Initiation and early development of a worldwide satellite communications system for aviation

by

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Abstract

Experiments by NASA and others in the 1960's showed that the use of artificial earth satellites to relay communications between the ground and aircraft in flight over oceans and remote land areas could mitigate inherent shortcomings of the HF radio system then employed for this purpose, enhancing safety and offering the potential to eliminate many of the resultant constraints on the flexibility and economics of aircraft operations in this airspace. There followed a long period of intense activity by numerous aviation and other organisations to arrive at solutions to the myriad technical and institutional problems that stood in the way of implementing a practical and economically viable aeronautical satellite communications system. Among these organisations was Inmarsat, established in 1979 to provide satellite communications services for ships at sea but also having a remit to study the possible extension of such services to the aeronautical community.

This paper recounts the history of both the earlier work and the design and development by Inmarsat and various other organisations of the first operational satellite communications system for civil aviation, which entered service in 1990. It describes the solutions found to the many engineering challenges faced both by Inmarsat as the designer of the system and by the manufacturers of satellite communications avionics, especially aircraft antennas. It also covers the initial reluctance by the aviation community to accept a system that shares satellites and ground earth station equipment with Inmarsat's maritime service, and the contributions made by Inmarsat to the deliberations of the international regulatory and air transport industry standards-setting bodies whose unified consensus on all matters concerning systems design and operation necessarily precedes the introduction of any new service into the civil aviation world. It goes on to present the authors' views on how the latest developments in mobile satellite communications technology are likely to affect future aeronautical satellite communications services and concludes with coverage of Inmarsat's involvement in augmenting Global Navigation Satellite Systems (GNSS) such as GPS, and the contributions it has made to the investigations of aviation accidents occurring in oceanic airspace.

The authors were members of the Inmarsat aeronautical service team responsible, respectively, for overall management and business strategy, service definition and system definition. The views expressed in this paper are those of the authors and do not necessarily reflect those of Inmarsat nor any of the other organisations or individuals mentioned.
## Glossary

<table>
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<tr>
<th>Abbreviation</th>
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<tr>
<td>ACARS</td>
<td>Aircraft Communications Addressing and Reporting System: a digital datalink system</td>
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<td>ADS-C</td>
<td>Automatic Dependent Surveillance-Contract: The ability to transmit aircraft position derived from on-board systems at specified intervals</td>
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<td>AESEC</td>
<td>Airlines Electronic Engineering Committee</td>
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<td>AES</td>
<td>Aircraft Earth Station: the transceivers and antennas on board aircraft to communicate with satellites</td>
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<td>ARINC</td>
<td>Aeronautical Radio, Incorporated</td>
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<td>ANC</td>
<td>ICAO Air Navigation Conference</td>
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<td>ASTRA</td>
<td>Application of Space Techniques Related to Aviation Panel of ICAO</td>
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<td>ATM</td>
<td>Air Traffic Management</td>
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<td>BGAN</td>
<td>Inmarsat’s Broadband Global Area Network service</td>
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<tr>
<td>dBi</td>
<td>dB(isotropic): The directional gain of an antenna relative to a theoretical antenna which radiates equally in all directions</td>
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<td>FDMA</td>
<td>Frequency Division Multiple Access: each user has its own frequency channel.</td>
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<td>FANS</td>
<td>ICAO Future Air Navigation System</td>
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<td>GAN</td>
<td>Inmarsat’s Global Area Network</td>
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<td>GES</td>
<td>Ground Earth Station: A fixed earth station in an aeronautical satellite system, providing connection to aeronautical and public terrestrial networks</td>
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<td>GNSS</td>
<td>Global Navigation Satellite System - the core satellite navigation constellations (i.e. Global Positioning System (GPS) and GLObal NAvigation Satellite System (GLONASS)), Galileo and augmentation systems.</td>
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<tr>
<td>IMO/IMCO</td>
<td>International Maritime Organisation, formerly Inter-Governmental Maritime Consultative Organisation</td>
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<tr>
<td>Ka-band*</td>
<td>The 20 – 30 GHz range of the radio spectrum</td>
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<td>Ku-band*</td>
<td>The 11 – 14 GHz range of the radio spectrum</td>
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<tr>
<td>L-Band*</td>
<td>The 1 to 2 GHz range of the radio spectrum</td>
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<tr>
<td>LRU</td>
<td>Line Replaceable Unit</td>
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* Definition for purposes of this paper: can differ between organisations
1. Introduction

Recent events have underlined the need for continuous, high-quality communications between aircraft in flight and the ground, both for air traffic management and for ground-based monitoring of aircraft systems. However, when operating over mid-ocean or remote terrestrial regions, aviation communications have typically been limited to relatively poor-quality voice connections between pilots and air traffic controllers, which are often unreliable and difficult to manage. Also, no facilities have existed for passenger communications services. Over the past twenty years, this situation has been gradually improving with the introduction of new communications services, particularly satellite communications, which provide reliable high-quality links, both for voice and data. Use of satellites has also enabled services to be extended to passengers on a virtually world-wide basis, both on airliners and on smaller corporate aircraft. In the past 3-5 years, passengers have increasingly been able to use their own digital devices such as laptops and tablets in flight, and to connect to the Internet using on-board WiFi access systems, much as they can at home. In addition, this new capability allows aircraft position and other key parameters to be reported to the ground automatically as required, from virtually anywhere.

How did this change come about? Historically, communications systems for civil aviation’s safety-of-life applications, i.e. air traffic control and aircraft operations management, have been owned and operated by the civil aviation community and employed exclusive RF spectrum allocations. Early work on satellite communications systems showed that, while exclusive RF spectrum could be expected, the costs associated with a system dedicated solely to aeronautical applications would be very high, possibly prohibitive. Based on its early
research and development work, Inmarsat became convinced that a viable path to the benefits of such systems for aviation could be achieved by sharing satellites and ground earth station equipment with Inmarsat's maritime service. It took some time for this to be fully understood. Initially, some members of the civil aviation community were doubtful, or even sceptical, that a shared system could meet the community's availability, reliability and integrity requirements for safety-of-life communications, especially if it was to provide passenger communications services as well. There was reluctance to invest in building such a system on a global scale. But the time was right; ICAO was developing its future vision of ATM through its FANS initiative, and despite their caution, sufficient entities (airlines, avionics manufacturers, OEMs, earth station and satellite operators and service providers) appreciated that something needed to be done. They weighed the risks, took the plunge and individually committed to support a joint effort to define and build the new system. They were thereby able to support an industry-wide effort which would guide Inmarsat’s development of the system design. Their concerns were eventually allayed, the project succeeded, and now many thousands of aircraft are equipped with a shared-facilities satellite communications system.

This paper recalls, from the view point of the three authors, then working at Inmarsat, how this first operational global aeronautical satellite communications system was conceived and successfully implemented, and how it has already shown benefits for air safety. While Inmarsat, as the major global mobile satellite communications operator, was deeply involved in the process, it was only a part of an industry-wide effort necessary to assure the success of the project.

2. Need for satellite communications: shortcomings of pre-satellite radio systems

2.1 Radio propagation at HF

Before the advent of aeronautical satellite communication systems, long distance communication with aircraft over the oceans and other remote regions was solely carried out using high frequency radio (HF), sometimes called shortwave, which can operate over the horizon. HF has its problems. On the one hand, if ionospheric conditions are unfavourable it is often impossible to contact aircraft on any of the frequency bands allocated for the mobile service, from 2.8 MHz to 23.4 MHz. On the other hand, if propagation conditions are good there is often considerable congestion due to interference by transmissions from other regions of the world on the same channel. Even on flights transiting the North Atlantic it is not uncommon to have periods where no useful contact can be made because there is either no propagation or serious congestion due to interference or atmospheric effects.

2.2 Issues

The HF system still used in aviation is very inefficient and difficult for pilots to use, especially during times of high workload or stress due to emergency situations. The fact that communications with air traffic controllers have to be made through radio operators on the ground also slows things down considerably. The availability of HF communications is a lot
poorer than the official statistics suggest because very often pilots expect it to be poor and do not report problems. Satellite communications do not suffer from these difficulties.

