Space-Based Automatic Dependent Surveillance Broadcast (ADS-B) Payload for In-Orbit Demonstration

A satellite-based solution for aeronautical applications.

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***Abstract*—Automatic Dependent Surveillance Broadcast (ADS-B) is a technology that enables Air Traffic Management (ATM) services by means of aircraft broadcasting signals including flight related information on a regular basis. Terrestrial-based ADS-B infrastructure is already deployed as alternative or add-on to radars. However, it is not feasible for remote, polar, and oceanic areas, accounting for 71% of the world surface. Space-based ADS-B is an innovative technology that covers this gap by making use of satellites to provide global coverage. Thales Alenia Space Deutschland GmbH is leading the "Space Based ADS-B In-Orbit Demonstration Payload Development for Air Traffic Surveillance Project" (SABIP) under the framework of the European Space Agency (ESA) General Support Technology Program (GSTP). This project is mainly aimed at demonstrating the functionality of this technology under representative space environment conditions, and to verifying the link budget of this payload for the various ADS-B compatible equipment onboard aircraft on different geo-locations. This paper goes through the mission requirements that drive the payload system design and introduces an advanced architecture, consisting of a dedicated antenna and a receiver unit. Likewise, it introduces benefits behind the development of this technology. ESA's support for the In-Orbit Demonstration (IOD) of this technology, expected in the final phase of this project, is key to lower the technical risks and hence, helps introduce this new technology.**

Keywords: space-based ADS-B, satellite-based solutions for aeronautical applications, advanced payload architectures, in-orbit demonstration, emerging technologies.

I. INTRODUCTION

Automatic Dependent Surveillance Broadcast is a data link principle based on aircraft broadcasting signals containing existing aircraft onboard data during all phases of flight on a regular basis. The signal includes flight related information such as position, speed, flight number; enabling air-to-air and air-to-ground surveillance, as depicted in Fig. 1. ADS-B Mode S 1090ES data signals are broadcast (ADS-B out) at low L-band frequencies (1090 MHz) with typical periodicity of 0.5s to 5s, with a power from 125 Watts upwards for the aircraft to be considered in this context.

ADS-B is primarily a terrestrial based system. Terrestrial based ADS-B services are currently deployed as an add-on to radars or as an alternative in regions were a traditional ATM system based on radar stations is not cost effective. The ADS-B services will thus extend ATM services in those areas where a ground based infrastructure can be installed.

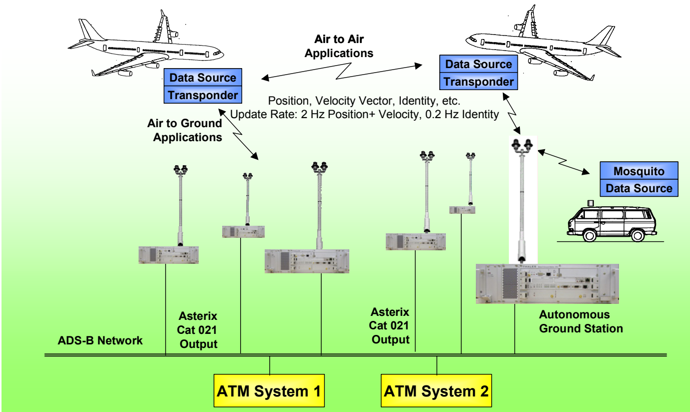

Figure 1. ADS-B principle.

ADS-B is one of the most important underlying technologies to complement the radar-based air traffic control with Global Navigation Satellite-based Systems (GNSS). As cornerstones of the Single European Sky ATM Research (SESAR) programme and the U.S. Federal Aviation Administration (FAA) Next Generation of Air Transportation System (NextGen) plan, ADS-B will be the global standard for

ATM and will provide significant benefits to commercial airlines through the world before year 2020.

However, for most areas of the world, the installation of an ATM network based on radars or terrestrial ADS-B stations is not cost effective either and too complex. This is particularly true for the oceanic areas, which account for the 71% of the World surface, but also for continental areas such as Africa, South America, South East Asia, and the North Pole. A complete surveillance of these remote areas (so called non-radar airspaces, NRA) by terrestrial services is beyond the current technical and budgetary means, hence confining the reach of Air Traffic Control (ATC) operations to the land masses where radar and/or ADS-B are deployed.

