATCOM in Current and Future A/G Communications Systems

A SATCOM-based data link must fit within the greater (presumably ATN-based) aeronautical data communications system. Important issues include the division of responsibility and interoperability between ATN and SATCOM subsystems, whether SATCOM can provide necessary bandwidth and SATCOM performance requirements.

6.3.2.1 Voice over NGSS SATCOM

It is possible that, even in the medium term, SATCOM will be used for voice communications, on a limited basis, in areas supported by the terrestrial infrastructure. For example, this might be appropriate for flights transitioning from oceanic routes. It is reasonable to expect that initially the hybrid system will have to emulate current system operations. In the early medium term, we still expect that a SATCOM connection between the controllers and pilots will be point-to-point. In order to emulate the 'party-line' capability that exists among a controller and the aircraft in a sector, a virtual multicast group could be used. In such a multicast group, the SATCOM equipped aircraft and the controller form a star-topology network (see Figure 7). The ground controllers, broadcast their messages to not only the VHF A/G equipped aircraft but also the SATCOM equipped aircraft via point-to-point connections. The messages, coming from the pilots, are received by the controller, and are also forwarded to the SATCOM equipped aircraft via existing unicast connections.

Due to the high call set-up delays imposed by the satellite communications, special hand-off process may be needed. This problem is discussed in detail in the later sections.

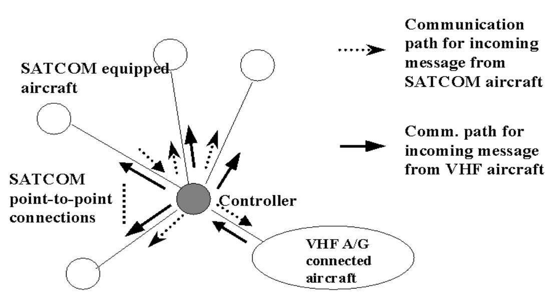

Figure 7-Multicast communication in a hybrid broadcast network with point-to-point connections

6.3.2.2 Division of Control Responsibility between ATN Layer and NGSS Layer

Current thinking indicates that ATN will be the interconnecting network architecture for all aeronautical systems including air traffic management and flight service systems. ATN is designed for data communications and has the goal of achieving an environment in which the choice between the two data links is totally transparent to both the sender and the receiver. Under the ATN concept a message which is sent to an aircraft from any location in the ATN infrastructure, will reach its destination via the best available terrestrial and A/G communications links. If ATN alone is supposed to achieve this goal, the design and the implementation would be quite complicated. In fact, in this case ATN should continuously update the location information of each aircraft in the NAS. This requires a significant message overhead in the ATN layer.

Any NGSS service provider would have to keep track of the location of its users. Thus, there is a potential duplication of functionality of routing and mobility management between the ATN and the NGSS. The responsibility of routing should be divided between the ATN and the NGSS subnetwork, so that no two functions are implemented twice (for efficiency), and the operational requirements for the ATN are met.

One approach to the solution of this problem could be for the ATN layer may estimate the best A/G link rather than exactly determining it. This could be achieved by only knowing an estimate of the location of the aircraft and its equipage. With this information, the ATN layer could choose an A/G link, then leave the final routing responsibility to the NGSS subnetwork.

6.4 Long-Term Applications

In the long-term it is assumed that the majority of aircraft flying domestic routes will be SATCOM equipped. At the same time, a hybrid communications architecture will still exist. SATCOM will be used for both data and voice communications.

6.4.1 Multicast Call Problem in the NGSS Satellite Communications

In the long-term, when a significant number of aircraft have the necessary NGSS equipment, NGSS can provide integrated voice and data services. At this time, the primary means of communication will be satellite communications. In the FAA NAS architecture documents, as well as NEXCOM system requirements, a ‘party-line’ capability is a requirement [25], [2]. That is, the communication between the pilots and a controller should be received by all aircraft in a particular sector. It is argued that, by receiving such communications, pilots will have improved situational awareness over a point-to-point alternative.

While we acknowledge the need for a ‘party-line’ capability in the future, we recognize that, under free flight, the traditional method of controlling traffic in a sector could change substantially as well as the concept of a sector itself. With the future ‘party-line’ capability, an appropriate group of airborne users, air traffic controllers and flight service specialists would form a *multicast group*. The current underlying medium of the ATS system dictates that this multicast group is only formed by the users and controllers of a physical airspace called a sector. In the future, however, from a communications standpoint, the concept of a ‘sector’ should be interpreted in a more general sense. Sectors may be dynamic and may not necessarily reflect a physical area. They should be interpreted as representing a “community of interest”. The members of a multicast group should receive all the messages that are addressed to that multicast group. Each aircraft entering the sector should automatically become the member of that multicast group, while each leaving aircraft should be removed from the membership.

