

# Competitive Analysis of Current and Upcoming Satellite Systems for ATM Services

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**Abstract –**

Satellites systems are a promising solution to cope with the capacity limitations of current air traffic control (ATC) systems. It is necessary to evaluate and assess existing and upcoming satellite systems taking into account air traffic management (ATM) requirements. This paper reviews a representative set of satellite communications (SatCom) systems and presents a competitive analysis based on objective criteria, to assess their suitability to support aeronautical services. Key drivers that should be considered for future systems design are identified and discussed. These key drivers are finally grouped to fulfil three complementary objectives that may not be possible to achieve through a single solution: improve service area, provide additional capability and capacity to existing terrestrial systems in high density airspace and to provide new services to passengers and airlines.

**Keywords – Satellite system analysis, satellite system comparison, satellite system design, Air Traffic Management (ATM), aeronautical services, ATM requirements.**

## I. INTRODUCTION

The availability of satellite systems for communication and navigation in conjunction with the forecasted increase in air traffic [1], and the capacity limitations of current Air Traffic Control (ATC) systems [2] lead to the necessity of assessing the possible use of these satellite-based services for civil aircraft operation.

This paper aims to evaluate existing and upcoming satellite communications (SatCom) systems from an Air Traffic Management (ATM) usage perspective and discuss their suitability to support aeronautical services. The provision of passenger services over satellite is also evaluated, since recent studies encourage the idea of providing cockpit and cabin services through the same satellite system. This option offers attractive costs benefits to both satellite operational costs and avionics costs, with the respective saving of space and fuel thanks to the reduction of required equipment.

An effort has been done to keep this evaluation as objective as possible. From the definition of measurable requirements in Section IV and their level of fulfilment, a competitive analysis among the SatCom systems reviewed is derived in Section V. The study covers end to end system aspects, avionics, and provided services. This information establishes the key drivers for future aeronautical SatCom systems design that are identified in Section VI.

The paper starts with a review of a set of SatCom systems in Section II. Section III presents the constraints that may offer the choice of a frequency band for

aeronautical services provision in terms of regulatory and channel impairments aspects.

## II. SATELLITE SYSTEMS UNDER EVALUATION

This section presents a brief review of existing and planned satellite communication systems that are used or might be used for aeronautical services. Obviously, a comprehensive review of all such satellite communication systems cannot be presented due to space limitations. During the selections of the systems to be reviewed, a good balance was aimed between different frequency bands (L-band, S-band, Ku/Ka-bands), between different orbital constellations (geostationary (GEO) and low low-earth (LEO) orbits), and between operational and planned systems. Accordingly, Inmarsat's GEO satellite system, MTSAT, Iridium LLC, Globalstar, Connexion-by-Boeing, ARINC SkyLink, and Mobile DVB-RCS satellite systems were selected for further review and evaluation.

### A. *Inmarsat*

Inmarsat fleet is comprised by 11 GEO satellites (four I2, five I3, and two I4 satellites) all operating in L-band user and C-band feeder links (see Table 1). Inmarsat **classic aero** services (Aero-L, Aero-I, Aero-H/H+) are designed to comply with the Standard's and Recommended Practices (SARPs) of the International Civil Aviation Organisation's (ICAO). Classic aero services are approved and operational today for voice and data Air Traffic Services on both Boeing and Airbus aircrafts, e.g. Automatic Dependent Surveillance (ADS) and Controller Pilot Data Link Communications (CPDLC) (see Table 1). In addition to classic aero, higher voice/data transmission rates – 64 kbps upto 256 kbps by

channel bonding – are provided by Swift64 Mobile ISDN (Integrated Service Digital Network) and Swift64 MPDS (Mobile Packet Data System) services thanks to the spotbeam technology of I3 satellites (maximum seven spotbeams).

The most recent members of the Inmarsat fleet, the two I4 satellites, can support upto 228 re-configurable narrow and 19 wide spotbeams in addition to one global beam. In addition to the main communications payload, the I4 also carry a Navigation Payload which is designed to support Satellite Based Augmentation System (SBAS) operations [3], which is a geostationary complement to Global Positioning System (GPS) to provide seamless precision navigation information over a wider area, increasing integrity, accuracy and availability of navigation data offered by classical GPS. In comparison to an I3 satellite, each I4 satellite can provide 60 times more power and 20 times more capacity. BGAN (Broadband Global Area Network) is designed to take advantage of this high capacity. BGAN defines a new air interface, IAI-2 (Inmarsat Air Interface-2), that supports symbol rates upto 151.2 kbauds/sec, QPSK and 16-QAM modulation schemes with adaptive Forward Error Correction (FEC) coding and modulation. Up to 432 kbps can be achieved with BGAN IAI-2. BGAN network architecture is based on UMTS Rel.4 with the UTRAN (UMTS Terrestrial Radio Access Network) replaced by the BGAN IAI-2. Thus, both circuit-switched and IP-based multimedia and data services can be supported in the QoS classes defined by UMTS specification. BGAN Aeronautical services that will be offered by BGAN are referred to as SwiftBroadband or Aero-BGAN. SwiftBroadband service launch is scheduled for the end 2006 and a service enhancement providing netted voice and multicast is foreseen to be operational in 2007.