3. **1960s: Early aeronautical satellite initiatives**

### 3.1 First demonstrations of feasibility

Recognising that satellite communications could potentially improve communications for aviation, studies and experiments commenced as early as the mid-1960's to demonstrate feasibility. The early communication satellites had limited performance: they were not very sensitive for receiving signals from aircraft, and had little power for the signals they transmitted to the aircraft. Those limitations can be mitigated by increasing the size of the antenna system on the aircraft, but there is only very limited scope to do this because of the weight and aerodynamic drag of the antenna. Nevertheless, studies indicated that low bandwidth transmissions should be possible. The US Air Transport Association, NASA, Hughes, Bendix and FAA conducted successful ground-to-air tests late in 1964, then in 1965 air-to-ground messaging was demonstrated between a regular PanAm flight and the US, using the Syncom III geostationary satellite over the Pacific. The US, GE and international airlines also carried out other tests at VHF using the ATS-I and ATS-III satellites during 1966-68 and in 1972 the US Federal Aviation Administration (FAA) performed experiments at L-band using the ATS-6 satellite. These were continued in 1974 and 1975 in a series of tests performed by the FAA, NASA and the European Space Research Organisation (ESRO - predecessor of ESA) (1). The basic feasibility of geostationary satellite communications for aircraft had therefore been firmly established by the early 1970s although many more trials were to follow to validate the eventual system design.

### 3.2 AEROSAT and After

In 1968 the International Civil Aviation Organisation (ICAO) formed the ASTRA Panel (Application of Space Techniques Related to Aviation), which reported to ICAO's 7th Air Navigation Conference (ANC) in 1971 and, on the basis of the report's recommendations, a memorandum of understanding was signed by a consortium comprising Canada, the FAA and ESRO covering the development of an operational aeronautical satellite system. This project was named AEROSAT, and it aimed initially to cover North Atlantic regions. After considerable debate, L-band frequencies were selected for the service, and a programme structure was agreed involving NASA, the FAA and ESRO, among others.

By 1973, specifications had been produced for a relatively low-rate satellite communications data link for Air Traffic Management (ATM) purposes, to serve the North Atlantic Flight Information Regions (FIRs). Based on this, a request-for-proposals (RFP) was sent to satellite vendors, and by mid-1976 proposals had been received. However, the US Government decided not to fund the construction of the new system, which would require new satellite repeaters, carried either on new dedicated communications satellites, or hosted on already-planned satellites. As the costs and the potential capabilities of the system became clearer, the air transport industry made clear that it would not fund the programme, which was then
stopped. Aviation still had no satellite communications service, even though aircraft were becoming larger, more complex and automated, and the skies busier.

But the seed had been planted, and various bodies, particularly under the auspices of ICAO, continued to explore how to provide satellite communications services to aircraft. Among these were the Committee to Review the Application of Satellites and Other Techniques to Civil Aviation (Aviation Review Committee – ARC), the ICAO Review of Aviation System Planning, the Oceanic Area Systems Improvement Study (OASIS) and the US Radio Technical Commission for Aeronautics (RTCA) Special Committee SC-155, which studied the subject from 1983 to 1986. The European Organisation for Civil Aviation Equipment (EUROCAE) also had a group working in this area.

4. 1970s: Inmarsat Maritime Satellites lead the way
4.1 Problems of maritime communications

Since the early part of the 20th century, radio had provided the means of communication between ships at sea and land. This medium had served the shipping community well, though for long distances it used HF, with the issues already mentioned for aviation. By the 1960s and 1970s significant improvements had been made with such innovations as single sideband (SSB), use of VHF frequencies, radio telex and assignment of high frequencies for distress calling. Nevertheless, use of Morse code (at 500kHz) and frequencies around 2MHz were still common, and undeniably the radio medium was experiencing difficulties with congestion of frequencies, interference to coast stations, and being subject to the vagaries of the ionosphere. Furthermore, the services were generally manually operated and incapable of automatic connection to the worldwide telephone and telex networks.

4.2 Establishment of the International Maritime Satellite Organisation (Inmarsat) (2)

Recognising the problems inherent in maritime communications, the Inter-Governmental Maritime Consultative Organisation (IMCO, now the International Maritime Organisation – IMO) in 1972 established a Panel of Experts to study maritime satellite communications, which in turn led IMCO in November 1973 to convene a series of three international conferences. These culminated in the adoption of a Convention and Operating Agreement on the International Maritime Satellite Organisation (Inmarsat) in 1976, which came into force in 1979 and resulted in the formation of the Inmarsat organisation in July of that year. Parties to the Convention were States, but Parties to the Operating Agreement (known as Signatories, who would own and operate the system) were either telecommunications organisations or maritime entities nominated by their States.

4.3 Allocation of adjacent frequency bands for aeronautical and maritime satellite communications

The aviation industry has always striven to win and keep enough spectrum to meet its safety and operational communications needs and as long ago as 1947 had obtained exclusive allocation of the 1,530 - 1,670MHz band (L-band) for the aeronautical radio-navigation
service. The need for spectrum for maritime satellites was recognised at the 1971 International Telecommunication Union (ITU) Maritime World Administrative Radio Conference (WARC) and resulted in some of the band being re-allocated, with allocations being created for both the aeronautical and the maritime satellite services. Reflecting foresight about the similarity of the two services, the allocations were made adjacent. In 1979, the ITU General WARC readjusted these allocations to reflect the expected creation of Inmarsat and the demise of AEROSAT, and allocated nearly equal spectrum for the maritime mobile satellite service and the aeronautical mobile satellite (R) service, with a 1MHz common band for all mobile services for distress and safety. Subsequent WARC in 1987 and 1992 modified these allocations, with the aeronautical service losing 5MHz to land mobile satellite services, such that the spectrum available for aeronautical satellite communications was then 1545MHz-1555MHz downlink (satellite to aircraft) and 1646.5MHz-1655MHz uplink (aircraft to satellite). The bands allocated to aeronautical were initially designated (R), indicating that they were only for en-route safety and airline operational communications, but it was agreed at the 1987 WARC that they could also be used for public correspondence (that is, telephone and other communications services for aircraft passengers), provided that safety services retained priority.

4.4 The beginnings of Inmarsat maritime services

Inmarsat in its early days did not design or implement a new system – it inherited a working maritime satellite communications system. Well before the advent of Inmarsat, Comsat Corporation in 1976 established a maritime communications system known as Marisat, partly to satisfy a need for the US Navy and partly in recognition of the trend to maritime communications by satellite. Inmarsat took over operation in February 1982 and leased the Marisat satellites, augmenting them with the lease of two Marecs satellites developed by the European Space Agency (ESA) and the lease of three maritime packages on Intelsat satellites to give near-global coverage. From 1990 onwards, Inmarsat started to deploy its own specified "Inmarsat-2" satellites. Inmarsat also adopted the ship earth station standard (SES) from Marisat, the ‘Standard-A’ which required a rather large (>1m) parabolic tracking antenna on each ship and was therefore usually applied to larger vessels. It provided analogue voice service, telex, plus fax and data via modems. In 1990 Inmarsat introduced Standard C, or ‘Inmarsat-C’ which had a small non-tracking antenna, designed to be small enough to fit the smallest vessels. It provided low-rate and low-cost messaging services, not voice, but could implement group calling, and was accepted by IMO for Safety of Life At Sea applications. Since then, there have been further Standards, progressively reducing SES sizes (M, GAN, BGAN) with adaptations to be used on land as well as in the air. To support them, large investments have had to be made in upgraded satellites, with substantially improved receiver sensitivity, transmit power, and capacity (as described later).

4.5 Impact of satellite communications on the maritime world

The impact of fully automatic and affordable satellite communications on the maritime world has been profound, in terms of improved operations and safety provisions. Already by end-1991, the first decade of its operation, Inmarsat had commissioned about 14,500 ship earth stations, providing service through 24 coast earth stations. Revenue in 1991 was $261
million, predominantly from telephone services, and growing at over 40% p.a. With the enhancements mentioned above, the Inmarsat system continues as a thriving and profitable business, and many benefits flow from it to the maritime industry, especially in terms of support for safety services. It was natural to seek to achieve similar benefits and results for the aviation industry.

5. 1980s: Inmarsat moves toward aeronautical services

5.1 Early visionaries

It will be clear from the foregoing that the potential of aeronautical satellite communications had already become part of a shared vision among forward-thinkers across the aviation world. This was also true within ICAO, as seen in its FANS initiative – see 5.4 below – but a major obstacle to progress was finding a way to make the economics work. Unlike satellite navigation services, governments were not willing to fund a new aeronautical communications system as a public service. A viable business case needed to be made, and the key to this was sharing facilities and operating costs.