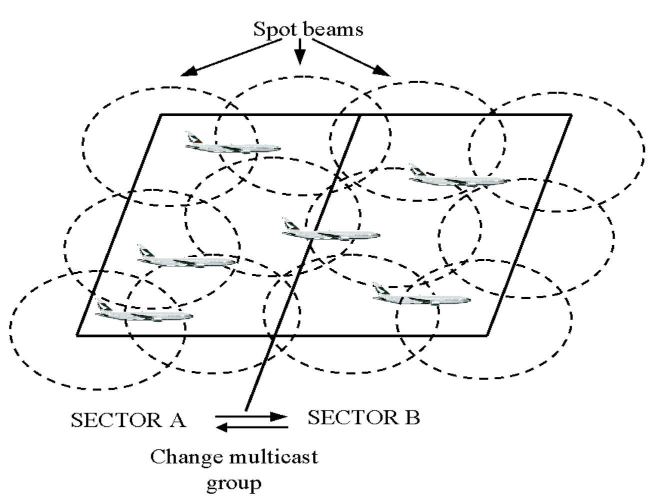

Figure 8- Multicast Call Problem in NGSS

The NGSS's use spot beams to cover the Earth. A sector may be covered by multiple spot beams and multiple satellites at a particular instant. The coverage area of the spot beams as well as the satellites change constantly in time, due to the movement of the LEO/MEO satellites.

An important research problem is the management of multicast membership and message routing in such a dynamic system, where both the communication links (spot beams) that are servicing the multicast group and the members are changing frequently. In answering this question, one must address basic issues of how to implement the multicast group efficiently, including the possibility of taking advantage of SATCOM broadcast features. From the perspective of the pilot/aircraft, changes in multicast group membership, i.e., hand off 's, should be transparent to the users.

6.4.2 Transparent Hand-offs

In the current A/G system, as the aircraft changes sectors, the pilots are required to manually adjust the radio to the frequency of the new sector. The frequency of the new sector is provided by the controller of the previous sector in the form of a handoff message. It is reported that 1 in 7 messages that are currently exchanged is a handoff message. [21] With the use of NEXCOM radios and data link, the hand off process can be automated. As the aircraft approaches to a new sector, data link messages could be exchanged between the controller of the old sector and the airborne user, in order to provide the airborne user with the frequency and time slot of the new controller. This information can be used for switching the NEXCOM radio to the new frequency and time slot automatically.

The handoff process in NGSS is not as simple as for NEXCOM radios. The NEXCOM (digital voice and VDL3) system still uses fixed radio channel allocations for each of the sector; now in the form of frequency and time slot. However, the NGSS physical layer operations are handled by the NGSS service provider, and the physical layer operations are transparent to the air traffic controller. In many cases, there may not even be any single fixed channel assignment to any sector. Finally, since the call set up delays are high, breaking up the previous connection and setting up a new one every time an aircraft changes sectors is not feasible. For these reasons, a special handoff process must be designed.

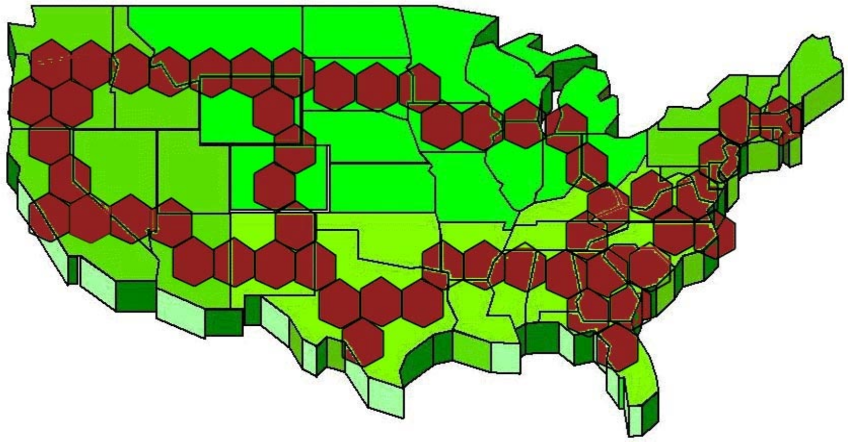

Figure 9- Hybrid Communication with Reduced Infrastructure— The hexagonal areas are sample air traffic routes with guaranteed terrestrial communications connectivity.

