ADS-B over Satellite
The world's first ADS-B receiver in Space

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Abstract *More efficient use of airspace and flight routes as well as more economic flight trajectories require to extend controlled airspace to regions, for which ground based surveillance cannot be applied. In this paper the world's first in-orbit demonstration for space based ADS-B surveillance is presented, hosted on the ESA satellite PROBA-V.*

Index Terms: ADS-B, ATC, PROBA-V, SATELLITE

1 INTRODUCTION

Air traffic surveillance as required in controlled airspaces nowadays predominantly uses ground stations equipped with Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR) including Mode-S [1]. Seamless and continuous flight surveillance as necessary in airspace with high traffic density and separation minima of 5 respectively 3 nautical miles require an extensive ground infrastructure of radar stations, networks and surveillance data processing, as implemented in Central Europe, the U.S. or certain regions in Asia, thereby providing the necessary situation awareness to the controllers in the air traffic control centers.

In the recent years ADS-B (Automatic Dependent Surveillance Broadcast) as a further surveillance technology has evolved. Modern Mode-S transponders on board of aircraft transmit the flight position and other information by so-called Extended Squitter messages (1090ES) on the 1090 MHz SSR-Mode-S downlink frequency (ADS-B Out). In the future radar systems will be complemented or even replaced by less costly ADS-B ground stations, which will be integrated in the existing surveillance infrastructure. The European ADS-B Implementing Rule requires that new aircraft heavier than 5700 kg or faster than 250 knots will be equipped with ADS-B-Out from 2015 onwards when flying IFR, and for already operational aircraft a retrofit from end of 2017 on. In 2020 ADS-B surveillance shall become operational [2].

Anyway, most regions of the world are uncontrolled airspace. In areas without radar coverage (Non Radar Airspace, NRA), like oceanic airspaces, polar regions or structurally lagging continental regions the installation of ground stations is either impossible or too expensive. Today, aircraft surveillance in these regions is applied procedurally, i.e. by voice radio position reports of the pilots when the aircraft reaches certain waypoints. Also ADS-C (Automatic Dependent Surveillance – Contract) is used, a point-to-point data link connection (FANS1/A / Satcom), which transmits positional and other flight information only every 15 minutes due to limited bandwidth. In both cases no seamless and continuous flight surveillance is possible, with the consequence of relatively ample separation distances due to safety reasons. This becomes especially problematic for search and rescue activities in case of flight accidents: the location of the impact site of the crashed AF447 flight from Rio de Janeiro to Paris in 2009 took more than five days. However it must be stated with regard to a recent fatal accident, that either a technical failure of the transponder or the navigation system, from where the transponder gets the actual aircraft position, or a manual deactivation will prevent an aircraft from being tracked via its ADS-B signals.

In 2008, the German Aerospace Center (DLR) started to investigate the option to receive the 1090ES ADS-B signals broadcasted by aircraft on board of low earth orbiting (LEO) satellites. The efforts resulted in the DLR project ADS-B over Satellite (AOS), with the goal to develop an ADS-B payload for an In-Orbit Demonstration (IOD) and thereby demonstrate the feasibility of worldwide satellite based ADS-B surveillance.

This AOS In-Orbit Demonstrator is capable to receive, decode and forward all Mode-S downlink telegram formats. This includes the DF17 Extended Squitter comprising ADS-B information and DF11 All-Call reply. The AOS IOD was conducted in the frame of ESA’s PROBA-V mission (PROBA Vegetation [3]) and was successfully launched on top of Europe’s newest launch vehicle VEGA on 7th of May 2013 at 04:06:31 CEST from the European spaceport Centre Spatial Guyanese (CSG) in French Guyana.

The IOD is a first step for demonstration and verification of space based air traffic surveillance. A single satellite is equipped with a space-qualified ADS-B receiver, and due to limitations in cost, time and in particular resources available on PROBA-V in terms of power and geometry a relatively simple antenna and receiver design was implemented. A future operational system providing seamless world-wide coverage would consist of a fleet of satellites, each equipped with sophisticated multi-channel ADS-B receivers and antennas.

ADS-B over Satellite is the first experiment of its kind and has already proofed the feasibility of space based ADS-B. The results from this IOD will pave the way for future developments towards global satellite based air traffic surveillance.

2 TERRESTRIAL ADS-B

ADS-B is considered as an essential component of any future air traffic management system. It is incorporated in the US Next-Generation Air Transportation System (NextGen) as well as in the Single European Sky initiative (SESAR) and will provide enhanced surveillance capabilities. Ground based ADS-B stations are increasingly deployed, but the coverage area is limited typically to a few hundreds of kilometers. Air Services Australia as an example installed a huge number of ADS-B ground stations in order to cover the entire continent above Flight Level (FL) 300 eventually [4].