Currently Inmarsat fleet can provide global coverage except in polar regions. There is full service availability in the coverage area at 5° minimum elevation angle. In addition to this almost-global coverage, Inmarsat's suitability for Air Traffic Management (ATM) service-provision is further reinforced by the high reliability of L-band satellite channels and the fact that Inmarsat's user link in L-band is primarily allocated to Inmarsat and includes the spectrum allocated to Airborne Mobile Satellite Service (AMSS) and AMS(R)S (Regional). To date, Inmarsat is the only global mobile satellite operator compliant with ICAO SARPs. The long propagation delays inherent to GEO satellites (minimum 120 ms earth-to-satellite) may exceed the delay constraints of some voice-based air traffic services. The capacity provided by Inmarsat classic aero services is sufficient to meet the requirements of aeronautical communications. Moreover, with I3 spotbeams and, especially, I4 satellites the new aero services (Swift64 and SwiftBroadband) will be able to provide capacity that is well beyond the needs of future ATM services. However, due to the limited bandwidth in L-band spectrum, it will be challenging to provide multimedia-rich, bandwidth-hungry services to aeronautical passengers in an effort to reduce the satellite-based ATM service cost to the airline operators. Each I4 has a total maximum instantaneous capacity of 400 Mbps.

#### *B. MTSAT*

MTSAT (Multifunction Transport SATellite) is a GEO satellite system owned and operated by Japanese Civil Aviation Bureau and Japanese Meteorological Agency. MTSAT has a twofold mission: aeronautical and meteorological, each having its

own payload working independently of each other. Aeronautical mission of MTSAT, which is planned to be for 10 years, provides services that comply with the ICAO SARPs. It is designed to be compatible and interoperable with Inmarsat system. The interoperability mechanism has been coordinated by ICAO.

Two MTSAT satellites co-exist in the same orbital slot providing hot redundancy, i.e., operating simultaneously, sharing the same traffic volume. MTSAT provides six L-band spotbeams in the north pacific targeting the expanding air route between Japan and USA. Four Ku-band and three Ka-band feeder links are used to provide communications with ground stations. Voice and data communication services are supported between aircrafts and air traffic controllers at 9600 bps. In addition to communication service, the MTSAT aeronautical mission provides navigation services based on SBAS, the GPS augmentation concept. This service is known as MSAS (MTSAT Satellite-based Augmentation System). The MSAS has been designed to be interoperable with the other two currently existing SBAS solutions, the US WAAS and the European EGNOS. This ensures seamless SBAS services through the entire world with only one navigation avionics equipment. To the best of our knowledge, MTSAT system is not operational, and there is no known date for entrance into service.

### *C. Iridium*

Iridium satellite system is composed of 66 LEO satellites, 11 in each of 6 orbital planes at 780 km height with 86.4° inclination. Co-rotating planes have a longitude separation of 31.6° in the Equator and the two counter-rotating planes of 22°, forming a "seam". With this 66 constellation configuration, Iridium system

provides truly global coverage anywhere on earth including polar regions. Although Iridium provides global coverage, the minimum elevation angle of the transmission path is an important parameter in the assessment of link quality [4]. In Iridium, the probability of visibility for one satellite is 100% with elevation angle of  $8.2^\circ$  and below. With higher minimum elevation angles the probability of visibility decreases. A satellite can be seen from the Earth with a minimum elevation angle of  $8.2^\circ$  and for an average interval of 9 minutes [5]. Each satellite supports 48 user spotbeams in L-band, a feeder link with a gateway in K-band, and four inter-satellite links (ISL) in Ka-band. Iridium system provides voice and data communication services at 4.8 kbps and 2.4 kbps, respectively. In aviation market, more than 2500 aircrafts use Iridium-based equipments that are used to deliver customised news, financial, sports and weather related data to the aircraft. In the maritime market, agreements with four companies are reported resulting in more than 300 ships receiving Iridium services.

The most distinctive feature of Iridium is on-board satellite switching; voice calls and data transmissions are relayed from one satellite to another until they reach the satellite above the Iridium Subscriber Unit (handset) and the signal is relayed back to Earth. Inter-satellite links (ISL) are possible from a satellite to its fore and back satellite in the same plane (intraplane ISL) and to its two nearest neighbours in adjacent co-rotating planes (interplane ISL). ISL in the seam (cross-seam ISL) is not supported, which means that communication between two locations on opposite sides of the seam must be routed over a pole. Therefore, despite the short propagation delays inherent to LEO satellites (2.6 to 5 ms earth-to-Iridium satellite), the end-to-end propagation delay experienced in Iridium system can be

upto 120 ms depending on the locations of the caller and the callee. In addition, on-board processing delay and speech compression delay increases a typical Iridium call end-to-end latency to 160 ms.

The L-band user link capacity that is primarily allocated to Iridium is 5.15 MHz. This bandwidth is divided into 120 carriers where each carrier can support four voice calls. Each one of the 48 Iridium spotbeams is allocated 10 such carriers. With a re-use of factor of four, each Iridium satellite can theoretically accommodate simultaneous 1920 voice calls. In practice, the number of simultaneous calls is power limited, and each satellite can support 1100 concurrent calls [8].

Iridium's global coverage, short latency figures, primarily allocated and reliable L-band spectrum ([1621.35-1626.5 MHz], albeit not part of AMSS and AMS(R)S spectrum) are in accordance with the general requirements of ATM services. However, Iridium's highly limited channel rate (4.8 kbps voice and 2.4 kbps modem data) may prove to be insufficient for future ATM services. In addition current Iridium satellites will reach their end of lives in 2014. To this date, we are not aware of any public plans either to improve Iridium air interface or to launch new Iridium satellites.