A potential solution for this limitation is to monitor the global air traffic via satellite. A space-based solution deploying ADS-B receivers on satellites can enable universal air traffic surveillance services by providing true global ADS-B coverage over oceans, the poles and remote areas. Fig. 2 depicts the primary areas of interest, which are most particularly those oceanic Flight Information Regions (FIRs) with a lot of trans-oceanic traffic and the polar routes.

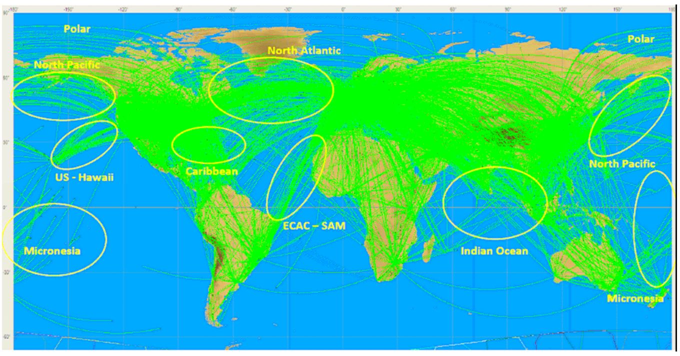

Figure 2. World air traffic flow and potential service areas of primary interest.

II. SPACE-BASED ADS-B CONCEPT

Space-based ADS-B is based on the acquisition by satellite of Mode S 1090MHz Extended Squitter data signals broadcasted by an aircraft [1]. Once received by the space payload, the ADS-B data gets downlinked in real time to the ground and consolidated before relayed to the Air Navigation Service Providers (ANSP) systems. Fig. 3 shows how space-based ADS-B technology complements existing systems.

However, the reception of ADS-B signal by the space payload imposes several technical challenges:

- ADS-B shares the radio-frequency (RF) channel with all radar and Traffic Collision Avoidance System (TCAS) surveillance signals. The traffic generated by that surveillance signals in high density areas exceeds the ADS-B traffic by a factor of five and more.
- ADS-B broadcast is on a random-access basis on the RF channel, so there are no fixed time-slots available. Hence, a high number of aircraft cause overlapping signals.
- For space-based ADS-B the area from which extended squitters are received is much larger than for the terrestrial case. For example, for a low Earth orbit (LEO) the footprint diameter is approximately 3200 nautical miles compared to approximately 200 nautical miles for a terrestrial receiver. Consequently, a space-based receiver could be flooded with extended squitters if areas with a high density of aircraft enter into the footprint (see Figure 4). This significantly degrades the detection of squitters for the actual area of interest.

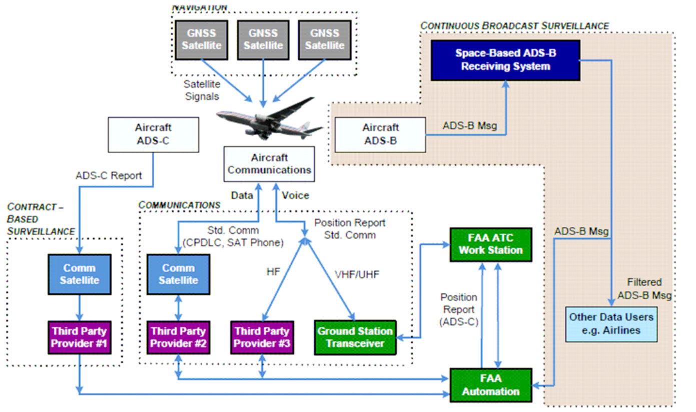

Figure 3. Space-based ADS-B system complementing existing systems. Source: U.S. Federal Aviation Administration [2].