The seeds for providing aeronautical services by satellite had already been sown in Inmarsat’s Convention, adopted in 1976, which established Inmarsat, and also, on the basis of submissions by the US (4), recommended that "arrangements should be made to undertake at an early date the study of the use by Inmarsat of multi-purpose satellites providing both a maritime mobile and aeronautical mobile capability (5).

At that time, aeronautical services were not perceived as future ‘core-business’ for Inmarsat, so it needed strong and clear leadership to persuade its shareholders to venture into this potential new business. A number of visionaries, notably Ed Martin and Dave Lipke from COMSAT, Inmarsat’s USA Signatory, together with Inmarsat’s first Director General, Olof Lundberg, were convinced that the benefits of satellite communications on aeronautical operations could be comparable with those on maritime operations, sufficient to sustain a business, and began to review the possibilities and promote the service concept within the organization. In particular, they recognised that using Inmarsat could give the aviation industry much lower entry costs to satellite communications, as they would be using an existing satellite system most of whose costs were already being met by the maritime industry.

5.2 Accomplishing the vision

There had been no original commitment or requirement on Signatories to support an extension of satellite communications to aircraft: nevertheless, this was discussed in the Inmarsat Council as early as 1981 (6).

Starting in 1982 the Signatories agreed to support some basic research and feasibility studies into the matter, including a lynchpin system study commissioned from Racal in 1984, which led Inmarsat to propose certain key system parameters (antenna gains, bit rates, signal powers) and, over the next years, evolved into a major development effort by Inmarsat. This involved
attendance at numerous aviation forums and supporting aviation-entity trials and demonstrations using satellite capacity provided free-of-charge by Inmarsat; stimulation of antenna and avionics development by letting Inmarsat contracts for pre-operational equipment; encouragement of aircraft manufacturers to offer satellite communications systems in their aircraft; encouragement of Signatories to construct ground earth stations; and, very importantly, encouraging States to amend Inmarsat’s Convention to establish the legal basis for the organisation to provide aeronautical services. This milestone was achieved in 1985, the amendment entering into force in 1989. This provided reassurance to many doubting airlines and other entities that Inmarsat was indeed to be regarded as a potentially serious provider of such services.

5.3 Credibility of Inmarsat as industry newcomer

As a newcomer to the aviation industry, Inmarsat’s promotion of its resources to serve aviation not unexpectedly aroused scepticism in some quarters. Airlines in particular were not expecting to have to share resources and costs with maritime interests. It took some time to realize that such sharing was essential to the economic case. One of the authors even recalls Inmarsat being called "carpet salesmen" in an early presentation to aviation specialists, in which he attempted to show the benefits of an aeronautical satellite system sharing facilities and costs with Inmarsat’s maritime system. Also, the future vision was not always fully shared, and there were even some who believed that satellite communications would merely be a backup for HF and not replace it. At one ICAO meeting, the national representative from a State even maintained that radio communications officers would be too busy trying to communicate on HF to answer calls from aircraft via satellite! However, by continuing to focus objectively on the technical and performance issues, Inmarsat gradually began to gain acceptance and agreement on a design.

5.4 Liaison with ICAO and aviation authorities

In considering the use of satellites for communications with aircraft, it was always expected that there would be three main users: the aviation authorities for services related to the control and safety of aircraft; the airlines for control and management of aircraft; and finally, the passengers, to meet their normal communications needs. In its early steps toward aeronautical communications Inmarsat therefore heeded the Recommendation in its Convention, namely that "the advice, participation and cooperation of the appropriate aeronautical authorities should be sought" and in this regard ICAO, as the world’s primary body regulating aviation, was the key organisation.

As a result of the earlier studies in its various bodies, ICAO in 1983 had established the Special Committee on Future Air Navigation Services (FANS), to study "technical, operational, institutional and economic questions ---- relating to future air navigation systems" *. The committee met four times, held many working group meetings, and reported in 1988.

* In ICAO ‘air navigation’ covers an extremely broad spectrum of activities, ranging from short take-off and landing aircraft to supersonic transports, from security questions to the impact of aviation on the environment, from training and operating practices for pilots to the facilities required at airports as well as the conventional communication, navigation and surveillance systems.

Recognising the key nature of this committee, and at the invitation of ICAO, Inmarsat staff made many contributions to its work, and those of its successor committees, and their final recommendations could be met by the system design being developed by Inmarsat, whilst still reflecting the strict requirements of aviation.

In addition, ICAO support was sought and achieved in a number of other ways. In 1983, based on an expression of interest by ICAO, Inmarsat included 3MHz of aeronautical spectrum in the specifications for its 2nd generation satellites issued that year. Subsequently, in 1987 ICAO and Inmarsat negotiated an Agreement of Cooperation that was formally adopted in 1989. But the main contribution of ICAO was perhaps in establishing a set of core requirements for a satellite communications system to support air safety. Without such a foundation, it was not feasible to develop a new system and gain universal acceptance of it.

By 1990, progress had reached the point where the Secretary-General of ICAO, Dr. Shivinder Singh Sidhu, would say that the FANS Committee was the most important committee of the Council and he expected that its work would have the same impact on aviation as the introduction of jet aircraft in the 1950’s (7).

5.5 Coordination with the aviation industry

For maritime and land mobile systems, Inmarsat had always been free to specify its technical and performance requirements independently. However, matters work differently in the air transport world, which requires equipment to be constructed, and to function, to industry standards and recommended practices. Therefore, for each system, an avionics architecture is defined where the major system functions are assigned between a number of standardised units (Line Replaceable Units – LRUs). This helps give assurance that the equipment and the system it supports have undergone a thorough open scrutiny, and will satisfy all safety and operational requirements. It also standardises aircraft wiring and provides for interchangeability of equivalent LRUs from different manufacturers. None of these standards existed for aeronautical satellite communications, so they had to be generated and agreed in parallel with the system functional design. The open consensual process needed close communication and cooperation between the parties involved.

For airlines, the main standards or ‘ARINC Characteristics’ for equipment are set by the AEEC (Airlines Electronic Engineering Committee), which defines ‘form, fit, and function’ of the specific LRUs installed on aircraft to implement the intended system. In principle, an airline can procure units which are entirely interchangeable from different competing manufacturers. For aero satellite communications, the AEEC designated a new Characteristic, ARINC-741, which became the main vehicle into which Inmarsat fed its system design contributions*

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*ARINC (originally Aeronautical Radio Inc., later ARINC Inc.), was an air transport industry owned corporation that provided air-ground and fixed point-to-point communications services for aircraft operational control and other airline management functions. It also administered a number of air transport industry committees, of which the AEEC was one. The company passed into private equity ownership in 2007 and was subsequently purchased by Rockwell Collins in 2013. Following the Rockwell Collins acquisition, the management of the AEEC was taken over by the US Society of Automotive Engineers (SAE), where it remains.
In terms of construction and performance, Minimum Operational Performance Standards (MOPS) are established in the US by RTCA (Radio Technical Commission for Aeronautics) and in Europe by the European Organisation for Civil Aviation Electronics - EUROCAE).

For ATM and safety services, ICAO is the primary agency. It produces SARPs – Standards and Recommended Practices defining how systems should be operated.

Inmarsat’s design recommendations therefore had to be promoted actively in all these bodies in parallel, sometimes in competition with other proposals which were mainly from ARINC (at one stage promoting a competing airline-owned satellite system called AvSat) and ESA (developing a low-data rate PRODAT system). The meetings held regularly by these bodies became the focal point for discussions between airlines and other stakeholders, including the civil aviation authorities and equipment manufacturers, and resulted in a punishing schedule of travel for Inmarsat staff with many periods of negotiations, conferences, and associated meetings, presentations and other discussions. The design process had been much simpler in the maritime world!

5.6 Inmarsat Directorate staff

Much of Inmarsat’s work was performed by its Directorate, headquartered in London, and in the 1980’s a separate Aeronautical Services Division was established within the Directorate charged with developing the planned aeronautical services. In time this Division numbered about 40 people. Being an inter-governmental organization, Inmarsat’s Convention obliged it to hire staff from the various countries which had signed the Convention and this was reflected in the international make-up of the Aeronautical Services Division, which comprised people from various nationalities and various ethnic backgrounds. The professional staff were primarily engineers, with communications or aviation backgrounds, but also included some economists. One of the objectives was to have people who could provide a bridge between engineers developing space communications systems and the needs of the aviation industry. In this regard we were fortunate that in time our staff included such people as a former Aer Lingus senior captain as well as a former chairman of AEEC, both with an engineering background. The international nature of the people led to some interesting situations. A notable case was that of a young lady from Brazil, who had come to London for a working holiday and was hired as an office helper. After some time, however, it emerged that she had technical qualifications and had worked for the aircraft manufacturer Embraer in Brazil, whereupon she was quickly upgraded to a technical assistant position as the workload was very demanding. Being from South America, she also gave other interested staff lambada lessons in the evenings!