#### *D. Globalstar*

Globalstar satellite system is composed of 48 LEO satellites, orbiting in eight planes at  $52^\circ$  inclination, at an altitude of 1.414 km. The satellite orbits are optimised to provide highest link availability in the area between  $\pm 70^\circ$  latitude on earth excluding mid-ocean regions [9]. Extended coverage provides weaker signal

in middle north Atlantic region. Each satellite pass, as viewed from a user location on earth, typically lasts about 10 to 15 minutes. Each Globalstar satellite has 16 spotbeams and uses L-band in user uplink, S-band in user downlink, and C-band in feeder links. Unlike Iridium, Globalstar satellites are transparent satellites. Globalstar's basic design tenet has been to provide an extension to existing cellular telephone service [10]. Services supported by Globalstar include [11, 12] near-toll quality digital voice and asynchronous circuit-switched data transmission up to 9600 bps between user terminals, and between user terminals and PSTN/PLMN. Globalstar provides specially-designed communication solutions for in-flight voice and data services aboard both helicopters and fixed-wing aircraft, using small, omni-directional antennas. ARNAV RCOM-100 and NAT STX-100 provide circuit and packet-switched full-duplex data transmission at 9600 bps. An experimental system, QUALCOMM MDSS (Medium Data rate Satcom System) can provide 128 kbps packet data with an extension to 600 kbps with Globalstar.

Globalstar air interface uses QUALCOMM's CDMA technology and is based on IS-95 terrestrial cellular system standard, although there are significant differences in signal design, handover procedures, search strategies, etc. The total bandwidth in user link is 16.5 MHz, which is divided into thirteen 1.23-MHz carriers. The whole 16.5-MHz bandwidth is re-used in each of the 16 spotbeam. Moreover, with right-hand and left-hand circular polarisation the system capacity is doubled. A total of 120 traffic channels are defined for each 1.23-MHz carrier. However, since CDMA systems are interference-limited, the actual number of simultaneous calls that can be supported is lower. According to simulation

analyses in [13], each 1.23 MHz carrier between 16 to 19 calls can be supported at 9600 bps at a voice activity ratio of 0.4 and bit error rate of  $10^{-3}$ . According to these results, more than 6000 simultaneous calls can be supported with each Globalstar satellite. In addition to these figure, system call blocking probability is reported to be less than 2% in most regions, where call setup can take as long as 30 s [14]. In comparison to Iridium, end-to-end propagation delay is higher on the average (due to two satellite hops), but less variable. In comparison to Iridium, Globalstar constellation provides higher probability of visibility at higher minimum elevation angles [15]. However, note that Globalstar coverage is limited to  $\pm 70^\circ$  latitude.

Similar to Iridium, Globalstar delay budget may be sufficient to meet the requirements of ATM services. Globalstar air interface can provide higher transmission rates (upto 128 kbps reported) than can be attained with Iridium. However, the coverage of Globalstar system may prove to be too intermittent; large sections of earth such as sub-Sahara, Indian subcontinent, China, Indian ocean are still outside Globalstar coverage. Moreover, Globalstar cannot claim protection against interference from other CDMA-based mobile satellite systems over its L-band and S-band spectrum, which does not include AMSS and AMS(R)S spectrum. Finally, Globalstar satellites are approaching the end of their lives in about 2010. There is no public information available regarding whether or not new Globalstar satellite will be launched soon.

### *E. Connexion by Boeing*

Connexion by Boeing (CbB) system provides passenger communication services for in-flight entertainment via leased capacity over an existing global network of Ku-band GEO satellites and gateways. Each forward link from the ground to the aircraft via satellite uses a FSS (Fixed Satellite System) transponder that is received by many airborne terminals. Each airborne terminal may receive multiple forward links from the same satellite. For the return link from the aircraft to the ground via satellite, an FSS transponder is shared among multiple airborne terminals. Separate FSS transponders are used for forward and return links. The system has centralised protocols that control airborne terminal entry into the network, authorisation for the terminal to transmit, authorisation to change transmitted power/data rates and transponder assignment. The transmit power from each airborne terminal is monitored on the ground by the network operation centre (NOC) and managed within a narrow range on an individual and aggregate (per transponder) basis. The NOC also keeps track of the location and heading of each authorised aircraft in flight. Finally, fault management both on the ground and in the airborne terminals assures that no transmission will occur from any airborne terminal without positive control from the ground. The airborne terminal will automatically cease transmission if contact with the NOC is lost or if the NOC fails to send the periodic "keep alive" confirmation of authorisation to transmit. Both the forward and return link waveforms use direct sequence spread spectrum modulation. This reduces the equivalent isotropically radiated power (EIRP) spectral density of the waveform and allows multiple aircrafts to share a return link transponder using spread spectrum multiple access. The aircraft

forward link operates at a nominal information rate of 4.86 Mbps (one carrier per transponder) and the aircraft return link operates at information rates between 16 and 1.024 kbps (multi-carrier transponder). The chip rate is held constant (independent of data rate) so that the spreading bandwidth is equal to 90% of the transponder bandwidth. For a 27 MHz transponder the spreading bandwidth is 24.3 MHz.

A patchwork of beams supports continuous CbB coverage over CONUS, Canada, the NAOR, Europe, and most of Asia. Beam-to-beam and satellite-to-satellite handovers are supported for the seven transition regions across the coverage area. With the launch of the Worldsat-3 satellite coverage will be greatly expanded supporting flights throughout the Pacific Ocean Region. Additional satellite coverage is anticipated as airline demand for service increases.

CbB has worked with the world's radio regulatory community to provide a technical solution that strictly limits interference between 14.0 and 14.5 GHz. Three general categories of methods were used to eliminate interference; 1) reducing the total power spectral density, 2) actively monitoring and controlling total system power spectral density, and 3) controlling transmit antenna sidelobes. Special operational limitations are also being made to inhibit harmful interference to Radio Astronomy and Space Research users of the FSS frequency band. The regulatory process concluded with voting on Agenda Item 1.11 at WRC-03 secondary access to AMSS spectrum. Since WRC-03, CbB regulatory efforts have been focused on gaining country-by-country authorizations for AMSS operations in each individual jurisdiction.