However, an adequate solution for a global surveillance of air traffic movements based on ground based ADS-B appears to be out of scope due to technical, operational and political constraints:

- Oceanic Coverage would implicate the deployment of ADS-B stations on innumerous buoys.
- Terrestrial Coverage would implicate the deployment and operation of ADS-B stations in inaccessible terrain.
- The global airspace is fragmented and thus operated by a large number of local ATC providers.
- Political obstacles in particular in unstable regions prevent any transnational regulation and operation.

2.1 THE 1090 MHZ MODE-S EXTENDED SQUITTER (1090ES)

SSR including Mode-S is using an uplink frequency of 1030MHz in order to interrogate aircraft within operating coverage. Possible interrogations are e.g. the Mode-S-All-Call (any aircraft within the coverage will respond to the call) or selective interrogations for identity, altitude and other information using the worldwide unique technical Mode-S-address assigned to every aircraft. Once an aircraft has been interrogated, it will reply on the 1090MHz downlink channel. As ADS-B is an automatic broadcast system it does not need an interrogation and just makes use of the 1090 MHz Mode-S downlink format DF17 employing a Pulse Position Modulation (PPM) and random channel access. ADS-B messages are generated at intervals specified for the diverse message types as given in the 1090 MHz Extended Squitter minimum operational performance standards [5], and transmitted alternately from the top and the bottom ATC antenna of an aircraft. The DF17 contains position, altitude, identity, flight direction, speed and aircraft status in consecutive messages. At the receivers side the messages will be assembled to ADS-B reports, using the Mode-S-address comprised in the messages.

3 SPACE BASED ADS-B

Only satellites have the capability to provide a global coverage at any possible flight level, avoiding limitations imposed by terrestrial ADS-B. This could be implemented by receiving ADS-B signals, which are broadcasted regularly by each equipped aircraft and which contain information on position, speed, direction etc. by LEO satellites. This data can then be made available to already existing ATC ground infrastructures.

Therefore, a satellite-based surveillance network will provide enhanced Air Traffic Services in areas where the traffic density, the location, or the cost of “conventional” ATC equipment would not justify any installation of radar and/or terrestrial ADS-B. It can also include VHF coverage fringe areas and areas where existing radar is to be de-commissioned, and where the replacement costs are not justified.

4 ADS-B OVER SATELLITE

The focus of "ADS-B over Satellite" is primarily on the en-route phase of aircrafts. Departure/climbing and/or approach/landing as well as the Taxi inbound and outbound (TMA areas) was not concentrated upon.

The primary goal of the DLR project ADS-B over Satellite was to demonstrate the feasibility of an orbital ADS-B system by means of an In Orbit Demonstration and to evaluate the characteristics and performances which may be important for future space based air traffic control systems. As preparatory missions DLR conducted in 2010 the first of a series of high altitude test flights. During a test flight in northern Sweden a terrestrial ADS-B receiver has been used and basic assumptions regarding the maximum reception distance in NRA could be verified [6]. Based on these trials and pre-development studies a system concept for a space based ADS-B reception has been developed, mostly based on commercial of-the-shelf (COTS) hardware. This system is based on two assemblies consisting of a passive planar L-Band antenna array and the associated receiver unit.

4.1 The space based 1090ES ADS-B Receiver

The basic design concept of the 1090ES receiver (Rx), as shown in Figure 1, is a single conversion superheterodyne receiver with a down conversion of 1090MHz to an intermediate frequency of 70MHz. The IF undersampling at 70 MHz is done by a 16 bit ADC at 105 MSPS which provides a virtual second IF at 35MHz.

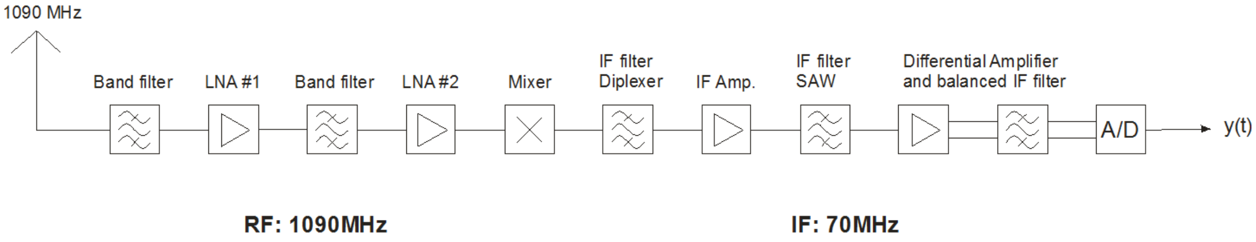

Figure 1: Single Superheterodyne Receiver Concept

FPGA and DSP blocks have been used for I/Q demodulation and filtering with an enhanced real time Mode-S Correlator design implemented in SystemVerilog, using video baseband and phase information (Figure 2) for reliable detection of all Mode S downlink telegrams, including the DF17 extended squitter.