Developing the aeronautical system was a complex engineering and management challenge, in which Inmarsat, while not a manufacturer or integrator, was a key enabler. The fact that the challenge was met is a tribute to the dedication and professional capabilities of the men and women of Inmarsat’s Aeronautical Services Division, and its close coordination with the aviation industry and its processes. It reflected the high level of motivation and activity throughout the established aviation industry as work progressed: by avionics manufacturers,
service providers, and regulatory organizations, whose dedication and hard work transformed a design concept from paper to a tangible, affordable, working reality.

There were too many players to give a complete listing, but key early participants included Inmarsat earth station operators, ARINC, SITA, Honeywell, Rockwell-Collins, Racal, Boeing, Airbus, Gulfstream, Ball Aerospace, E-Systems, DVI, CMC, EMS, NERA, IATA, ICAO.

6. INMARSAT Aeronautical System Design Process
6.1 Top-level Requirements Definition

To design a system, ideally the eventual user should first define comprehensively what that system is supposed to do, but this rarely happens – the requirements tend to evolve with the improving understanding of its capabilities by the users. In this case, in attempting to produce a proposal for an aeronautical satellite communications system, Inmarsat had no clear and agreed requirements to start from. It was however understood that while the design priority was to support aircraft safety, i.e. air traffic management communications, it was important that the same basic design and equipment should be able to support airline operational control traffic and public-correspondence without prejudice to safety.

Figure 1 shows an outline of the system with all its components, aircraft, satellite and earth station connected to the users.

![Figure 1: System Schematic](source: Inmarsat, London)

The industry’s standards development process described above, and particularly the definition of “Core” requirements by ICAO, provided a basic requirements framework, driven by the need to be able to support aircraft of all sizes using existing and planned Inmarsat L-band satellites, and hence avoid the full spacecraft cost falling on the aviation community. By cooperation between the various aviation stakeholders - ICAO forums,
CAAs, aviation forums, airline communications providers, airlines, avionics and aircraft manufacturers, and research organisations, a set of top-level requirements emerged. This process also imposed an engineering design discipline, to iterate efficiently to a common view of requirements and of system solutions. Inmarsat evolved the system design accordingly. The "core" system requirement was included in the Inmarsat system design as a 600 bps data service. Besides meeting air traffic management needs, data was also seen as important to airlines for operational control. Another key requirement was that this service should support Automatic Dependent Surveillance Contract (ADS-C), i.e. the ability to transmit four-dimensional aircraft position derived from on-board navigation and position-fixing systems, plus aircraft identification and additional data as agreed with the air traffic control.

Voice communication was also seen as a requirement to support air traffic services, but it was not clear whether, in the long term, it would remain the basic form of controller-pilot communication. Voice was also required for airline operational control, but its main requirement was expected to be for passenger communications.

The core system requirements were meant to apply everywhere over the earth where satellite coverage was available. For systems such as Inmarsat's based on geostationary satellites in orbit 35,786 km (22,236 miles) above the Earth (which means that each satellite appears to have an essentially fixed position in the sky above the equator) it is not possible to have full coverage of the extreme polar latitudes. However, not many routes were affected by this. Figure 2 shows an example of earth coverage of an Inmarsat constellation. As constellations grow, so the earth coverage improves incrementally, and techniques can be applied to achieve service almost to the Poles. Constellations vary from time to time as satellites are moved or replaced in orbit, and new satellites added.

Figure 2  Example of Inmarsat Core 4-Region Coverage (all areas within the solid lines)
Source: Inmarsat, London
6.2 Basic system issues and Requirements Flow-down

The limited size and hence performance of the aircraft antenna was basic in the design. A 1 metre parabolic dish antenna plus radome, as used on ships, was not suitable for aircraft, so various smaller alternatives were explored. Inmarsat’s initial design concept called for two types of aircraft antennas; so-called high-gain and low-gain. The low-gain antenna took the form of a small “blade” or fin, relatively easy to accommodate even on a small aircraft. Such an antenna is not physically steered, but gives a field of view of the whole hemisphere of sky above the aircraft’s position, taking into account the normal operating attitudes of the aircraft. In practice, this leads to an antenna gain, in the direction of the satellite, which varies but is bounded between approximately -1 and +3dBi. Figure 3 shows an example of a low-gain antenna, the Cobham LGA-3000, measuring about 38x5x12 cm.

![Figure 3 Cobham LGA-3000 Low Gain Antenna](Source: Cobham Aerospace Communications, Wimborne, UK)

The high-gain beam-steerable antenna had a gain about ten times higher (12dBi) with a field of view dependent upon the aircraft type and antenna location(s).

This concept ensured that two-way aeronautical data links of at least 600bit/s would be feasible using the existing satellites with the low-gain aircraft antenna, while permitting much higher rates, including voice communications at 9.6kbit/s, using a high-gain aircraft antenna. The high-gain antenna posed a very substantial engineering challenge to manufacturers and there were even occasional suggestions that Inmarsat engineers had produced an unattainable specification! Nevertheless, the various manufacturers duly succeeded in producing compliant antennas.

Manufacturers developed two main types of practical high-gain implementations—single top-mounted designs and dual-antenna side-mounted designs. These were mainly phased arrays, steered electrically, although mechanically steered antennas were used in some corporate aircraft installations. Figure 4 below shows an example of a top-mount design (Canadian Marconi CMA-2102SB) fitted to an Airbus 330 aircraft.

![Figure 4 Canadian Marconi CMA-2102SB](Source: Cobham Aerospace Communications, Wimborne, UK)

Besides the above, the system design took into account the following additional key issues which were rather new in the wider mobile-satellite world:

- Effects of multipath transmission of radio signals in the aircraft-specific context
- Robust signal design or ‘signal-in-space’ (coding and modulation) for aero-specific environments
- Avoidance of interference to GNSS and other navigation signals in adjacent frequency bands
- Aircraft registration/logon and associated aircraft earth station (AES) management procedures
- Prioritized access to the satellite resource (16 level) corresponding to ATM usage
• Need to support ACARS* messaging, and also bit-oriented protocols.**

The design faced some specific technical challenges, for which timely solutions were just emerging from the general progress in electronics:

• Aircraft diplexer providing over 120dB receive signal isolation from the transmitter, just 100MHz away, and also to protect the GNSS receiver. Recent developments in dual-mode filter design allowed this.

• Stringent linearity and efficiency requirements on the aircraft transmit power-amplifier, which became feasible following intense development work on solid-state amplifiers in the cellular phone industry.

• Software complexity. The new satellite avionics typified a new order of magnitude of complexity (‘lines of code’), which the industry succeeded in delivering.

As a result, the following top-level requirements were used in the system design concept, with confidence they could be delivered:

6.2.1 Core installations:

• Providing duplex low-rate reliable (positively acknowledged) data at rates of at least 600bit/s when using a global-beam satellite and a hemispherical-coverage aircraft antenna

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* ACARS: Aircraft Communications Addressing and Reporting System. A character-oriented air-ground messaging service adopted by the air transport industry in the 1980s for operational control applications. Normally operates over VHF radio, and sometimes HF radio, but needs to be supported by satellite links where there is no terrestrial coverage.

** Air-ground data traffic is migrating to use of the Internet Protocol (IP) based on bit-oriented communications.
• Providing a satellite reference signal receivable by all aircraft, to control access to the satellite system, and to manage a registration (log-on) process
• Supporting character-oriented data messages (ACARS format) to and from aircraft

6.2.2 Upgraded installations (with high-gain antennas):
• Supporting all data functions at higher rates up to 10.5kbit/s per carrier
• Supporting point-to-point voice calls (circuit-mode, 9.6kbit/s coding)
• Supporting multiple voice and data carriers

To provide the data-message capability efficiently, a TDM/TDMA* protocol was implemented.