CbB has demonstrated that it is today possible to define a constellation providing high-speed Internet access and in-flight entertainment services for airborne passengers over the main routes. In most of the cases, the capacity can easily be increased using additional transponders on-board the same satellites already used today. However, the lack of primary spectrum allocation, the high propagation impairments of Ku-band channels, and the currently patchy coverage of CbB raises questions regarding its eligibility for ATM services, which require high service availability and reliability. The fact that most existing Ku-band satellites do not cover oceanic areas also makes it difficult to improve the coverage to a global scale. In addition, due to the GEO satellite systems, end-to-end latency that can be provided by CbB may exceed the delay budget of some voice-based ATM services.

#### *F. SkyLink*

In October 2003, ARINC launched its “SkyLink by ARINC Direct” satellite broadband data system for business aircrafts. A new business unit, ARINC Satellite Services, combines the company’s GLOBALink/Satellite operations, which provides Inmarsat voice and data communications to airlines, government, and military customers, with its SkyLink Ku-band satellite business, currently targeted at the large business jet market. SkyLink provides high-speed Internet and Intranet services at 128 kbps on the upstream and 3.5 Mbps on the downstream. SkyLink operates with one or more leased transponders on SES Americom’s AMC-1 satellite at 103°W and a hub earth station in California. Currently, SkyLink coverage is limited over CONUS and border countries.

The most distinct feature of SkyLink is its bandwidth management scheme. User uplinks and feeder uplink use the same frequency band. In accordance, user downlink and feeder downlink use the same frequency band. The resulting system combines all signals from all Aircraft Earth Stations (AES) and the hub, and relays this combined signal to all AESs and the hub. The resulting combined signal is separated using Code Reuse Multiple Access (CRMA) and Asymmetric Paired Carrier Multiple Access (A-PCMA) schemes. A Network Management System (NMS) co-located with the hub earth station controls access to the SkyLink System and employs both open-loop and closed-loop power control to manage operation of logged-in AES terminals. The open-loop power control provides an estimate of the required uplink transmit power, based on a combination of the received signal strength at the AES receiver and an adjustment parameter provided in parameter-change messages from the NMS. The closed-loop algorithm accounts for signal losses and noise floor increases in both the return uplink to the satellite and the return downlink to the hub earth station and determines the content of the adjustment messages. The SkyLink System uses on-board and ground-based fault-management controls to minimize interference from malfunctioning AES terminals.

In comparison to CbB, SkyLink coverage is currently much more limited. Both systems, while providing significant transmission rates for Internet and Intranet access, face the same challenges in terms lack of primary spectrum allocation and Ku-band propagation impairments as far as ATM service provision is concerned. In addition, the peculiar bandwidth management of SkyLink, which may enable more efficient bandwidth usage for completely random traffic patterns, is

inherently unsuitable for voice communications since it relies on random access. Finally, the potential new satellites that may be used by SkyLink will have to provide symmetrical coverage for both uplink and download in order to comply with PCMA requirements.

*G. Mobile DVB-RCS*

Digital Video Broadcast - Return Channel Via Satellite (DVB-RCS) is an open standard targeting fixed broadband interactive services via Ku- and Ka-band GEO satellite systems. It is based on the broadcasting of a high-speed data carrier on the forward link, transmitted using either the DVB-S or the new DVB-S2 standards. Recently (beginning of year 2005), the DVB-RCS community has included in the guideline document of the DVB-RCS standard an annex (annex L: "Applicability of DVB-RCS to mobile services") demonstrating the capability of the DVB-RCS standard to support and provide services to mobile terminals. Currently, no mobile DVB-RCS system for aeronautical or other services exists. Several projects, like the project "DVB-RCS Adaptation to Mobile" of EADS Astrium in partnership with EMS Technologies (Canada) performed in the frame of the ESA Artes-3 program, or the MOWGLY project performed in the frame of the EC FP6 program, currently investigate, specify and design DVB-RCS solutions for mobile services (not only for aeronautical applications, but also for maritime and terrestrial applications). It demonstrates the high potential of this standard to provide broadband mobile services, in particular on-board the aircraft in the near future.

DVB-RCS is a return link specification. On the forward link, the transmission rates attainable depend on the selected forward link standard (typically 40 Mbps with DVB-S and 52 Mbps with DVB-S2 in a 36-MHz transponder). On the return link, DVB-RCS supports upto 2048 kbps. Dynamic capacity allocation is supported by the DVB-RCS uplink access mechanism that operates on top a MF-TDMA shared-medium uplink. Via Constant Rate Assignment, DVB-RCS is capable of accommodate constant bit rate applications such as voice. The total system capacity on the return link is in the order of 25 Mbps in a 36-MHz transponder.

Assuming the mobility-induced problems have been solved, Mobile DVB-RCS face similar problems with CbB. More specifically, the lack of primary spectrum allocation, the propagation impairments experienced in Ku- and Ka- bands, and the fact that most existing Ku and Ka-band satellites do not cover oceanic areas are the factors that work against the acceptance of Mobile DVB-RCS in ATM service provision.

### **III. FREQUENCY BAND ISSUES**

The frequency band is a parameter that critically determines the whole design of a SatCom system. This section is devoted to highlight two critical aspects link with the frequency band choice, regulatory constraints and link budget considerations.

#### *A. Regulatory Issues*

To offer any type of aeronautical applications, it is necessary to use a frequency band allocated to AMSS services. Today, various frequency bands have this allocation, but with different protection levels. L and S bands assume a primary

allocation for AMSS services, while at Ku-band, aeronautical applications only have a secondary allocation for the return link (aircraft to ground). This means that aeronautical services cannot claim any protection against potential jamming. More than this, aeronautical users will have to cope with coordination constraints set by the other users of the band. Since spectrum sharing is based on spatial discrimination between operational satellites, terminal antenna shall be able to accurately manage the signals coming from (or send to) the various satellites, meaning that omni-directional antenna are excluded. It should be note that, despite the coordination agreement has been defined considering fixed VSAT terminals, aeronautical (mobile) terminals will have to reach the same level of performances.