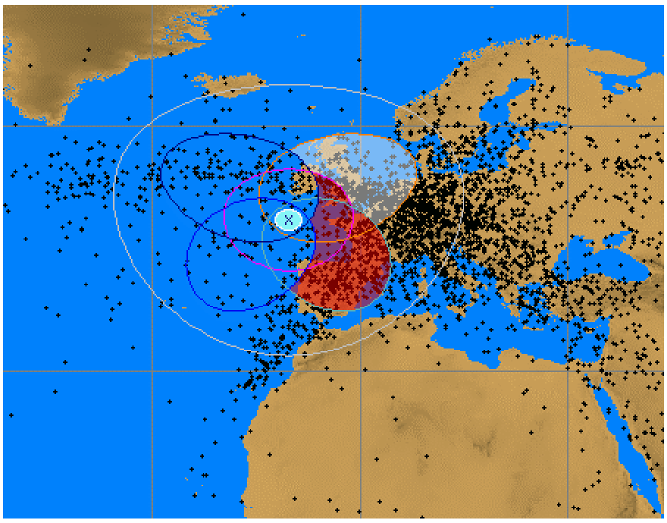

Figure 4. Multi-beam antenna footprint over Europe.

A later operational system will have to ensure worldwide coverage and surveillance of low density areas including oceans, polar regions and remote continental regions. This could be realized with e.g. a constellation of LEO satellites. Typically there is no need for space based ADS-B to serve continental high density airspaces due to existing radar and terrestrial surveillance systems. However the tracking towards the coastline of a high density airspace with a seamless handover to the terrestrial surveillance systems could be a challenge due to interference and FRUIT (see Figure 4).

Therefore, the approach is to sectorise the footprint by using a multi-beam antenna, with each beam covering a part of the footprint and the overlaps between beams properly adjusted, as depicted in Fig. 4.

Still, a single sector may severely degrade, but the remaining sectors will still have full decoding performances (if not 'blinded' by further high density areas) for the area of interest. It is a matter of design to define the number and arrangement of beams.

III. The SABIP Project

ESA contributes to the funding of SABIP under the framework of the GSTP. The objective of the project is twofold;

- To develop a space-based ADS-B receiving system for In Orbit Demonstration (ADS-B IOD payload) and to demonstrate its functionality under representative space environmental conditions, compliant with requirements defined for spacecraft units and experimental payloads.
- To verify its link budget in LEO satellites for the different ADS-B transponder classes and antenna configurations onboard different aircraft and to assess the detection probability for different aircraft on different geo-locations; putting an emphasis on those identified as most critical.

This mission and system study was launched in November 2011. This will entail an analysis of the design trade-offs including pre-development, breadboards and prototyping to mitigate the development risk. A subsequent Development Phase (Phase 2) will lead to the development of the payload and evaluation software for a possible future operational system; as well as the assessment of such a new Air Traffic Surveillance service and mission.

Finally, the aim of SABIP is to perform an IOD using the payload for a proof of concept.

IV. Mission Requirements

Space based ADS-B faces several challenges, where models on ground are not accurate enough and should be verified on space:

- Verify link budgets from space – especially considering that the ADS-B signals were not designed for a global system from space.
- Verify receiver degarbling capability; even over low density areas. Typical degarbling requirements for ADS-B equipment do not account for a visibility footprint as seen from space.
- Verify multi-beam antenna concept and derive optimized antenna designs for commercial missions.
- Verify traffic models and RF environment models as seen from space and derive reference scenarios for further commercially driven missions.
- It will not be scope of IOD to provide a gapless coverage or a multi-satellite data fusion; this is objective of a further commercially driven system.

An IOD mission attempts to develop a single payload only to be hosted in an experimental satellite. These satellites, to the contrary of those that belong to a constellation, are typically limited in size, weight and power. Hence, a lightweight payload has to be designed, which can be accommodated on a small satellite and fulfills the objectives above. Envisaged parameters are:

- Size as maximum 45 * 45 * 30 cm (antenna with integrated receiver).
- Power requirement below 20 Watts averaged over one orbit.
- Mass below 20 kg (preferably 15 kg).
- Operation of the payload over at least half an orbit; offline download to the ground segment.
- Mission on a typical LEO platform at orbits in the 700 to 800 km range.
- Design lifetime from two years on.