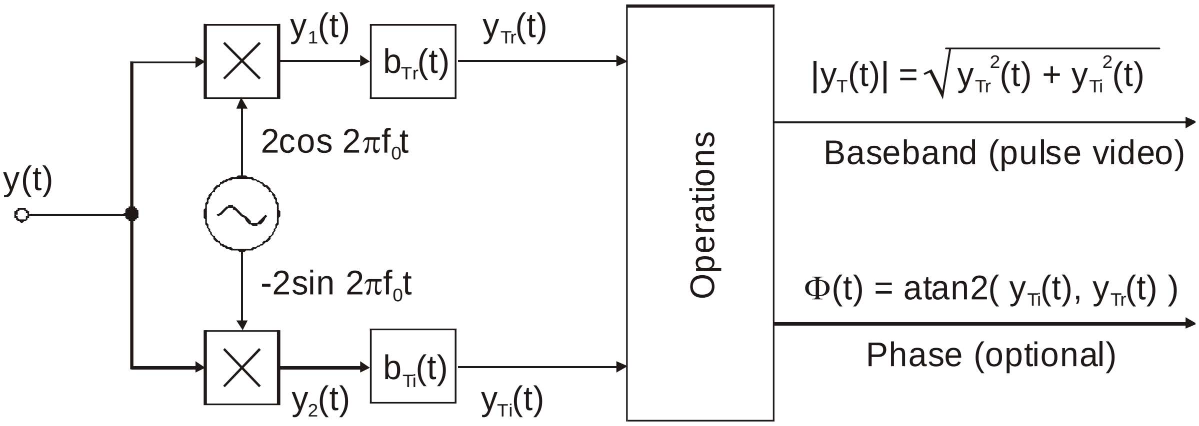

Figure 2: IF and Baseband Section

The FPGA comes with a 32 bit embedded processor to handle the satellite-borne interface. The communication to the spacecraft and commanding of the receiver is done through RS-422 UARTs at a baud rate of 115kbps. The input sensitivity of the receiver depends on the frequency condition of the incoming message and has a minimum trigger level of about -96dBm.

One must be aware that the hosted payload in LEO is seeking for very weak Mode-S signals. Typical aircraft transponder have not been developed for usage below -90dBm in general and have poor correlation properties. In this innovative approach an additional signal processing algorithm makes also use of the phase information of the transmitted signals. This technique will be tested and improved during mission runtime since the receiver FPGA configuration and the processor firmware can be changed from ground. This feature has already been tested successfully.

Due to limitations on-board the satellite, no further pre-processing of decoded Mode-S telegram bits is done in orbit. Instead, all raw telegram data is downlinked to the ground for decoding and analysis. This allows maximum flexibility since the system is not limited to DF17. Furthermore, an even more raw data format is given by the sampled signal y(t) in Figure 1. These continuous IF samples of an entire telegram can be stored and downlinked for a limited number of Mode-S transmissions. In a lab, these signals may be used to test new receivers under real-world conditions obtained from LEO.

4.2 The Space-Based ADS-B Antenna

The antenna used for ADS-B over Satellite is an antenna array of two elements. Each element is a capacitive fed, shorted patch antenna. There is no direct mechanical bonding between the feeding structure and the patch. This makes the patch assembly very easy. Except for the feeder no dielectric material is used. It has been found that this gives an extra 12% gain increase. The patch antenna is shorted in the center of the patch to the ground plane of the spacecraft (S/C) structure. This avoids potential charging.

The coupling structure is specially formed to generate a resonance around 1.09 GHz. It is stabilized by a structure made of Teflon which is required to avoid structural deformations due to the vibration loads during the launch of the satellite. The feed module is placed on the lower right edge of each antenna for right hand circular polarization. Additional structural stabilization of the antenna patch is realized with four small TECAPEI cylinders.

The array elements are combined with a HAIGH-FARR combiner. The total array including the combiner is matched to 50 Ohm at a frequency of 1.09 GHz. The -10 dB bandwidth of the reflection coefficient is 134 MHz according to 12% relative bandwidth.

The simulation of the antenna on the nadir panel of the satellite shows a maximum gain of 11.2 dBi. According to these results the half beam width has an elevation axis of around 73° with an azimuth axis of around 33° (see Figure 3, 4 and Table 1).