Initial access to the satellite, and short messages, used a random access technique. For the voice calls, full-duplex digital circuits were set up, using FDMA**, with out-of-band call setup signalling making use of the TDM/TDMA system. For both data and voice, a 16-level system of priority access to the satellite was implemented.

These installations became the basis for the vast majority of Inmarsat’s aeronautical service offerings, and have been in operation for twenty years. As a mature service package, they have come to be known as “Inmarsat Classic Aero”.

Although the data service supports ACARS character-oriented message formats, it uses underlying bit-oriented protocols and the design has internetworking capability. However, the emerging requirements originally called for an ISO 8208 network-level interface, which the design supported. It soon became apparent that instead, TCP/IP would become the eventual internetwork data standard.

6.3 Design Authority

There was no formally-agreed owner of the system design, there being rather a joint ownership by the industry’s standards groups. There was no single definitive test-bed, and no point of arbitration in case of incompatibilities between different manufacturer’s products.

In practice, Inmarsat undertook this role, and helped to expedite links between aircraft avionics and ground earth station manufacturers, including funding some equipment developments as

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*TDM/TDMA: time division multiplex/time division multiple access. TDM is typically used ground to air, where data for multiple aircraft is mixed on a time-shared basis (multiplexed) onto a single radio signal. Aircraft receiving this signal see all data but read only that addressed to them. TDMA works air to ground, where each individual aircraft transmits its own dedicated signal, but the system pre-assigns time slots for transmission, to preclude interference between different aircraft. Until it has been assigned slots, an aircraft must transmit with random timing which leads to inefficiencies through interference.

**FDMA: frequency division multiple access. In both directions, air-ground and ground-air, each aircraft is assigned one or more radio channels full-time, but only for the duration of the connection.
described in the next section. From around 1989 Inmarsat began to broadcast a test signal over an Atlantic satellite, containing all the characteristics of the system design. This proved very helpful to the manufacturers and the design team to interpret specifications correctly and resolve ambiguities, etc. Inmarsat also developed and made available a reference test system for the system protocols.

7. **Inmarsat Support for Aviation Industry Activities**

7.1 **R&D studies**

From its inception in 1982 the Inmarsat R&D programme provided for the study of multi-purpose satellites, including services to aircraft, whilst the 1983 programme provided specifically for the study of aeronautical mobile satellite systems and aircraft terminals. This included the Racal Avionics study mentioned previously, and these studies and manufacturer’s inputs determined and validated the key system parameters. Link protocols were designed and simulations were performed, both in-house and under contract, to validate the protocols to be employed and the parameters of the radio frequency links.

7.2 **Industry interest.**

By 1987, the aviation industry had become more involved and active in assessing satellite communications, for instance, by establishing an Aeronautical Satellite Trials Group comprising airlines, manufacturers, SITA, ARINC, Inmarsat Signatories, some civil aviation authorities and other organisations. Inmarsat supported this practical work as a means of aiding and validating the system design work, but especially to encourage the growth of confidence and uptake of services.

7.3 **Purchase of Antennas and avionics equipment**

To stimulate manufacturers to develop operational equipment for an aeronautical satellite service, Inmarsat in 1987 let four contracts for $3.3 million for representative aircraft antennas and associated avionics. The contractors included Racal Avionics (avionics and antennas), Rockwell International (avionics), Ball Aerospace (antennas), E-Systems (antennas and avionics) and KDD Japan (voice codecs). The purchase of this equipment and the resulting stimulus it provided to avionics and antenna manufacturers was certainly a major contributor to the early take-up of the aeronautical services.

7.4 **Validation Trials and demonstrations**

To allow manufacturers to validate the selected system design parameters, as well as to demonstrate the applicability of satellite communications to air traffic control and other applications, and also to stimulate interest by the aviation industry, Inmarsat in the mid-1980’s agreed to provide satellite capacity free-of-charge for these purposes. As result in the following years a substantial series of trials and demonstrations took place, summarized in Appendix 1.
In the early days of trialling, when problems occurred, suspicion often fell first on the satellite – the new and unknown element for most participants. However, understanding and confidence quickly built up as experience was gained.

8. **1990s: Commencement of aeronautical services through Inmarsat**

By late-1988, the Inmarsat Aeronautical Division reported that "the extended period of 'wait-and-see' by airlines seems to be over and past months have seen the emergence of significant orders from some airlines with emphasis on data and cockpit voice”. Manufacturer interest had changed from polite technical interest to a determination to build the best system and have it on the market as early as possible, and by 1988/89 various avionics and antenna manufacturers were reporting significant orders from airlines and other operators. At this time Boeing announced that it would incorporate a low data rate system as standard fitment in its new 747-400 aircraft. It was clear to Inmarsat that a milestone had been achieved when, on a visit to Boeing’s site in Everett, Washington, a technician showed one of the authors her work schedule for that day: it included a recent addition: installing the RF cable to connect the satellite electronics to the low-gain top-mounted antenna. Finally, satellite communications had arrived as a standard fit. Boeing and Honeywell built a FANS application to run on the existing ACARS system. This avionics package became known as FANS-1 and was certified on a Qantas 747-400 in June 1995, a key milestone in the adoption of satellite communications for safety services. The Airbus equivalent system was known FANS-A or A+, and these systems were known collectively as FANS-1/A.

Brian O’Keeffe, who was the Australian member of the ICAO FANS committee and chaired the ICAO FANS II Committee until it completed its work in 1993, well remembers watching real time position plots of Qantas 747 aircraft as they flew all the way from Sydney to London. This was amazing for the time and was referred to by some as "pseudo radar.” According to Brian, of particular importance was that it showed for the first time the tracks that aircraft were actually flying and not where they were supposed to fly.

8.1 **Initial service providers**

A number of Inmarsat Signatories were keen to start providing aeronautical services, and in 1989 three consortia were announced aiming to construct ground earth stations. However, Signatories also realised that to secure aviation communications business, particularly data, they had to associate with at least one of the two major airline communications providers, SITA or ARINC and the following associations were formed:

<table>
<thead>
<tr>
<th>Signatory Consortium</th>
<th>Aviation Communications Provider associated with Signatory Consortium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skyphone - British Telecom/ Norwegian Telecom / Singapore Telecoms</td>
<td>ARINC</td>
</tr>
<tr>
<td>Comsat /KDD (Japan)</td>
<td>ARINC</td>
</tr>
<tr>
<td>Satellite Aircom - OTC (Australia)/Teleglobe (Canada) /IDB Communications (US)/France Telecom</td>
<td>SITA (later also with ARINC)</td>
</tr>
</tbody>
</table>
Figure 5 shows the GES on Sentosa Island in Singapore operated by Singapore Telecom.

8.3 Avionics

The avionics to support these services were developed by various manufacturers, notably Rockwell-Collins, Honeywell, and Racal. The LRUs were originally in accordance with ARINC-741. These products have evolved considerably, though still within the original architecture. Figure 6 shows examples of satellite data units offered by Rockwell-Collins and Honeywell, but now, over 25 years after Aero Classic was introduced, the various manufacturers have developed rationalised product lines which are more compact and intended to simplify retrofitting as improved service capabilities are brought in by satellite operators. For example, the same LRU format can support also ARINC-781 for the newer SBB services (see later).

In 1988 British Airways equipped a 747-400 (and later a second) with pre-operational Racal voice equipment, and in conjunction with British Telecom (BT), very successfully demonstrated voice communication via BT’s Goonhilly (UK) ground earth station, and offered this as a pre-operational service to passengers ("Skyphone"). The trial received UK Government funding. In mid-1989 this trial, which used equipment not yet fully compliant with Inmarsat specifications, nevertheless was permitted to become operational, and Inmarsat started to receive payment for use of its satellites for aeronautical services. At about the same time the trial with the Canadian Air Ambulance Service was permitted to become a commercial operational service, although it, too, was using non-standard equipment.
In late-1990, following successful tests, an initial commercial voice service was authorised via the Goonhilly GES, the first GES to be authorised for service. Subsequently, the first satellite telephone installation complying with Inmarsat specifications on board an aircraft (a Gulfstream IV equipped with a Racal AES) was signed off by Inmarsat on 2nd November 1990. To mark the occasion a small ceremony was held at Inmarsat Headquarters in London and Gulfstream Director of Completion Engineering, Brian McCarthy, made the first inaugural call from a Gulfstream IV aircraft in Savannah, Georgia to Guntis Berzins, General Manager of the Inmarsat Aeronautical Division in London. This was the commencement of operational and commercial aeronautical services via Inmarsat. This created a situation in which passengers and cabin crew could make a phone call to anywhere on earth while airborne, but the pilots still had to struggle with HF, as portrayed pointedly in Figure 7.