For ATC purpose, it is necessary to use a frequency band allocated on a primary basis to AMS(R)S on a world wide basis. Today, only L-band offers such an allocation [ref- ITU-R]. Mobile-satellite systems shall not cause unacceptable interference to, or claim protection from, AMS(R)S communications.

#### *B. Impact on Link Budget*

Propagation impairments affecting satellite communication systems strongly depend on the frequency. While L and S bands suffer from ionospheric effects, as Faraday rotation and scintillation, Ku and Ka bands are sensitive to atmospheric effects, namely to rain and clouds attenuation. Faraday rotation is counter measured with circular polarisation. Scintillation depends also on the solar activity and on earth location and can reach up to 20 dB; for a link availability of 99.5% of the time a fading margin of 6.5 dB has to be accounting in the link

budget [16]. Signal attenuation due to rain can become very important at Ku and even more at Ka-band. Intense rain events may drastically reduce local link availability for long periods of time for aircraft altitudes below 5 Km. Propagation losses obviously increase with frequency for the same constellation type and therefore higher antenna sizes are required.

#### **IV. EVALUATION PROCEDURE AND REQUIREMENTS DEFINITION**

A systematic evaluation procedure has been defined to conduct an objective competitive analysis among the systems described in Section II. This evaluation procedure is inspired in the approach followed in [17], which has been adapted to the satellite case. Tables 2 to 5 summarize the requirements used for this analysis split into four categories: related to cockpit voice services, cockpit data services, cabin data services and ATM general requirements. Requirements identifiers in Table 5 are later used to describe the metrics for the evaluation process. The first three requirements categories cover functional, capacity and performance requirements.

A trend towards more data based services in ATM applications in front of a decrease of voice based services is happening. Nevertheless, it has been considered important to evaluate voice services with the same importance as data services in this study. Even if this evaluation pretends to present a future perspective view, it is not likely that ATM voice services will completely disappear.

The evaluation procedure consists on assigning a score to each requirement according to a criterion evaluation. The possible scores are limited to 1, 0.5, and

0, which use to correspond to (i) the evaluated system requires no modifications or very small and/or low risk modifications to fulfil the requirement, (ii) the evaluated system requires moderate modifications to meet this requirement, and (iii) the evaluated system can not reasonably implement this capability with moderate modifications. Other cases are specified in the tables.

#### A. *Evaluation Metrics*

One score is obtained for voice cockpit (*VoiceCockpit*), data cockpit (*DataCockpit*) and data cabin (*DataCabin*) resulting from an average of their own scoring weighted by a figure derived from ATM general requirements scoring.

The weighting factor used for voice and data cockpit marks is given by

$$CockpitWFactor = [(1'+2')/2+3'+4'+5'+(6'+7')/2]/5 \quad (1)$$

and the weighting factor used for cabin data mark is

$$CabinWFactor = (1'+3'+6'+7')/4 \quad , \quad (2)$$

where the quoted numbers in (1) and (2) refer to the scores given to the requirements with these identifiers as listed in Table 4.

The final score of the satellite system is finally calculated according to

$$Score = 0.4 \cdot VoiceCockpit + 0.4 \cdot DataCockpit + 0.2 \cdot DataCabin \quad , \quad (3)$$

provided that none of them is scored with 0, otherwise the final rate is also 0. Note that less weight is given to cabin data score, since ATM services are the main focus of this competitive analysis.

A different factor has been used for cockpit and cabin services because certification for secure services, spectrum protection and support of authentication and integrity do not play an important role for cabin communications provision.

## V. EVALUATION RESULTS AND DISCUSSION

After rating all requirements shown in Tables 2 to 5, the scores are calculated as explained in Section IV and the results are presented in Figures 1 and 2. Intermediate results are shown in Figure 1, where the score obtained by each satellite system in terms of Cockpit Voice, Cockpit Data and Cabin Data criteria can be observed and compared also with the weighting factors that will be applied to the rating of Cockpit and Cabin services, respectively.

The results show that in general, L-band systems are more appropriate for voice services, while Ku/Ka-band systems are more suited for data services. MTSAT and Iridium score 0 for cabin data services due to the low data rates offered, while SkyLink scores 0 for voice services, since it does not provide real time applications.

Several satellite systems achieve high scoring for specific services, but only Inmarsat and Globalstar, followed by DVB-RCS, get high scoring for all scoring criteria (especially Inmarsat presents a very good balance). However, Mobile DVB-RCS is significantly penalized by both weighting factors, which are conditioned by the cost of aircraft avionics (more expensive in general in Ku/Ka-Band), the signal availability, the spectrum protection status (not protected in these bands) and certification risk for safety related services of the technology. On the other hand, Iridium is favoured by the weighing factor for cabin services, mainly due to the cheap terminals, the maturity of the technology for aeronautical communications and the global coverage.

The scores in Figure 1 are combined with the corresponding weighting factors by multiplying them in order to provide a single score per service category and

satellite system. Finally, each satellite system is given a single score by combining the contributions of each services area, according to equation (3). These figures, depicted in Figure 2, allow comparing the competitiveness of the analysed satellite systems from an aeronautical service point of view. However, it should be noted that the relative importance given to each service in equation (3) is subject to the authors criteria.

In Figure 2 it can be observed that Inmarsat leads the ranking (MTSAT and Iridium are scored with 0, since they do not fulfil cabin service requirements). However, the relevance of the availability of cabin services for the provision of ATM services is again subjective. Cabin and cockpit services can be provided using the same or different satellite systems. The second solution is currently preferred by the most conservative ATM stakeholders, since it appears to be an intrinsic secure solution for cockpit communications, although this has not been strictly demonstrated. However, the benefits of using the same system are very attractive: the amount of hardware to be carried is reduced (saving fuel) and offering commercial services allows for easily covering investments and costs. The security implications of each solution are for further study.