V. The IOD ADS-B payload

The IOD ADS-B payload to be developed consists of a phased array antenna forming multiple beams simultaneously, a multi-channel receiver and an interface to the spacecraft.

A. ADS-B IOD Payload Antenna Design

The antenna shall be able to detect all aircraft in view equipped with a range of ADS-B transmitted (power) types and different transmitting aircraft antenna configurations.

The antenna design is driven by several impacts:

- The link budget determines the minimum gain needed for any antenna beam.
- The receiver degarbling capacity drives the maximum footprint of a beam; if it gets too big, the receiver can not longer pick up signals from single aircraft due to signal garbling.

For SABIP we have chosen a five-beam design, as it will allow to demonstrate the principle and verify the achievable performances.

For the design of this antenna, detailed simulations on the expected signal characteristics (antenna beam pattern, polarization, modulation, coverage, field of view, interferences, etc.) at different elevation and angles between receiver and transponder need to be performed.

These simulations shall be based on real world aircraft transmit antenna beam patterns and Air Traffic models which are assumed to be provided by ANSPs and other sources.

The following Fig. 5 provides a view of the multi-beam antenna design.

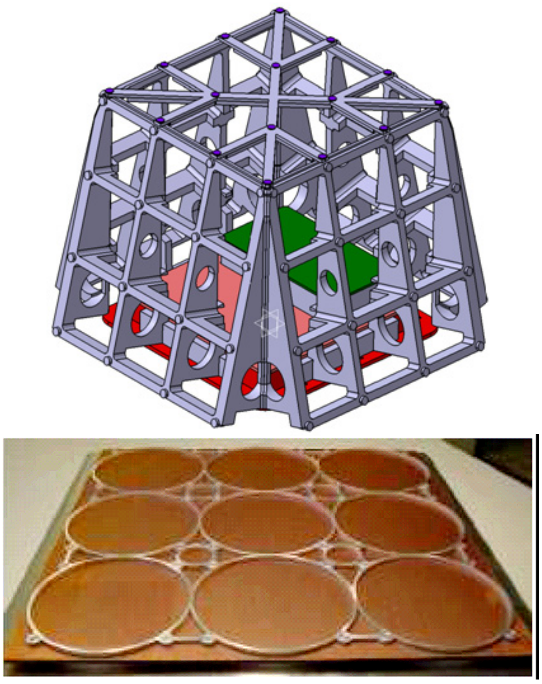

Figure 5. Multi-beam antenna design

B. *ADS-B IOD Receiver Description*

The multi-channel receiver itself is a Software Designed Radio (SDR) concept, where the 1090 MHz signal is down-converted into an intermediate frequency (IF) at around 86 MHz and then sampled by high speed analog-to-digital (AD) converters.

The further processing is performed in a Virtex 4 Field Programmable Gate Array (FPGA), which holds a Power PC core as well. The FPGA part performs the real time decoding and the cyclic redundancy check (CRC) correction according to DO260 performance requirements [3] whereas the Power PC core assembles the target reports out of the single ADS-B squitters, stores and relays the data to the spacecraft, as depicted in Fig. 6.

The ADS-B payload receives raw Mode-S telegrams from the air. This comprises not only the ADS-B requirement, but also all responses to terrestrial radars and TCAS. The ADS-B payload shall then:

- Characterize the RF environment, which fraction of the messages is ADS-B and how is the noise level at different times and positions. For this reasons, some traces of raw data can be recorded and down linked to the ground.
- Record ADS-B messages, do the decoding and assemble target reports to be sent on ground.
- Do baseband recordings for RF processing algorithms and downlink them to ground. This is needed, because no models exist so far for the false replies unsynchronized in time (FRUIT) environment seen from orbital receivers.

Due to the demonstrator nature, the receiver needs to have additional access to internal data beside the ADS-B or Mode-S reports. The most important features are:

- In-circuit update of firmware and software.
- Configurable output of raw data (DF0 to 24 messages), ADS-B squitters or readily assembled target reports.
- Configurable "bent-pipe" mode for direct baseband samples (as digitized data).
- Establishing metrics for RF channel load, garbling and reception probabilities, to be later on used as real time performance measurements.
- Processing is robust against faulty aircraft equipment.
- Degarbling.