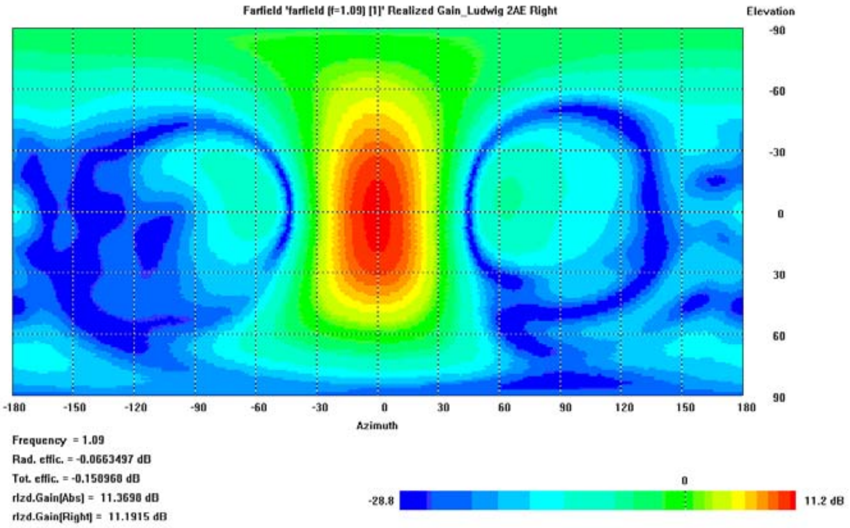

Figure 3: Simulated gain of the two element array

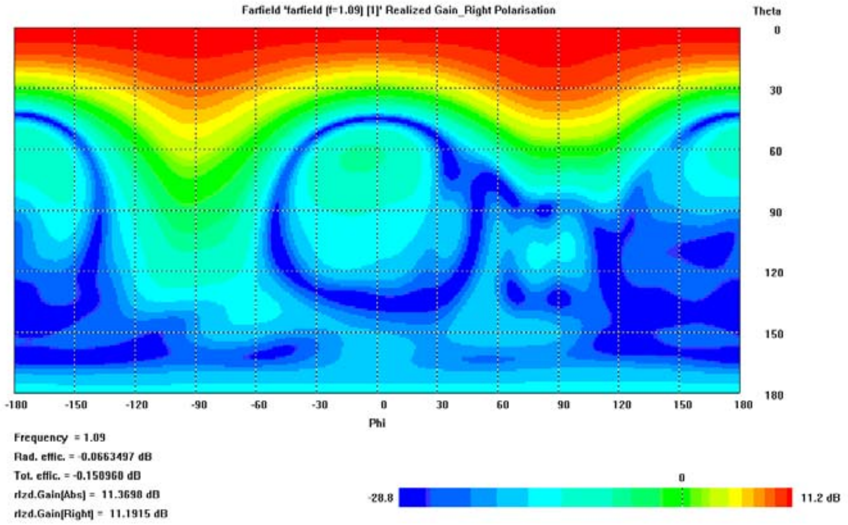

Figure 4: Simulated gain of the two element array

Description	Value
Type	Planar with two elements
Frequency	1090 MHz
Gain	11.2 dBi
$HPBW_{AZ}$	33°
$HPBW_{EL}$	73°
Polarization	Right Hand Circular

Table 1: Simulated Antenna Characteristics

A comparison between simulation and measurement showed good agreement (see Figure 10). The theoretically maximum achievable gain calculated above infinite ground and low loss combining is reduced by around 2dB due to the impact of the satellite structure to the array and combiner losses. It has been shown that it is possible to realize small, mechanical stable, gain improved patch antennas without the use of dielectric material. The dimension of one patch side is 43% of the free wavelength at 1.09 GHz.

4.3 PROBA-V

PROBA-V (Project for On-Board Autonomy - Vegetation) is the newest satellite in ESAs PROBA programme and the host satellite of AOS. Its main task is to provide actual vegetation data to the community and serve as gap filler between the SPOT-VGT and Sentinel-3 satellites [7] [8]. Prime Contractor QINETIQ SPACE NV is the prime contractor for the development of the satellite platform, the payload and the ground segment. PROBA-V has a total mass of about 140 kg and carries a new version of the Vegetation imager previously flown on the Spot satellites. In addition to the main mission instrument, PROBA-V carries five technology demonstrators.

5 RESULTS

5.1 General Aspects

The ADS-B receiver on board the satellite was the first experiment of its kind, receiving 1090ES ADS-B squitter signals transmitted from aircraft. Therefore the experimenter could not build on experiences or any evaluation results.

The assessment of the achieved results should take into account the constraints under which this experiment was realized, as there were limitations in cost and time but in particular available resources on the satellite in terms of available power and geometry.

The reception of 1090 Extended Squitter ADS-B messages on board of the PROBA-V satellite is mainly affected by the following issues, which may lead to a loss of ADS-B information:

- RF signal loss due to the low signal level resulting from the distance between the receiving satellite at an altitude of approximately 820 km and the transmitting aircraft at an altitude of 0 to 12 km.
- RF signal loss due to the shapes of the satellite antenna vertical radiation pattern and the aircraft antenna vertical radiation pattern.
- Corruption of messages by garbling, when several messages arriving at the ADS-B antenna onboard of the satellite at the same time overlap and thus cannot be decoded by the ADS-B receiver.
- Speed of the satellite of about 27000 km/h, which leads to a limited time of observation for each detected aircraft of about 3 minutes maximum.