Figure 7  Cartoon showing cabin crew with better communication than pilots (British Airways and Chris)

There was a lot of excitement from airline customers at the clarity of the connection using satellites when compared to HF. Many times in the middle of the night Inmarsat engineers were awakened with “guess where I am calls” from the middle of the Pacific.

The first commercial use of the Inmarsat data service is not clearly recorded, but it is recorded that in mid-1991 Qantas was the first airline to use the Satellite Aircom consortium low-rate data service for scheduled operations.
Inauguration of further GES's followed fast, and by mid-1990, besides the UK, GES's were also operational in the US (two), Canada, Norway, Australia (two), Singapore and Japan. The number of aircraft installations also grew fast, and by mid-1993, i.e. within 2½ years of commencing service, a total of 254 had been commissioned – 150 for voice, 104 for data. The most active airlines and number of installations, of which some were dual installations, were: United (39), Japan Airlines (20), Cathay (15), Singapore (15), and Qantas (10). About a third of the installations were on corporate jets (91).

8.4 Note on Position Determination

Classic Aero is a communication system, not a navigation or position determination system, but it registers every active and valid AES connected to the network, and maintains regular air-ground ‘handshakes’, even in the absence of traffic. By observing and recording the timing and radio frequency offsets of handshake messages it has been possible to estimate lines of position of aircraft. This can be relevant for accident investigation – see section 13.2.

9. Consolidation

So ends the story of the realisation of a vision – the successful development of an operational aeronautical satellite system which exemplified the aviation industry focussed and working at its best, and in which the authors were deeply involved. A development made possible by sharing satellites and other facilities, and thereby costs, with a maritime satellite system developed some years earlier. As mentioned previously, the resulting mature system is known as Inmarsat Classic Aero. It has become an integral part of oceanic ATM systems, and provides voice and data services to cockpit and cabin. It is fitted as standard to virtually all new wide-bodied aircraft, and is supported worldwide by seven Inmarsat satellites plus MTN (Japan).

In addition to supporting safety services, Classic Aero is used to provide in-cabin communications for passengers for voice and data using the passenger’s own GSM phone, for example by AeroMobile.

However, as in other forms of communications, the development of aeronautical satellite services has continued, both by Inmarsat and by others, as described in the following paragraphs, and has led to widespread use by airlines and passengers, as well as promising significant advances in air traffic management and accident investigation, advances which are as yet only partly realised.

10. Evolution of Inmarsat Aero

10.1 Satellite spot beam technology

The key to improving satellite communications capability lies in improved satellite antenna performance. The design of the ‘core’ system as outlined previously was constrained by the need for the basic data and voice services to work even with Inmarsat’s oldest and simplest
satellites, using respectively the low-gain and high-gain aircraft antennas. Those satellites are characterised by having a ‘global-beam’ coverage of the earth, which means they provide service, at least to a minimum level, over essentially all of the regions within the solid-line ‘circles’ shown in Figure 2.

By focussing the coverage of the satellite antenna such that it addresses a smaller part of the earth, the gain of the antenna increases in proportion to the reduction in covered area. So although less of the earth will be covered by the satellite beam, the gain will improve such that higher-rate services can be supported within those beams, using the same aircraft antennas. Coverage is maintained by increasing the number of beams (but the system has to be able to work in this multi-beam environment).

This principle applies of course to all mobile-satellite services, and accordingly, Inmarsat and other operators have been progressively adding higher-gain satellite antennas to improve the services that can be offered by a given size of mobile antenna. For Inmarsat, the process began at L-band with the Inmarsat-3 series of satellites, which from 1996 introduced regional beams to improve service capabilities in selected areas. The improved coverage regions are shown by the darker-shaded areas in Figure 2.

10.2 Evolution of the Classic Aero Design

Already with global-beam satellites, Inmarsat added the ‘Swift64’ service to Aero-H, which provides circuit-mode operation at rates up to 64kbit/s including ISDN-compatible services and uses a lower voice coding rate of 4.8kbit/s, improving resource efficiency. These installations are known as Aero-H+. There is also an intermediate-gain Aero-I version, with an aircraft antenna gain around 6-7dBi allowing voice and data services from Inmarsat’s third-generation satellites in the regional beams, and from all future generations supporting regional beams. In addition, certain system-level updates have been made to support TDMA sharing of the high-powered ‘P-Channel’ and operation with satellite regional spot beams. Today Inmarsat owns and operates a total of eleven spacecraft flying in geostationary orbit. Classic Aero has therefore been able to exploit the improved spacecraft beam technology – regional beams – to offer improved services.

In 2005 Inmarsat introduced its fourth-generation “I4” satellites which can each implement over 200 spot beams in addition to supporting 19 regional beams which cover the whole of the earth visible from each satellite. Figure 8 shows (left) an example of how I4 can lay down 200 beams, while simultaneously generating 19 regional beams (right). Each of the small spot beams has a diameter of about 1 degree, giving a gain advantage of about 300 times (over 20dB) compared with the I2 satellites. However, the Classic Aero design does not exploit this gain advantage because it was not designed to operate in such a multi-beam system. Twenty five years after its development, it is now dated, and Inmarsat has indicated that the Classic system Aero H service will be closed at end of 2018 \(^{(10)}\).
After Classic: Inmarsat’s new Aero Services

One reason that aero satellite communications became economically viable through Inmarsat was the sharing of satellites between land, sea, and air services. The next logical step in that process is to share more of the supporting infrastructure. The Classic Aero system is a custom design not sharing features with other Inmarsat standards. On the other hand, Inmarsat over the last decade has introduced a new service called BGAN (Broadband Global Area Network) which is a generic system able to support Internet services to land, sea and air domains at rates in the order of 400kbit/s. This system is a focus for Inmarsat’s development efforts, with the consequence that all these BGAN-based services may benefit from improvements and cost sharing.

BGAN applied to aviation is called the ‘Swift Broadband’ service (SBB) and it is now becoming Inmarsat’s standard aeronautical installation. It supports both voice and IP data services. An example of what this means in terms of service coverage is shown in Figure 9, Inmarsat’s illustration for the SB-200 service, as of September 2010.

Like Inmarsat Classic, SBB supports in-cabin voice and data services to passengers. For example, the Swiss company ‘OnAir’ (a SITA subsidiary) provides such services.

The SBB avionics are covered by ARINC Characteristic 781. Like Classic Aero, it uses high-gain and low-gain antennas, although the low-gain is specified to perform somewhat better than the original Classic low-gain.
Inmarsat has also proposed that SBB could be used to support future air traffic management and safety services and is working with appropriate agencies to implement ‘precursor’ demonstrations (IRIS-2017) in the broad context of the SESAR programme for future ATM services for Europe. The UK is providing funding to support these demonstrations and related systems work. In due course, this could feed into a possible global ATM standard.

Beyond BGAN, Inmarsat is introducing broadband satellite services delivered at Ka-band (19.7 – 20.6 GHz downlink, around 30 GHz uplink). These will use a new constellation of satellites in a system called ‘Global Xpress’, currently being deployed and shown in Figure 10 below. As with the L-band services, the new infrastructure will be shared between land, sea and air services. The underlying system design is developed from the mobile VSAT technology, and bit rates in excess of 1Mbit/s will be commonplace.

Growth in aeronautical services has been impressive. From the beginnings in the early-1990s, by September 2015 Inmarsat could indicate that for its SBB service the total active base of installed aircraft had increased to 6,883, of which around two-thirds are installed in the Business and General aviation segment; and for its legacy Classic Aero service the active base had increased to 7,632 aircraft.
11. Other Aero Satellite Systems

11.1 Iridium

The Iridium Satellite system is the only truly global mobile satellite voice and data system. With complete coverage of the Earth’s oceans, airspace, and Polar Regions, by virtue of using satellites in low earth orbits, Iridium delivers services to users around the globe. Iridium Satellite service began in 1998, but was commercially unsuccessful and went into Chapter 11 bankruptcy the next year. It was restarted in March 2001, and commercial satellite communications services were launched. The system is used extensively by the U.S. Government, and a new generation of satellites and terminals is under construction, ‘Iridium NEXT’, to provide enhanced voice and data communications. Iridium NEXT will also provide an opportunity to enable truly global, pole-to-pole surveillance as early as 2017. A company called Aireon plans to use hosted transponders on Iridium NEXT, Iridium’s next-generation constellation of 66 cross-linked Low Earth Orbit (LEO) satellites, to receive aircraft position and other data and relay these signals from Mode-S equipped commercial aircraft all over the world to air traffic controllers and aircraft operators on the ground. This system could be potentially a very valuable and effective long-term component for providing data reporting and messaging services, in competition with Inmarsat data services. On 11th November 2015 the ITU World Radio conference announced: “The frequency band 1087.7 - 1092.3 MHz has been allocated to the aeronautical mobile-satellite service (Earth-to-space) for reception by space stations of Automatic Dependent Surveillance-Broadcast (ADS-B) emissions from aircraft transmitters.”