6.4.3 Hybrid Communication with Reduced Ground Infrastructure

In the long term, a significant number of aircraft will have necessary SATCOM equipment, so it is possible for the FAA to consider reducing its ground infrastructure; thereby providing ATC mainly via the SATCOM. However, even in the long-term, some commercial aircraft and many smaller aircraft (general aviation) may not be equipped with SATCOM. Thus, the complete removal of the ground infrastructure may not be possible. This environment suggests a hybrid infrastructure, which guarantees terrestrial communications on specific flight routes that provide connectivity throughout the US. If an aircraft follows these routes, it should be able to go from any major airport to another. Thus, the safety of the NAS is not compromised even for the non-equipped aircraft. However, if an aircraft would like to fly outside of these routes, it must have the necessary SATCOM equipment. The environment will be similar to oceanic routes – apart from the guaranteed terrestrial communication routes the remaining areas have no communication options but SATCOM.

The motivation for this concept is that extensive savings can be achieved by the removal of a portion of the large ground infrastructure. Furthermore, by the use of automation systems, along with advanced communications, the SATCOM equipped aircraft may follow unrestricted routes thus realizing the Free Flight.

This concept requires research to determine the best terrestrial communication infrastructure that will minimize the ground infrastructure, while still maintaining the required system capacity and safety levels. The impact of such a system on the airspace congestion and the cost savings of this system should also be investigated. The airlines may adopt different equipage policies in response to such a system. These should be considered along with political issues related to such a system.

6.5 Improvements in the ATC operations enabled by NGSS

The current planned use for data link is largely based on the conversion of the existing voice communications functions. This seems to be highly restrictive as the current uses of A/G voice communications are largely dictated by the capabilities of the underlying medium. In the future, many enhanced high bandwidth applications for data link may be implemented. These applications may not only be the extensions and improvements of the current system applications, but could also reflect a much different approach to the air traffic control. The research approach should be to look for applications assuming no limitations on the communications channel. Then, the costs of providing the appropriate communications systems to support the applications should be considered and the benefits against the cost should be weighed. This work should consider the activities within the Collaborative Decision Making (CDM) project, where several NAS status information items have been identified for distribution over CDMNET. It could be that it is appropriate to distribute some of these to the cockpit. Two promising application domains that clearly should be considered are the distribution of the weather information, and the emerging set of communications requirements associated with air traffic management, particularly in the context of CDM.

Most research into advanced technologies, operational concepts and NAS architectures seem to assume that any required communications support can be provided. This is an important overlooked area that requires serious consideration. There seem to be agreement that the advanced communications requirements can only be provided by NGSS. Thus, the interplay between advanced air traffic control concepts and SATCOM is a vital research area.

7 Economic Justification and Conclusions

The FAA has undertaken a program to renew its entire ground infrastructure with the new digital radios. The cost and duration of the implementation of this system is quite high. If it is proven that the SATCOM can provide capacity enhancement with sufficient redundancy, while still meeting the operational requirements, investment in portion of the emerging digital ground-based infrastructure could be reduced. If this program can be impacted in any significant way, then substantial cost savings would be generated. The trade-off between the incremental investments in SATCOM, and the incremental investments in the ground-based architecture should be determined.

The airlines are cost sensitive. The very important question that must be answered is, whether the airlines will be willing to equip their aircraft to interface with the new SATCOM systems. For the installation of this new equipment, the airlines will look for benefits that justify their costs. These costs may be justified by improved efficiency and additional flights that can be supported by the NAS, or by fuel efficiency derived from Free Flight. The FAA could also look for ways to pass on savings from reduction in maintenance and operations costs in the ground infrastructure. Finally, if SATCOM is the only way to satisfy the future air traffic demand without any compromise to safety, then the FAA could mandate the equipment requirements.

In this report, we have investigated the use of Next Generation Satellite Systems for aeronautical communications. The NGSS have the potential to significantly impact, in a positive way, the current NAS architecture. NGSS may provide relief for the current communication infrastructure, by providing additional communication capacity. NGSS can provide remote and oceanic coverage. NGSS may enable the use of sophisticated automation systems that can increase the efficiency of the NAS. Finally, the use of satellite communications may be essential to achieving the advanced air traffic control concepts envisioned for the long term.

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