Moreover, with the integration of the ADS-B receiver on the satellite as a hosted payload, the experimental In-Orbit-Demonstration for satellite based surveillance experiences further constraints:

- Satellite attitude optimized for the visual angle of the vegetation scanner or other hosted payloads.
- Antenna mounting positions not directly optimal for space based 1090ES reception, but a compromise in order not to disturb the main satellite mission and other hosted payloads.

5.2 Aircraft Positions received on board of PROBA-V

In the following some examples of received and decoded aircraft tracks and position plots will be presented.

Figure 5 shows aircraft tracks recorded world-wide during pass 2699 on 11th February 2014. A pass covers several orbits around the Earth between two consecutive acquisitions of PROBA-V from the satellite operation center Redu in Belgium. Each red dot represents the track segment of an aircraft as seen by the satellite when its orbit passes the aircraft. With a size of the antenna footprint of approximately 1200 km in longitudinal and 500 km in lateral extension to the satellite's flight direction, PROBA-V scans the global airspace strip by strip.

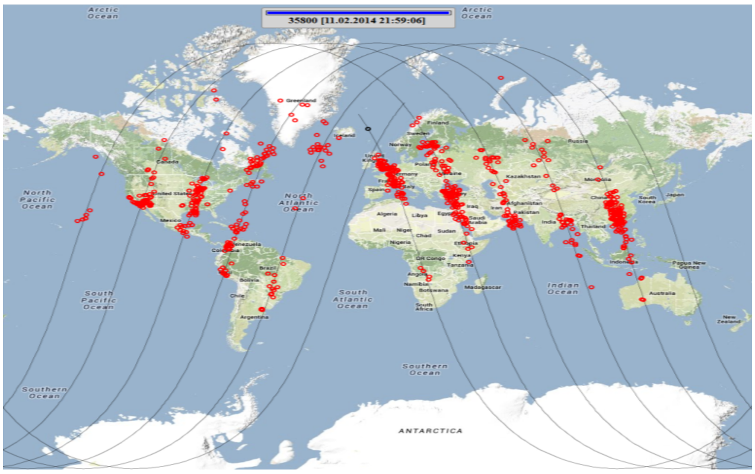

Figure 5: Aircraft Tracks observed by PROBA-V

Figure 6 shows a trajectory of an aircraft flying over France. The blue line with dots for every aircraft position shows gaps, where no position messages have been received on board the satellite. The red line is the ascending satellite flight path. Obvious is the short observation period for an aircraft in comparison to the length of the satellite’s orbital segment, when the satellite passes over the target with nearly 27.000 km/h, resulting in a footprint speed of about 23.000 km/h at the aircraft’s altitude.

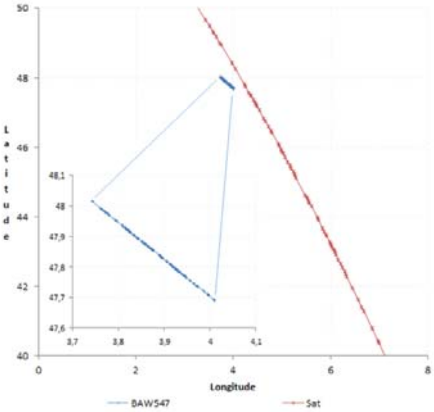

Figure 6: Trajectory of a flight from Rome to London observed over France

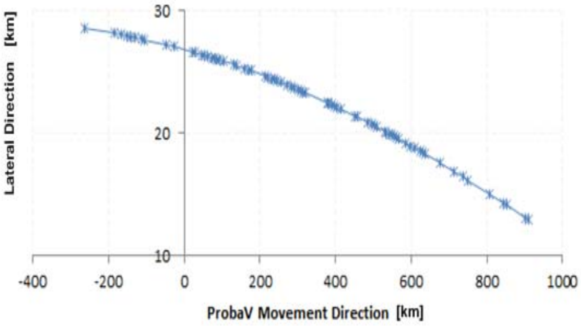

Figure 7: Trajectory of the flight within the footprint

Figure 7 shows the same trajectory as it is seen inside the footprint. The x-axis points in the flight direction of the satellite, with the positive values in front of Nadir. The y-axis presents the horizontal distance between the aircraft position plots and the orbit.

5.3 Antenna Footprint

The most important aspect for the reception of ADS-B messages in space are the receiving conditions for the 1090 MHz extended squitter signal on board the satellite. In comparison to ground based ADS-B surveillance with a range of up to 300 km maximum, the signal path between a LEO satellite orbiting at 820 km altitude and an aircraft is much longer, which results in a low signal level at the ADS-B receiver. Thus the Mode-S signals have to be detected nearly at noise level by a correlation process.