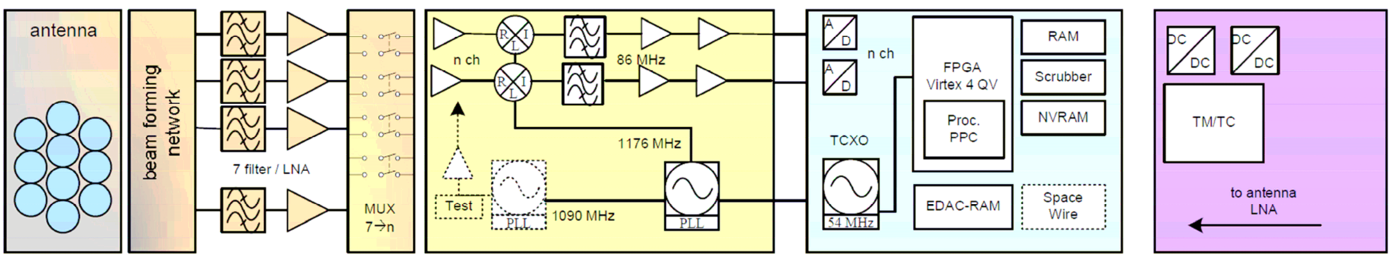

Figure 6. *Space-based ADS-B receiver design.*

C. *Electrical Ground Support Equipment (EGSE) and Data Analysis Tool*

A dedicated Electrical Ground Support Equipment (EGSE), depicted in Fig. 7 allows the validation of the functionality and performance of the engineering – and the flight model. This comprises not only the satellite platform simulation, but also the complex RF signal generation which is expected at the spacecraft. Since ADS-B processing requires multiple single received telegrams, the scenario generation has to reflect a real traffic scenario with moving targets. It is developed using commercial off-the shelf (COTS) equipment and instruments as well as required customized software. The commercial radar environment simulator (RES) tool is widely used to validate ground based radar and ADS-B equipment and will also be used in this project.

The EGSE along with the engineering model (EM) of the ADS-B receiver shall also be used as a development platform for design, validation and debugging of ADS-B receiver techniques targeted for the actual flight unit. Within the scope of the project, the enhancements of the receiver are to be implemented as firmware upgrades of the original design.