In summary, the selection of a satellite system for the provision of cockpit services should be only influenced by the availability of cabin services if both services are going to be deployed with the same satellite system. In this case, Inmarsat is, in short term, the most competitive satellite system by far among the analysed ones.

## **VI. DRIVERS FOR SATCOM SYSTEM DESIGN FOR ATM APPLICATIONS**

Besides the requirements described in Section IV, there are other relevant aspects, which are either too subjective to be rated or not so critical to be considered in the rating process, but still important to the final evaluation. This would be the case of longevity and commitment of the satellite system operator to offer ATM services, compliance of the used standards with ICAO SARPs for AMSS, operational costs, and acceptable transition characteristics including return on partial investment. It might be also interesting the possibility of supporting a combination of communications and navigation services or SBAS. These issues are not reflected in the previous evaluation process, but are aspects to be considered before choosing a SatCom system for ATM/ATC service provision. In the same way, regulatory constraints discussed in Section III are a key driver when designing a SatCom system for ATM provision. This section deals in detail with another critical issue, aircraft terminal aspects, and discusses later key drivers for ATM SatCom system design.

### *A. Aircraft Terminal*

Aircraft antenna technology maturity depends on the considered frequency band. While flat high gain antennas are available affordable at lower frequency bands, they become expensive at Ku and Ka-bands. Indeed, it seems that the first version on the phased array antenna design for CbB has been disused because of the difficulty to reach a solution fulfilling both technical and financial requirements. One of key impact is related to the size of the antenna. The key points are that for L and S band, designs ranging from omnidirectional antenna to high gain antenna

can be imagined, while for Ku and Ka-band, regulatory constraints impose the use of “high” directivity antenna.

In addition, the terminal complexity will depend on (i) the need for satellite tracking mechanism for non-omnidirectional antenna; (ii) the air interface definition including waveform and the link control mechanism, that could include fade mitigation technique or power management for compliance with regulatory constraints, cope with potential bottlenecks like limited spectrum, limited energy, multipath fading and propagation loss; (iii) the implemented mechanisms at upper layer like mobility management (which deals with the capability to authorise (small) interruption of active session), QoS management (prioritisation of network traffic), resources management (which deals with the capacity of the system to allocate satellite capacity according to the end user needs with particular rules and constraints). Each of those potential functionalities may induce extra power consumption and higher volume of the overall equipment.

#### *B. Key Drivers for ATM SatCom System Design*

The design of a complete SatCom system has to take into account various parameters, and to try to find an “optimal” trade-off between the different solutions. Key parameters that should be considered for future systems design are discussed in the following.

##### 1) End user requirements

This is probably the most critical point, since end users requirements are very difficult to collect and to sum up. Nevertheless, there is a need to distinguish between cockpit application and cabin applications as their requirements in terms

of capacity and reliability are opposite. Performances have to be in line with end users expectations, especially considering service availability since it could imply a lot of constraints on various part of the system. The service availability can be divided in link availability and resource availability.

## 2) Available spectrum

The availability of the frequency band is a key issue for cockpit applications, for which priority over other services is mandatory.

## 3) Regulatory issues

Both certification and licensing aspects have to be carefully considered, for both cockpit and cabin applications. Existing standards and services should be considered to avoid useless development and to refine system requirements.

## 4) Aircraft constraints

These are related to outside and inside aircraft unit. Power consumption, weight and size will be critical whatever the final application.

## 5) Satellite constraints

These mainly come from the selected orbit, which will impact both transmission delay and potential services area. Ground segment will be responsible for the system management and efficiency (resource management, mobility management) and for the interoperability with other networks, such as the air traffic network (ATN).

## 6) Propagation impairments

Channel constraints mainly concern cockpit applications, for which high reliability will be required.

## 7) Operational cost

Operational cost should be comparable with terrestrial solution. This is true for cockpit applications (price comparable to HF or VHF communication) and for passengers applications (service price should be roughly the same as for terrestrial services).

Considering aeronautical services the objective should not be to enlarge the competition between technical solutions, but provide improvement to existing solutions.

### *C. Final Considerations*

Trying to manage all potential improvements in a single solution may be difficult. Thus, key drivers for ATM SatCom system design have been split according to the three potential objectives.

First objective would be to improve service area. In this case, geographical availability will be a key driver. If the Poles can be excluded, then GEO constellation can be used. In this case, a minimum of three satellites would be required, but this could increase according to redundancy requirements. If a polar coverage is mandatory, then non-GEO satellites would be the only option. In this case, LEO, MEO and HEO orbits would have to be considered. The direct impact would be the need for more satellites. In addition, ground segment and/or space segment complexity would be increased, as is the case for Globalstar and Iridium

systems. Various combinations using GEO and non-GEO satellites can be envisaged to improve the coverage over given area. For the other areas of the Earth, providing an ad-hoc coverage will not face major issues, except the need to guarantee the financial viability of the solution. If aeronautical users are the only one, the cost of the service may be prohibitive.

The second proposed objective would be to provide additional capability and capacity to existing terrestrial solutions in high density airspace. In this case, the high availability of the system would be a key driver. This means that physical link availability would have to achieve the levels of the terrestrial solutions; ad-hoc quality of service would be required (especially considering priority of services aspects), and the aircraft avionics would have to be implemented in a very wide range of aircraft. In addition, seamless interaction with terrestrial infrastructure would be mandatory. Areas of high density airspace tend to have efficient, highly interconnected, ground infrastructures dedicated to communications (such as GSM for example). In consequence, it is difficult to envisage a situation where a satellite system could hope to compete with these systems on a cost effective basis. It follows that providing services additional to an aeronautical service in order to make a satellite system a commercially viable prospect can only be achieved if the new services are themselves somewhat specialised.