11.2 New broadband services and providers

Nowadays, although Inmarsat is still the dominant mobile-satellite services operator, other operators from the fixed-satellite world are seeing aeronautical services as a potential market.
This involves the adaptation of VSAT-based technologies for aircraft communication. These initiatives are being driven by commercial considerations. The expectations of passengers to remain connected to the Internet during flights, using their own personal devices, have become a strong competitive driver. These broadband services are implemented at much higher satellite frequencies than the ‘Classic’ L-band based satellite communications. They use Ku band (11GHz – 14GHz) and Ka band (20GHz – 30 GHz), which allow much wider service bandwidths, up to tens of Mbit/s per aircraft. These services are currently being implemented, and Inmarsat itself is a key player in Ka band, with its new Global Xpress service. All these new systems are further examples of sharing satellite infrastructure and system capabilities between land, sea, and air, to share costs. However, compromises are needed. To provide the high bandwidths economically, the satellites need some ‘HTS’ (High Throughput Satellite) features, in particular spot beams having specific, limited coverage.

These beams are limited in number, and so they need to be used to cover the highest traffic-density aviation routes. This in turn means that outside these routes the full broadband services may not be supported, so for global coverage ‘off-route’ it is necessary to sustain the older, lower-bandwidth systems.

11.3 Future Aero Satellite communications Services

As recently seen from the growth of its broadband services, aero satellite communications can be expected to respond to emerging market demands by taking advantage of the general improvements in technology becoming available in the satellite communications world. Many solutions are possible for the basic satellite link, and at this stage it is not clear that a single technology standard will prevail. More likely, we may see the co-existence of multiple technologies including L, Ku and Ka bands, and some non-GEO satellite constellations, each case reflecting the perceived optimum for its owners and operators for their customers. In fact, the means of delivery is not of main concern to passengers: the unifying theme is the availability of a standard Internet WiFi gateway on the aircraft, allowing passengers to use their own devices. This has only become possible in the past 3-5 years.

For air traffic services, satellite communications is now anticipated almost universally to become an integral part, not only in terms of coverage in remote and oceanic regions, but as part of continental airspace management. In Europe, the main vehicle for developing the future air traffic management system is the research programme SESAR (Single European Skies ATM Research) sponsored by the EU and Eurocontrol. A detailed set of ATM service requirements is under advanced development through SESAR, including the satellite component, for which the system requirements become quite onerous. As with the development of Classic Aero, many system solutions are possible, and the main concept under development is called ‘ANTARES’. This approach calls for a completely new satellite system dedicated to ATM, and is planned to provide a sustainable long-term ATM capability at a user cost of €5 per flight. Whatever the outcome, of course, there remains the need to look beyond specific regions to ensure aircraft can interwork globally with the regional ATM systems.

In the USA, the FAA defines the future ATM system as “NextGen”, an incremental programme which is an upgrade to make full use of satellite navigation: “Satellite navigation
will let pilots know the precise locations of other airplanes around them. That allows more aircraft in the sky while enhancing the safety of travel. Satellite landing procedures will let pilots arrive at airports more predictably and more efficiently. And once on the ground, satellite monitoring of airplanes leads to getting you to the gate faster.”

12. **Inmarsat's involvement in navigation**

Besides communication, the aviation industry was highly interested in the emergence of satellite navigation systems, as they could radically improve aviation navigation. The US initially developed GPS and some years later the Soviet Union developed GLONASS, which employed somewhat different techniques. However, as these were national systems, and developed primarily for military purposes, with no guarantee of integrity, accuracy or continuity, there was understandable reluctance by the civil aviation community to accept them as primary navigation aids. Initially there was international pressure, including by Inmarsat, to make the later system, GLONASS, compatible with GPS, but this proved unsuccessful. The GPS service available to civilian users initially had a deliberate random error, so-called 'selective availability', to preclude its use by enemies for accurate military needs, which thereby considerably reduced its benefit to aviation. This error, or dither, could be removed in military receivers equipped with the required correcting code. To overcome this for civil use, the concept of differential GPS evolved, whereby the position given by GPS would be measured at a known ground location and a correction signal broadcast to users in the area. Eventually, it was realised that this concept could also enhance safety (and hence acceptance) by guarding against errors or failures in the satellite navigation systems. Inmarsat was very interested in the acceptance of satellite navigation systems for aviation and as a result decided to include a navigation transponder in its third generation of satellites, and subsequently also its fourth generation.

These navigation transponders are designed to augment GPS and GLONASS. They are used mainly by the US FAA for its Wide Area Augmentation System (WAAS) and the European Commission for its European Geostationary Navigation Overlay Service (EGNOS).

The three functions provided by these systems are:

- **Integrity** because the ground stations transmit the status of all the GPS and GLONASS satellites on the same frequency as the GPS signal. The signal is received directly by the GNSS receiver.
- **Increased accuracy** because the ionospheric delay at L-Band is measured at the ground stations and corrections sent to the aircraft.
- **Availability** because the Inmarsat satellites add four more “pseudo GNSS” satellites to the navigation constellations.

12.1 **GPS and GLONASS constellations.**

Using WAAS, in the USA, aircraft can access over 3,000 runway ends in poor weather conditions. WAAS can even guide aircraft to a safe landing in places where an Instrument
Landing System (ILS) may not be available. There are now twice as many WAAS procedures as there are ILS glide slopes in the U.S. National Airspace System.

13. Inmarsat’s role in Accident Investigation.

13.1 Air France 447 Rio de Janeiro to Paris

In June 2009, an Air France Airbus A330 flight AF447 was lost in the South Atlantic while flying from Rio de Janeiro to Paris. The pilots were manoeuvring to avoid storm clouds at the time. The aircraft's "black boxes" eventually confirmed what had already been signalled by automatic satellite messages from the aircraft, that the pilots had been confused by a loss of airspeed information lasting less than a minute. This lack of the basic airspeed information, required by the automatic flight control systems, was caused by ice crystals blocking the probes used to measure this parameter. What might be considered a minor loss of information set in train a sequence of events culminating in the catastrophic loss of the aircraft and all on-board. The autopilot handed control to the pilots, but they quickly lost control of the aircraft.

On the night in question Air France got 24 maintenance related messages via the Inmarsat AOR-W satellite and the Inmarsat Aeronautical Earth Station at Aussaguel in France and the SITA network. The messages all referred to system failures related to loss of airspeed sensing. Although the flight and cockpit voice recorders were not recovered until about two years following the crash, critical information relating to the impaired functioning of the pitot tubes under certain icing conditions was identified and the systems upgraded. An important early step was taken in preventing further accidents.

While Inmarsat was not directly involved in this investigation, the company took steps to store more data fields with the thought that this information could prove valuable in the future. It was, as indicated in the next section.

13.2 Malaysian 370 Kuala Lumpur to Beijing.

Malaysia Airlines Flight 370 was a scheduled flight that disappeared on Saturday, 8 March 2014, while flying from Kuala Lumpur International Airport to Beijing. In the case of the Malaysian Boeing 777, even though the systems that provided aircraft information were switched off or somehow disabled, the satellite systems continued to talk to the Inmarsat satellites. For this reason Inmarsat was able to determine that the aircraft had electrical power and was “powered up” for about 7 hours after communication was lost. The Inmarsat Indian Ocean Region satellite that received the signals was stationed 22,000 miles above the equator at 64 degrees east of the Greenwich meridian (see Figure 2). This point on the equator is about 3000 miles from Kuala Lumpur where the Boeing 777 took off. Unfortunately, this was the only satellite communicating with the aircraft, so a range will put the aircraft somewhere on a circle with the satellite at the centre. Taking other things into account it can be calculated that the aircraft was on an arc of a circle either north over Asia or south into the Indian Ocean. This information of course reduces the search area.
It seems, but has yet to be verified, that the aircraft crashed at the limit of its fuel reserves, about 1500 miles south west of Perth in Australia. The discovery in July 2015 of a control surface of the aircraft confirmed it had indeed crashed somewhere in the Indian Ocean. Why the automated communications systems failed and why nobody from the aircraft answered the calls from air traffic control may never be known, except perhaps in the event that the flight data and cockpit voice recorders are found.