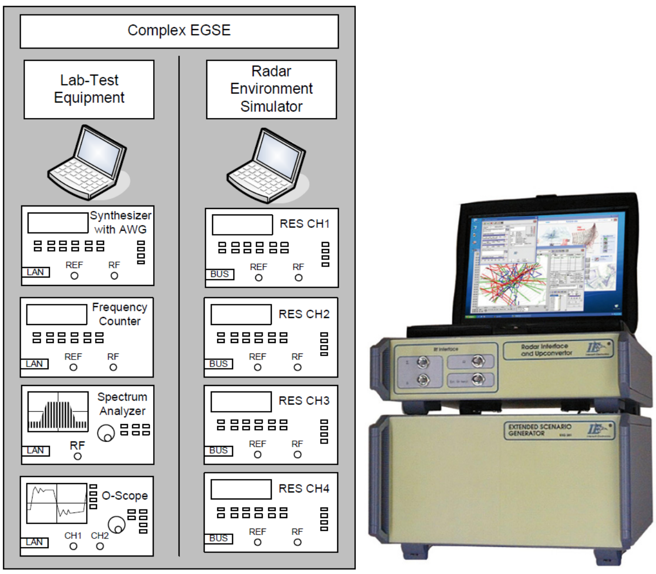

Figure 7. Electrical Ground Support Equipment

Besides, a dedicated data analysis tool is to automatically collect, process, and store relevant space and ground segments data and perform a (semi-) automatic analysis of the detection probability, among other parameters, as depicted in Fig. 8. Hence, this tool is not only focused on the ADS-B track analysis, but also considers the payload's operation. It offers an interface for ground systems to allow comparison of the aircraft detected by ground and space systems. In addition to the comparison of tracks generated by space and ground systems, it processes the RF load seen from the payload at any given time, and other vital processing parameters like degarbling performance, ADS-B message and FRUIT count (which depends on the equipage ratio, radar environment and traffic mix), bit and message error rate. The results are visualized geographically and over time. For long term comparison, all data are stored in a common database. An operational commercial system would have to downlink these data in real time (latency should be typically less than 10 seconds); however the demonstrator system can be operated in offline mode, so that the data is downlinked once per orbit only. This concept relaxes the need for a complex ground segment consisting either in many ground stations and/or a worldwide, real time capable Wireless Area Network (WAN). For that reason, the data analysis tool is considered to be an offline tool and not operating in real time.

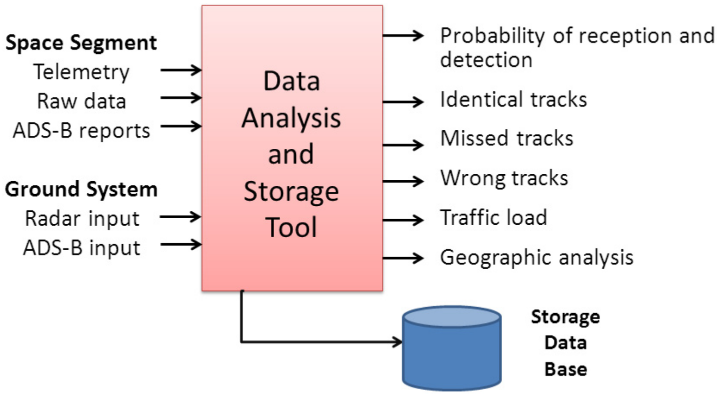

Figure 8. Data Analysis and Storage Tool.

VI. COMPATIBILITY WITH EXISTING SYSTEMS

The space-based ADS-B does not require any change in existing ADS-B aircraft equipment, since it uses the existing Mode-S equipment standard, whose international standardization is already established for the terrestrial ADS-B systems.

This is of importance since aircraft equipment is designed for life times of several decades and the introduction of new avionics in the aerospace community is lengthy and costly. Likewise, it is difficult to get international agreement for changes in aviation standards and it is virtually impossible to introduce new equipment standards in aviation in the short term.

Besides, this technical solution provides the following benefits;

- It allows maximum re-use existing and proven terrestrial ADS-B equipment (especially reception and degarbling techniques), which is already operational and certified in terrestrial applications.
- The test environment for functional and performance tests is fully re-usable from terrestrial ADS-B receiver, thus a proven concept is available, for savings in development time and risks.

VII. In-Orbit Demonstration

IOD of high-risk technologies at an early stage of a project enable better systems design and planning, hence it mitigates their technical and programmatic risks. IOD activities are essential to de-risk innovation and accelerate the infusion of new technologies.

Despite of the concept of space-based ADS-B seems feasible, demonstration activities are still missing. IOD of space-based ADS-B is essential to lower the risks and accelerate the market entry of this technology, hence increasing its competitiveness.

The demonstration activities increase the perceived reliability of these technologies by lenders, partners and customers. Credible price and schedule commitment are possible when critical technologies have been pre-developed, tested, and secured. Demonstration of this space-based ADS-B solution would provide confidence to customers and lead to higher payoff.

The Agency's support to these activities is critical to boost the European industry competitiveness in the development of the space-based ADS-B system, payload and related services, and empowers the industry to confront strong international competition (which, in the case of space-based ADS-B, mainly arises from the US aerospace industry).

Besides, in many cases, since service revenues obtained from innovative technologies might only be generated when initial operative, ESA's funding support for the development and deployment phases of such technologies is key to overcome these budget constraints and support innovation.

The payload is designed as flexible as possible such that it can be adapted to different spacecraft for LEO.

VIII. Acknowledgement

Thales Alenia Space Deutschland thanks ESA for its institutional and financial support to SABIP under the GSTP, and for the future co-operation with respect to the in-orbit demonstration of this technology.

IX. References

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