The shape and extent of the footprint was determined by compiling histograms, which reflect the number of received messages with respect to the aircraft position in relation to the satellite position projected to an x-y plane. Figure 8 shows a histogram for all decoded position messages received during May 2014.

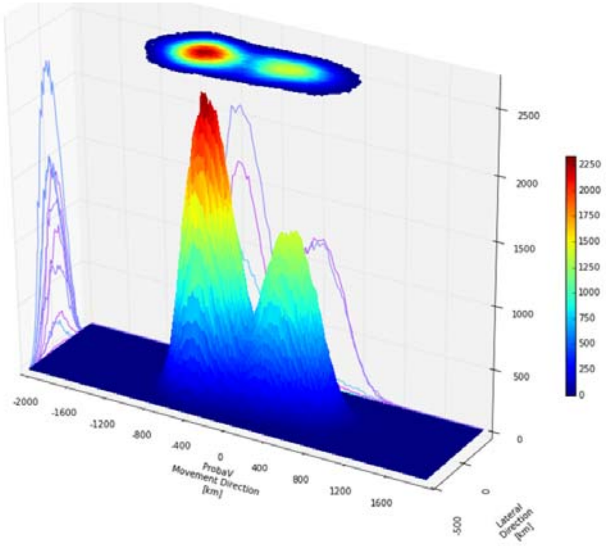

Figure 8: Histogram of all received Position Messages in the Antenna Footprint

Remarkable are the two peaks, one lower in front of the movement direction and the other higher behind the satellite, with a dip at the Nadir position. The footprint is not symmetrical, which is caused by the asymmetric mounting positions of the patch antennas on board of the satellite, as well as other equipment mounted at the underside and a solar panel which protrudes over the front edge of the lower surface.

The peaks of the histogram can be explained by the antenna radiation patterns of the receiving antennas of the satellite and the transmitting antenna of the aircraft. Figure 9 shows the measured radiation pattern of the ADS-B patch antennas mounted on the NADIR panel of PROBA-V. The resulting combined antenna radiation pattern has an overall oval shape in the direction of the satellite movement and the maximum sensitivity slightly behind the Nadir direction below the satellite.

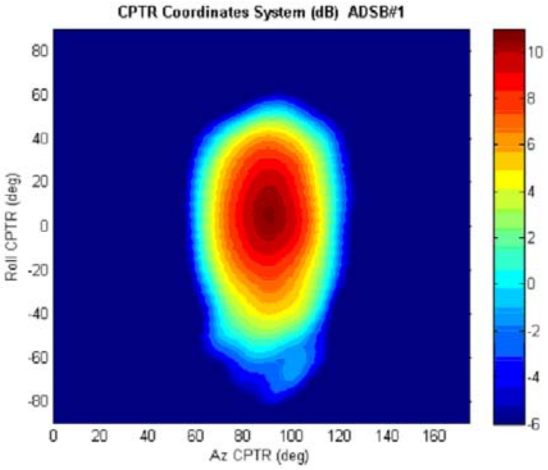

Figure 9: Antenna Radiation Pattern of the PROBA-V ADS-B Antenna

Aircraft are equipped with two ATC antennas, one on top and one at the bottom of the fuselage, which transmit alternatingly. Due to the geometry, the satellite will receive signals from the top antenna. The typical vertical antenna radiation pattern of a top antenna is shown in Figure 10.

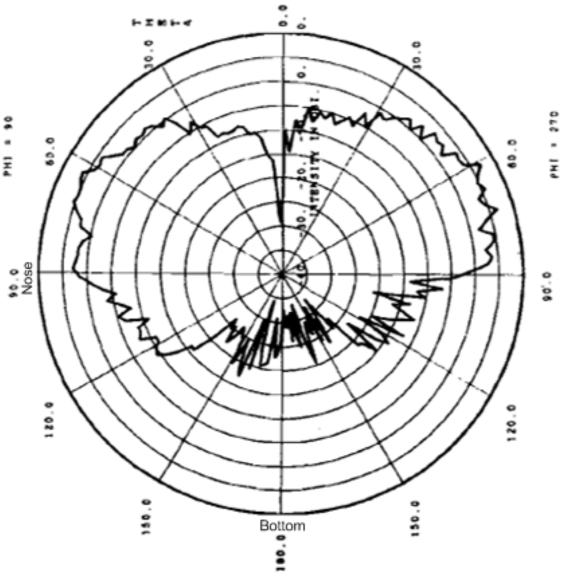

Figure 10: Vertical Antenna Radiation Pattern of a top mounted L-Band Antenna **[9]**

The shape is toroidal with a recess in the center at 0 degrees, which results in the so-called “cone of silence” vertically above an aircraft, so that an aircraft more or less directly below the satellite might not be detected on board of the satellite. It should be noted, that dependent on both the mounting position of the antenna and the geometry of the fuselage the radiation patterns of different aircraft types differ substantially. So for some aircraft the recess in the center is wider and the bulges are shallower.