Analysis of the timing and frequency changes of the signals received from the satellite were invaluable in locating the approximate position where the aircraft probably crashed. The fact that this data was available was thanks to additional storage capacity Inmarsat had incorporated during its ground network upgrade in 2013. This, in turn, was a direct result of the company’s assistance in the search for Air France 447 flight in 2009, where 229 people lost their lives.

14. Conclusion

The successful realisation of a vision – the development of an operational aeronautical satellite system - was made possible by sharing satellites and other facilities, and thereby costs, with a maritime satellite system developed some years earlier.

However, it is only recently that the aeronautical community has started to appreciate the real value of satellite systems. It is true to say that a golden opportunity was missed to take up the service in the 90s when it was first introduced. Claims that the service was too expensive are belied by the fact that the huge resources demanded in both manpower and equipment for HF voice operations were never entered into the equation. Another consideration was an attachment by the ATS authorities, and to a lesser extent the aircraft operators, to the glamour and enthusiasm associated with the uncertainty of HF.

Air traffic services authorities were also slower to embrace satellite communications than the airlines who very early on recognised the usefulness of reliable data communications for aircraft system monitoring and operational management. There is little doubt that undue emphasis on voice services and the much higher power and antenna gain requirements for these services delayed the uptake.

It is true even today that in many cases the passengers have better messaging capability than the pilots. Sharing capacity with other users such as mariners has made satellite services economical. The aeronautical community has realised that having dedicated satellites solely for traffic generated from aviation is not economically viable. Fears of satellite failures have also receded with adequate redundant coverage worldwide.

The advent of satellite services has revolutionised aircraft management for aircraft operators, particularly since the introduction of condition-based maintenance of aircraft engines and other systems. Very soon, with the increased take up by air traffic control authorities of satellite communication, navigation and surveillance systems, flights in oceanic and other remote areas will be able to operate much more efficiently saving large amounts in fuel and
time. This will be achieved with a level of safety considerably higher than is available with the necessarily wasteful and conservative separations of today.

Already, from the 7th February 2015, all aircraft operating from 35,000 to 39,000 feet (inclusive) on all tracks within the North Atlantic Organized Track System (OTS) are required to have Data Link capability (FANS 1A).

The authors are gratified that a quarter of a century ago, they were able to participate, with many others in the industry, in turning what was then only a vision into a reality.

References


Appendix 1  Trials and demonstrations

Trials and demonstrations supporting the aeronautical satellite communications development work for which Inmarsat provided space segment free-of-charge in the late 1980’s and early 1990’s

- UK and Spanish CAA trial of low data rate for air traffic control with aircraft from TAP, Varig, Sabena and a UK entity equipped with ESA PRODAT avionics (1987-1989); this trial was later modified to include SITA and to test airline operations. This project received funding from the British National Space Centre (BNSC) and was considered very successful. (Racal Avionics received the UK Queen’s Award for Technological Achievement in 1997 for its Satfone system.) The same system, with a different antenna, was installed on Gulfstream IV corporate aircraft. Most early voice installations were on corporate aircraft.

- Technical trial by Comsat with Mitre to test a Rockwell Corp. low gain system on an aircraft

- KDD (Japan) and Japan Airline flight trial of voice service to a 747 aircraft flying over the Pacific (testing use of 9.6 kb/s vocoders) (1987-1989);

- British Telecom, British Airways and Racal-Decca telephony service trial with two British Airways 747’s, which was released to passengers in Feb. 1989 on a test basis, and in Nov. 1989 became a pre-operational commercial Skyphone service;

- Canadian Research Corporation (CRC) test of low data rate service with a Canadian Air Ambulance aircraft equipped with a low-gain antenna, and flying in the far North, testing radio propagation at low elevation angles (1987-1988). Ultimately this became a commercial service around 1989.

- FAA programme in cooperation with Comsat and ARINC with two aims, firstly to evaluate the potential for air traffic control purposes of voice via satellite links equipped with low data rate voice codecs and secondly to gain operational experience and
demonstrate the utility of using satellite links for ADS. As part of this programme an FAA B-727 equipped with Rockwell-Collins avionics and working with a Comsat earth station was used to evaluate the voice transmission in early 1989. In parallel, FAA tested ADS in the North Pacific working with a Northwest 747-400 using Inmarsat during 1989 and 1990. The FAA also conducted a demonstration of ADS on a round-the-world flight in Dec 1989. Sometime in this period FAA decided to use ADS at Oakland US when available, and to allow United to discontinue use (but not carriage) of HF radio, subject to a four weeks proof of satellite communications reliability.


- The UK, Spanish, ESA trial made history on the 24th October 1988 when all messages to a Racal Jetstream on approach to Madrid Airport (including en-route descent, approach clearance, radar vectoring and weather) were given exclusively by low rate date via satellite and this became the first flight in the history of civil aviation to have air traffic services provided only by satellite.

- US National Science Foundation test in conjunction with Comsat and E-Systems conducting a series of flights with a satellite communications equipped Hercules throughout Antarctica, which showed that communication with the aircraft was possible even very close to the South Pole. (1990)

The authors

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Born in Riga, Latvia in 1938, Guntis is an Electrical Engineering graduate (specialising in Telecommunications) from the University of N.S.W. in Sydney, Australia. He joined the Overseas Telecommunications Commission (Australia) and from 1960 until 1980 held various engineering and management positions concerned with planning and operation of submarine cables, satellite earth stations and maritime radio stations, in his last position being responsible for the technical definition of the AUSSAT satellite system.

In 1980 he joined Inmarsat, initially as Operations Manager, then Technical Manager. In 1985 he became Assistant Director, Development, and from 1987 until 1992 was General Manager, Aeronautical Services Division, in both positions responsible for developing Inmarsat’s aeronautical satellite services. From 1992 to 1993 he was responsible for liaison with Central and Eastern Europe.

Guntis returned to Latvia in 1993, initially as Director of the Department of Communications (Ministry of Transport) as well as board member of the privatised “Lattelekom”. In 2002 he became a Member of the Latvian Parliament (Saeima) and served two terms (2002-2006 and 2009-2010), being elected Chairman of the Budget and Finance Committee during the second term. He retired in 2010.
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An Electrical Engineering graduate from University College Dublin, Fintan joined the Irish Aeronautical Radio Services in 1963 and worked at Dublin and Shannon Airports. In 1965 he was accepted as an Aer Lingus Pilot Cadet and for 20 years was an airline pilot with Aer Lingus, the last five as a senior captain. He was an "Accredited Accident Investigator" for the International Federation of Airline Pilots' Associations and has logged about 9000 flying hours, mostly on Boeing 737s.

In 1985 he joined Inmarsat in London and was a member of the team that designed their Aeronautical Satellite Communications, Navigation and Surveillance System. He has served on many International Civil Aviation Organisation (ICAO) Expert Panels including the All Weather Operations Panel and the Global Navigation Satellite Systems Panel.

A Chartered Engineer, Fintan is now retired but still doing occasional consultancy work.

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A UK national, Keith studied Electronic Engineering at Manchester University, followed by a Doctorate in Automatic Control. After working with the Marconi Company on communications systems design including maritime satellite communications, he joined the European Space Agency where he contributed to the definition and development of several space communication programmes such as ECS, Marecs, Meteosat, Olympus, and was responsible for several R&D programmes. He subsequently joined the recently-formed Inmarsat in London, responsible for new systems development. He consolidated the design concept for the new Inmarsat-C messaging system, and set up its technical development and implementation team. He subsequently formed and led the engineering team which designed and implemented Inmarsat’s aeronautical satellite service. He headed the engineering team of Inmarsat spin-off company, ICO Global, which designed an innovative satellite phone service. More recently, he has helped establish start-up companies built around public WiFi services in the UK. He then led a large systems engineering team which successfully delivered a major global satellite communications system for government and military customers. Keith is a Fellow of the IET, Life Member of the IEEE, and has been a Visiting Professor at the University of Surrey.