The third objective would be to provide new services to airlines and passengers. Since those services are not linked to flight safety, innovative communications solutions can be envisaged. In this case, geographical availability could be an issue, especially if it is required to provide service over the North Pole. Another

point to considerer is the possibility to adapt available services depending on the size of the aircraft or the category of the flight. From a technical point of view, a seamless integration with terrestrial technology appears mandatory. End users should be able to use the same equipment they use in their everyday life. The operational cost of the service would probably be the key driver, forcing the optimisation of the allocation of satellite resources, data compression and the encapsulation efficiency and the aircraft terminal, especially the size of the antenna. Finally, it should be noted that only private funding is envisaged for this type of application. Therefore, compatibility with other markets will also influence the design of the system.

## **VII. CONCLUSIONS**

This paper presents an overview of the existing and planned satcom systems that could be used for aeronautical applications. Although all these systems already provide, or may provide in the future, aeronautical services, only MTSAT was designed specifically for aeronautical purposes. All the other systems share some parts of their network (space segment or ground segment) with other applications, such as terrestrial or maritime for instance.

For each system, attention has been given to the various elements that make up the entire system, such as the aircraft terminal, the space segment, and the ground segment. In addition, a particular emphasis has been placed on the frequency bands used, since this directly impacts the definition of the entire system. Compatibility of the available spectrum with the demand placed on the system affects the various parts of the system (satellite payload, aircraft terminal, ground

segment, constraints on the physical link, etc). For cockpit applications, it stands out that the need for high reliability favours L-band systems which, as of today, are the only systems that provide AMS(R)S allocation. For cabin applications, cost and capacity provided by Ku- or Ka-band system make them viable competitors.

Based on the satellite systems description of Section II, a competitive analysis has been presented in order to underline advantages and drawbacks, and to identify required improvement regarding user requirements. This confirmed that for cockpit services, L-band systems (namely Inmarsat, MTSAT, Iridium and Globalstar) are clearly more suitable, whilst the Ku-band systems have appeal for passenger services.

Nevertheless, as could be expected, none of the analysed systems fulfil the overall requirements. This stems from the wide diversity of potential aeronautical applications. Cockpit applications require low data rate and high availability, while cabin applications need high data rate but are less sensitive to service disruption.

Since an all-embracing system does not seem to make sense, it has been proposed for the future studies to distinguish between the three complementary objectives: improve service area, provide additional capability and capacity to existing terrestrial systems in high density airspace and to provide new services to passengers and airlines.

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Tables:

Table 1:

Classic Aero Service Summary

Service	Antenna Gain (dBiC)	Voice Codec Rate (bps)	Data Rate (pre FEC) (bps)	Typical HPA Power (W)	Service Type	Availability Per Satellite Generation and Beam Used		
						I1	I3	I4
Aero H	12	9600	600, 1200, 10500	40	Real Time	Yes, Global Beam	Yes, Global Beam	Yes, Global Beam
Aero H+	12	4800	600, 1200	40	Real Time	No	Yes, Global & Spot Beam	Yes, Global & Regional Beam
Aero L	0	n/a	600, 1200	40	Real Time	Yes, Global Beam	Yes, Global Beam	Yes, Global Beam
Aero I	6	4800	600, 1200	20	Real Time	No	Yes, Global & Spot Beam	Yes, Global & Regional Beam

Table 2

Cockpit voice requirements and corresponding evaluation criteria

Requirement Description	Evaluation Criteria
The system shall be able to setup and maintenance of a group conference call between a controller and all of the pilots in the domain of that Controller (partyline).	1 Fulfilled
	0.5 Modifications needed
	0 Not fulfilled
The system shall be able to support a call and dialog between a controller and a selected pilot that is not overheard by other pilots.	1 Fulfilled
	0.5 Modifications needed
	0 Not fulfilled
The system shall provide a voice broadcast capability.	1 Fulfilled
	0.5 Modifications needed
	0 Not fulfilled
The system shall allow pilots to talk directly with each other without requiring other intermediary facilities.	1 System has mesh connectivity regenerative payload, or requires very small and/or low risk modifications to meet this requirement
	0.5 System supports ground switching without by passing a backbone network
	0 System can not reasonably implement this capability with moderate modifications
The system shall provide a capacity increase with respect to current ATC systems.	1 At least double capacity increase
	0.5 Moderate capacity increase
	0 Maximum marginally more capacity increase
The system shall be able to manage a talk group of 20 users.	1 > 20
	0.5 = 20
	0 < 20
The system shall dynamically manage Talk Groups as aircraft members join and leave (aircraft mobility management).	1 Fulfilled
	0.5 Modifications needed
	0 Not fulfilled
End-to-end one-way voice latency for 95% of the time without considering setup time shall be lower than 250 ms.	1 <=250 ms
	0.5 250 to 400 ms
	0 >400 ms

Table 3

## Cockpit data requirements and corresponding evaluation criteria

Requirement Description	Evaluation Criteria	
The system shall support air-to-ground and ground-to-air Addressed Data Transport.	1	Fulfilled
	0.5	Modifications needed
	0	Not fulfilled
The system shall support ground-to-air Broadcast Data Transport	1	Fulfilled
	0.5	Modifications needed
	0	Not fulfilled
The system shall allow pilots to exchange data with each other. It is not necessary that this function be provided as a direct avionics-to-avionics transport (as is the case with pilot-to-pilot voice). An intermediary option is acceptable when provisioning this service.	1	Fulfilled
	0.5	Modifications needed
	0	Not fulfilled
The system shall provide a symmetrical aggregate data rate per aircraft of at least 2 Mbps.	1	$\geq 2$ Mbps
	0.5	31.5 kbps to 2 Mbps
	0	$< 31.5$ kbps
The system shall be able to manage more than 200 addressed user per group.	1	$> 200$
	0.5	20 to 200
	0	$< 20$
The system shall offer QoS for different priority levels such that traffic at a lower priority does not degrade higher priority traffic beyond its required QoS for both up- and downlink.	1	Fulfilled
	0.5	Modifications needed
	0	Not fulfilled
The system shall meet end-to-end latency requirements by classes of traffic as specified by ICAO.	1	The system meets ATSC Class B: 4.5 s.
	0.5	The system meets ATSC Class C: 7.2 s.
	0	The system meets ATSC Class D or lower: 13.5 s