As can be seen from the shape of the footprint, the both “complementary” antenna patterns do not compensate each other, which results in an articulate recess of ADS-B signal reception in the middle of the footprint, caused by the “cone of silence” of the aircraft antenna. A later operational configuration must compensate for this effect.

The ADS-B receiver developed for the PROBA-V in-orbit demonstration provides in its output data no direct signal level measurement values, which mainly would represent the noise level. Instead the receiver provides a correlation gain value for each successfully decoded message, which denotes the performance of the correlation process. Figure 11 shows the histogram for the measured correlation gain in the antenna footprint, with respect to the aircraft position relative to the satellite position.

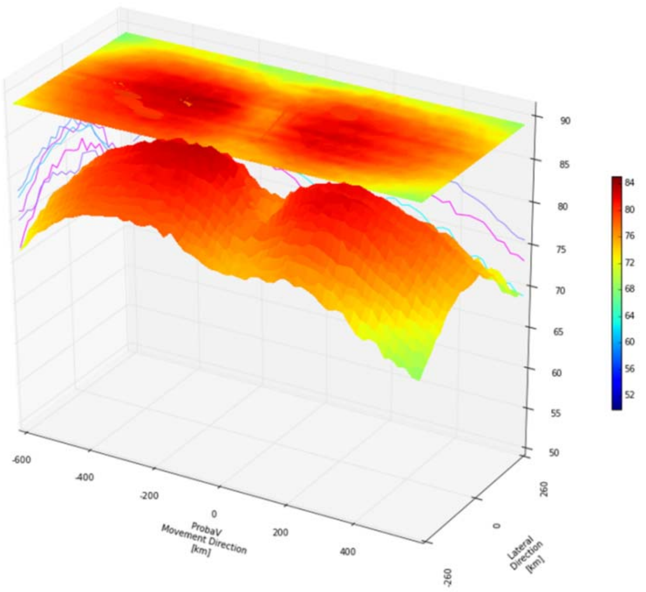

Figure 11: Histogram for Correlation Gain in the Antenna Footprint

5.4 Performance Parameters

For the verification of space based 1090ES ADS-B surveillance performance parameters have been identified, in accordance to requirements for ground based ADS-B surveillance as given by the respective documents by EUROCAE, ICAO and EUROCONTROL [10].

In the following some applicable performance parameters shall be shortly described.

5.4.1 Probability of Target Acquisition

As can be seen from the comparison of reference traffic and detected aircraft tracks certain targets are not detected at all when passed over by the satellite's antenna footprint. Thus a specific performance parameter for target position detection has been defined, which is called "Probability of Target Acquisition" (PTA):

> *The Probability of Target Acquisition (PTA) shall be defined as the percentage ratio between the actual number of targets detected and the expected number of targets to be detected within a certain area or time of observation.*

Detection means the provision of positional data, i.e. the reception of at least one ADS-B position message within the footprint.

5.4.2 Probability of Detection

The Probability of Detection (POD) is defined as follows:

> *The probability of detection (POD) shall be defined as the percentage ratio between the actual number of position messages received and the expected number of position messages.*

The nominal transmission rate for 1090ES position messages is 1 Hz from the aircraft top antenna and 1 Hz from the bottom antenna.

5.4.3 Probability of Target Identification

The Probability of Target Identification (PTI) is defined as follows:

> *The Probability of Target Identification (PTI) is the percentage ratio between the actual number of aircraft identified and the expected number of aircraft which should have been identified.*

Aircraft normally will not change their identification (call sign) during flight, and thus a relatively sporadic identification will do, as by the ICAO address comprised in every ADS-B message each message can be allocated to a flight once identified.

5.4.4 Probability of Identification

The Probability of Identification (POI) is defined as follows:

> *The probability of identification (POI) is the percentage ratio between the actual number of identification messages received and the expected number of identification messages.*

5.5 Evaluation of Performance Parameters

For the evaluation of the performance parameters mentioned above a zone filtering has been provided, which allows filtering received ADS-B messages in accordance to defined areas on the Earth. This allows e.g. to mask out areas with high traffic density and thus a high risk of garbling und therefor non-decodable messages. On the other hand the filtering allows for the performance evaluation for certain areas, like north Atlantic or Pacific transoceanic flight routes. Figure **12** shows an example of filtering for airspace over Pacific, north Atlantic and Australia.

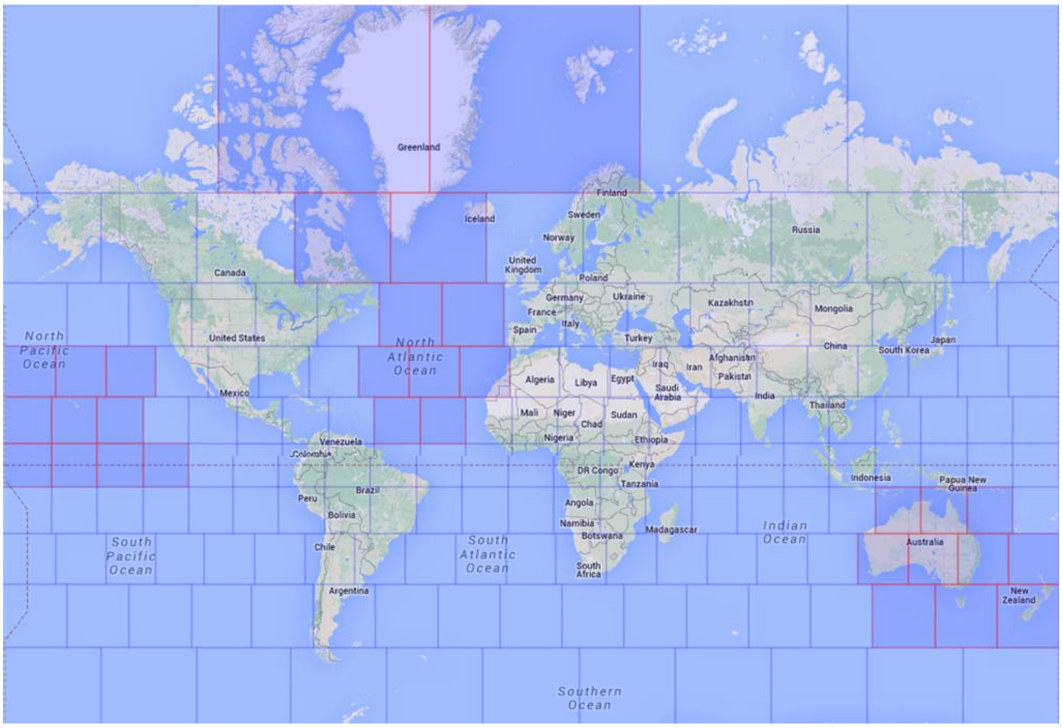

Figure 12: Selected areas of Airspace over Pacific, North Atlantic and Australia

The performance parameters have been computed from ADS-B messages received during March 2014. Concerning the zone filters applied, “default” stands for masking out areas with high traffic density as is North- and South-America, Europe and Asia.

Zone Filter	**Aircraft detected**	**Aircraft expected**	**PTA [%]**	**Aircraft identified**	**PTI [%]**	**Average Correlation Gain**
All	61798	64652	95,6	44665	69,1	78,3
Australia	2426	2559	94,8	1790	69,9	77
Default	23943	30719	77,9	16578	54	75,7
East Asia	12743	13859	91,9	9142	66	79,2
Europe	15106	17235	87,6	9538	55,3	80,9
North Atlantic	5039	6201	81,3	3480	56,1	72,2
Pacific	997	1301	76,6	734	56,4	70,7

Zone Filter	**Positions detected**	**Positions expected**	**POD [%]**	**Ident Messages detected**	**Ident Messages expected**	**POI [%]**
All	1464447	10878627	13,5	149568	1087863	13,7
Australia	95203	425298	22,4	7240	42530	17,0
Default	520709	3376666	15,4	50641	337667	15,0
East Asia	270910	2102401	12,9	29439	210240	14,0
Europe	244345	2290756	10,7	24863	229076	10,9
North Atlantic	92458	780939	11,8	8887	78094	11,4
Pacific	20508	156205	13,1	2131	15621	13,6

6 SUMMARY

The results gained so far by the PROBA-V in-orbit demonstration prove, that space based 1090ES ADS-B surveillance is technically feasible, and thus the goals of the project “ADS-B over Satellite” have been attained.

Albeit the experimental equipment configuration available for this first in-orbit demonstration does not provide the required performance for later operational use, the results are essential and conclusions can be drawn for the design of a future operational system. An intended system providing a permanent worldwide coverage will consist of a fleet of satellites equipped with highly sophisticated multi-channel ADS-B receivers. Slantwise pointing spot beam antennas for each channel will avoid a signal overload of the single channels, likewise overcoming the cones of silence of aircraft transponder antennas and provide wide overall footprints for each satellite.

In order to encourage research and development of space based ADS-B, SES TechCom, Thales Alenia Space Germany and the German Aerospace Center (DLR) jointly formed an initiative, which will conduct a further space mission, based on advanced ADS-B receiver and antenna technology developed by industry. The efforts shall lead to an operational technical system as well as a commercial concept, which then will enable the introduction of a world-wide space based ADS-B surveillance service.

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