Table 4

## Cabin data requirements and corresponding evaluation criteria

Requirement Description	Evaluation Criteria	
The system shall support air-to-ground and ground-to-air Addressed Data Transport.	1	Fulfilled
	0.5	Modifications needed
	0	Not fulfilled
The system shall support ground-to-air Broadcast Data Transport	1	Fulfilled
	0.5	Modifications needed
	0	Not fulfilled
The system shall provide a downlink aggregate data rate per aircraft of at least 5 Mbps.	1	$\geq 5$ Mbps
	0.5	250 kbps to 5 Mbps
	0	$< 280$ kbps
The system shall provide an uplink aggregate data rate per aircraft of at least 1 Mbps.	1	$\geq 1$ Mbps
	0.5	128 kbps to 1 Mbps
	0	$< 128$ kbps
The system shall support VoIP. This facilitates the interface between the modem and the cabin network.	1	Fulfilled
	0.5	Modifications needed
	0	Not fulfilled

Table 5

## ATM general requirements and corresponding evaluation criteria

Identifier	Requirement Description	Evaluation Criteria	
1	The system shall have a mature Technology Readiness Level for introduction to the market.	1	Already operational
		0.5	Demonstrated in trials
		0	In development
2	The system shall be either currently certified for safety related services or known to be in this certification process.	1	Fulfilled
		0.5	Reasonably expected to be soon fulfilled
		0	Other situations
3	The cost to aircraft avionics including the modem and the antenna shall be less than 25 k\$.	1	$< 25$ k\$
		0.5	25 to 150 k\$
		0	$> 150$ k\$
4	The system shall use a spectrum assigned based upon the extent to which the potential frequency bands are consistent with aeronautical safety critical communications.	1	Fulfilled
		0.5	Reasonably expected to be soon fulfilled
		0	Other situations
5	The system shall support authentication and integrity.	1	Fulfilled
		0.5	Modifications needed
		0	Not fulfilled
6	The system shall offer global coverage or be compatible with a system offering global coverage.	1	Global coverage or compatible
		0.5	GEO coverage or compatible
		0	Regional coverage or compatible
7	Under LOS conditions the system shall be available for All Flight Phases (AFP).	1	AFP
		0.5	During cruise
		0	Not in cruise

Figure captions:

Figure 1:

Cockpit voice, cockpit data and cabin data average scoring with their respective weighting factors for each satellite system under evaluation.

Figure 2:

Cockpit voice, cockpit data and cabin data final scoring after weighting and final global score for each satellite system under evaluation.

Figure 1:

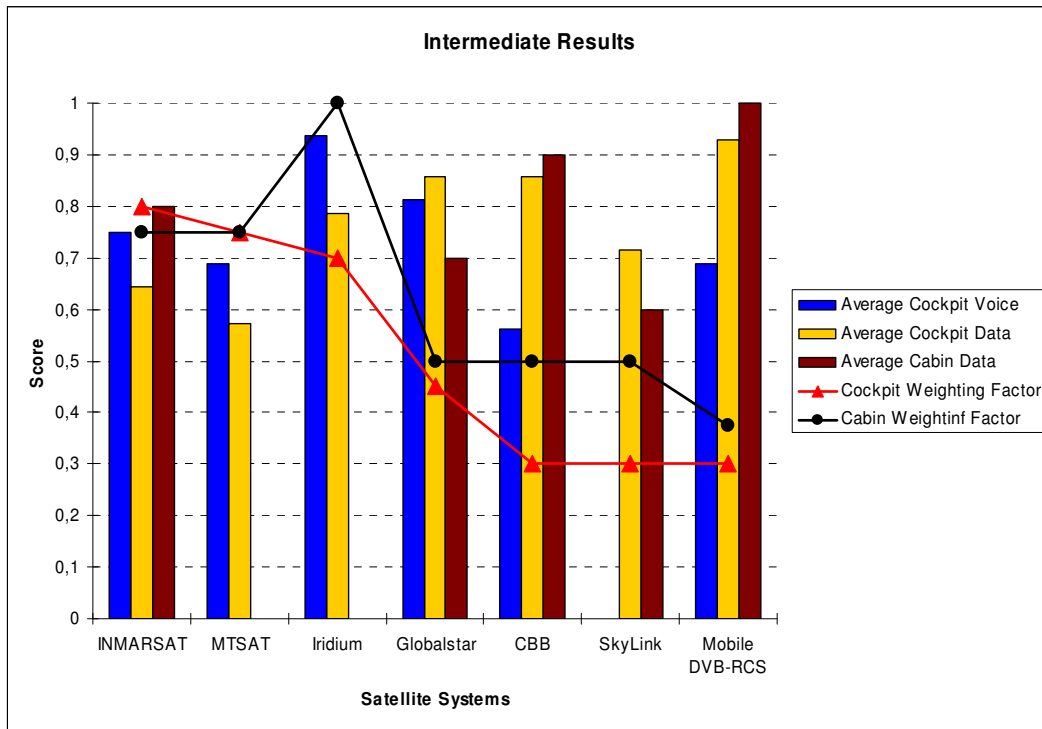


Figure 2:

