International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R M.2413-0
(11/2017)

Reception of automatic dependent surveillance broadcast via satellite and compatibility studies with incumbent systems in the frequency band 1 087.7-1 092.3 MHz

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Mobile, radiodetermination, amateur and related satellite services

International Telecommunication Union

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Note*: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

Electronic Publication
Geneva, 2017

REPORT ITU-R M.2413-0

Reception of automatic dependent surveillance broadcast via satellite and compatibility studies with incumbent systems in the frequency band 1 087.7-1 092.3 MHz

(2017)

Introduction

Automatic dependent surveillance (ADS) is a surveillance technique in which aircraft automatically provide, via a data link, data from the on-board navigation and position fixing systems, including aircraft identification, four-dimensional position (latitude, longitude, altitude and time) and additional data as appropriate. The technique is termed "automatic" because there is no intervention from the pilot or interrogation from terrestrial stations, and "dependent" because the data is dependent upon on-board systems such as global positioning system (GPS) and altimeter.

Different ADS system types have been standardised within the International Civil Aviation Organisation (ICAO), such as terrestrial ADS-broadcast (ADS-B) and ADS-contract (ADS-C)[1].

A description of ADS-C and its operation via mobile-satellite systems can be found in Report ITU-R M.2396-0 – Use of mobile-satellite service systems for flight tracking. In addition, another system, "MSS-satellite-retransmitted ADS-B", is also described in that Report.

Scope

The present Report provides a description of the current operation of the ICAO standardised ADS-B and study of the implementation of reception of ADS-B via satellite that would enhance coverage for aircraft suitably equipped, particularly in areas where terrestrial receivers cannot practically be deployed (such as oceanic, trans-polar and remote regions). Compatibility between the satellite reception of ADS-B and incumbent services is also examined in this Report.

Keywords

Flight tracking, satellite, aircraft, ADS-B

Glossary of abbreviations

1090 ES	1 090 MHz Mode S extended squitter
ACAS	Airborne collision avoidance system
ADS	Automatic dependent surveillance
ADS-B	Automatic dependent surveillance – broadcast
ADS-C	Automatic dependent surveillance – contract
AM(R)S	Aeronautical mobile (route) service
AMS(R)S	Aeronautical mobile satellite (route) service
ATC	Air traffic control

[1] ADS-rebroadcast (ADS-R), the rebroadcast by a ground station of surveillance information received via one ADS-B link over an alternative ADS-B link, is also standardised by ICAO but is not considered further in this Report.

ATCRBS	Air traffic control radar beacon system
ATM	Air traffic management
ARNS	Aeronautical radionavigation service
C/I	Carrier to interference
C/N	Carrier to noise
DME	Distance measuring equipment
ES	Extended squitter
FIR	Flight information region
FRUIT	False replies unsynchronized in time
FSS	Fixed satellite service
GNSS	Global navigation satellite system
GPS	Global positioning system
ICAO	International Civil Aviation Organisation
ISS	Inter satellite service
LEO	Low earth orbit
MSS	Mobile satellite service
NGSO	Non-geostationary orbit
PAM	Pulse amplitude modulation
PRF	Pulse repetition frequency
SBA	Spaced-based ADS-B
SSR	Secondary surveillance radar
TACAN	Tactical air navigation system
TCAS	Traffic collision avoidance system
UI	Update interval
UTC	Universal co-ordinated time.

1 Description of terrestrial automatic dependent surveillance – broadcast

Automatic dependent surveillance-broadcast (ADS-B) is the aircraft broadcast of a defined set of parameters including aircraft position (latitude, longitude and altitude), velocity, and aircraft identity obtained from on-board avionics systems.

ICAO’s vision of enhanced surveillance capabilities has resulted in the development of ADS-B, which can be implemented using multiple data-links such as:

– Universal access transceiver[2]

– 1 090 MHz Mode S extended squitter (1090 ES)

The globally predominant ADS-B implementation method in aircraft is via the 1090 ES data message format in the Mode S transponder. Mode S is a secondary surveillance radar technique that permits

[2] Universal access transceiver is not considered further in this Report.

selective interrogation of aircraft by means of a unique 24-bit aircraft address. These systems operate in conjunction with ground based surveillance interrogators.

To provide appropriate airspace management and separation of aircraft, the ground interrogators must be linked to an air traffic management facility for processing of the received aircraft data.

The aircraft position, velocity, and associated data quality indicators are usually obtained from an on-board global navigation satellite systems (GNSS). Aircraft inertial navigation sensors can also provide the position data, however without distance measurement equipment (DME) or GNSS input the position accuracy will decrease with time. ADS-B position messages from an inertial system are therefore usually transmitted with a declaration of lesser accuracy or integrity. Recent aircraft installations use an integrated GNSS and inertial navigation system to provide position, velocity and data quality indicators for the ADS-B transmission. These systems have better performance than a system based solely on GNSS since inertial and GNSS sensors have complementary characteristics that when combined together, can mitigate any potential dilution of position accuracy of each system. Altitude is also obtained from the pressure altitude encoder.

Aircraft which are equipped with ADS-B technology broadcast ADS-B messages on the frequency 1 090 MHz. This broadcast is received and processed by a standardized aeronautical receiver on board other aircraft and by ground stations with line-of-sight of the broadcasting aircraft.

As a result, ADS-B can support both ground-based and airborne surveillance applications. Information from ADS-B broadcasts is also used by other applications. In airborne applications, aircraft equipped with ADS-B receivers process the messages from other aircraft to determine the location of surrounding traffic in support of applications such as the cockpit display and traffic information (also known as ADS-B In).

The typical on-board aircraft ADS-B transmitter and pulse characteristics are provided in Table 1 and Figs 1 and 2.

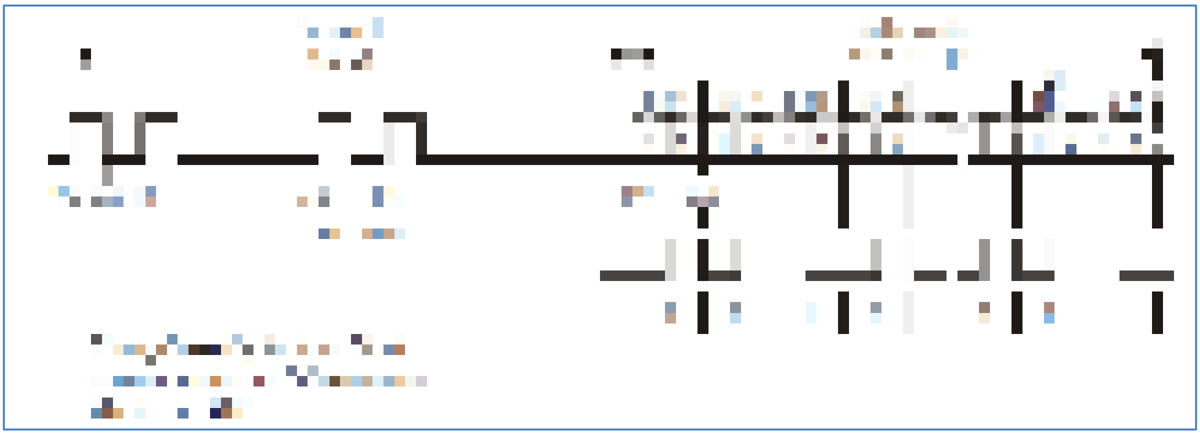
TABLE 1

Typical transmitter characteristics of 1 090 MHz automatic dependent surveillance – broadcast system

Parameter	Units	*Class A1/A2*	*Class A3*
Minimum Tx power top antenna	dBm	51	53
Minimum Tx power bottom antenna	dBm	51	53
Centre frequency	MHz	1 090	
Frequency stability	MHz	±1	
Polarisation		Vertical	
Antenna gain	dBi	(see Fig. 2)	
Bandwidth 3 dB 20 dB 40 dB 60 dB	MHz	±1.3 ±7 ±23 ±78	
Message length	μs	120	
Message period (minimum)	ms	161	
Message characteristics		(see Fig. 1)	
Message transmission rate	per sec	Up to 6.2	
Interval between successive positional message	sec	0.5 ± 0.1	
Number of other messages	per sec	Four	

FIGURE 1

Mode S message[3]

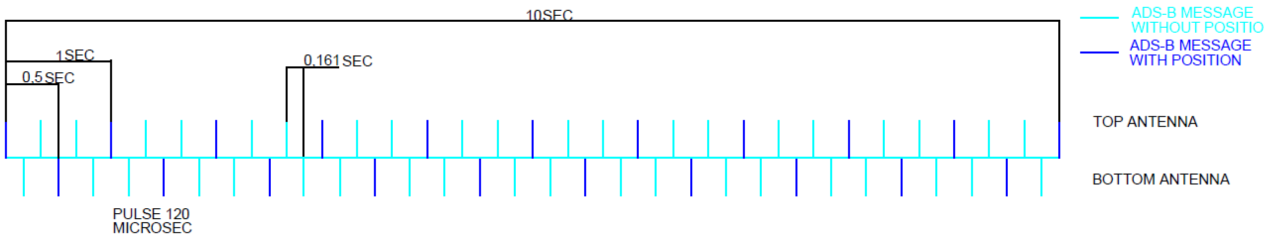


NOTE: ADS-B signals are all 120 μs in length (8 μs preamble plus 112 μs data block).

3 Source: ICAO Convention on International Civil Aviation, Annex 10, Vol. IV, 2014.

FIGURE 2

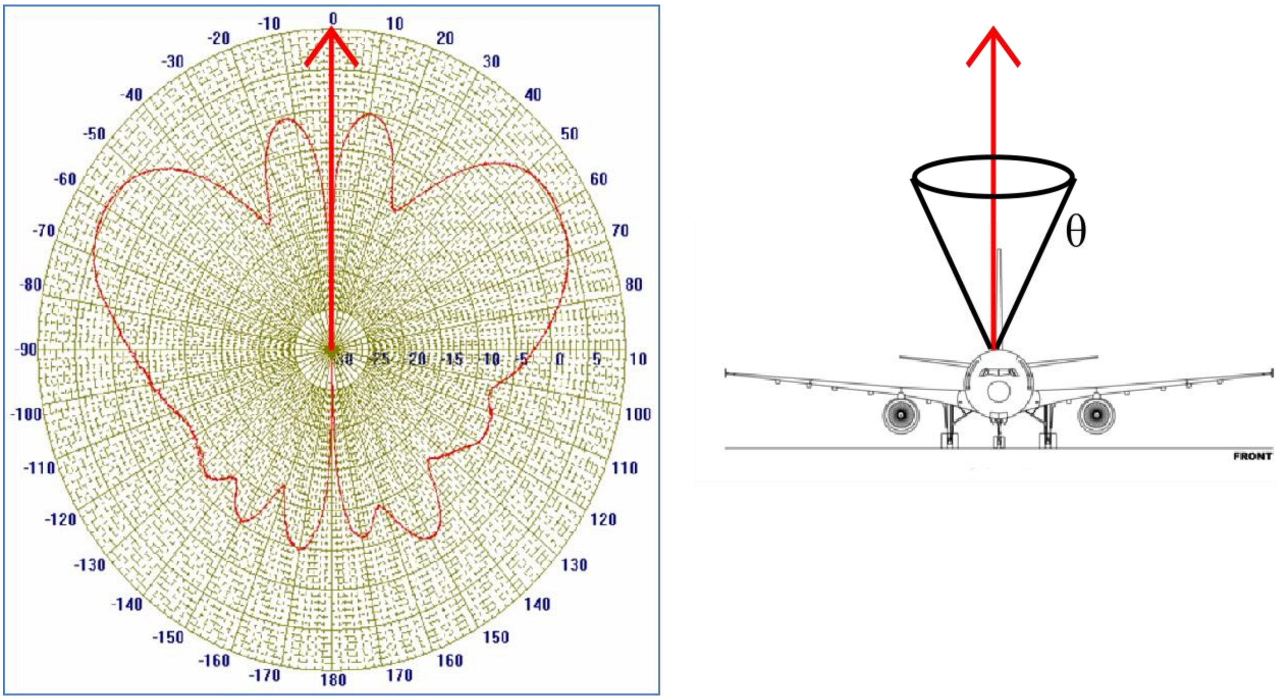
Timescale of the automatic dependent surveillance messages transmission with and without position information



NOTE: This Figure is meant to be a high level representation of ADS-B message timing at its highest transmission rate from a given aircraft and does not show the jitter of ±0.1s about each transmission, which results in ADS-B not being strictly periodic.

FIGURE 3

Automatic dependent surveillance – broadcast antenna characteristics



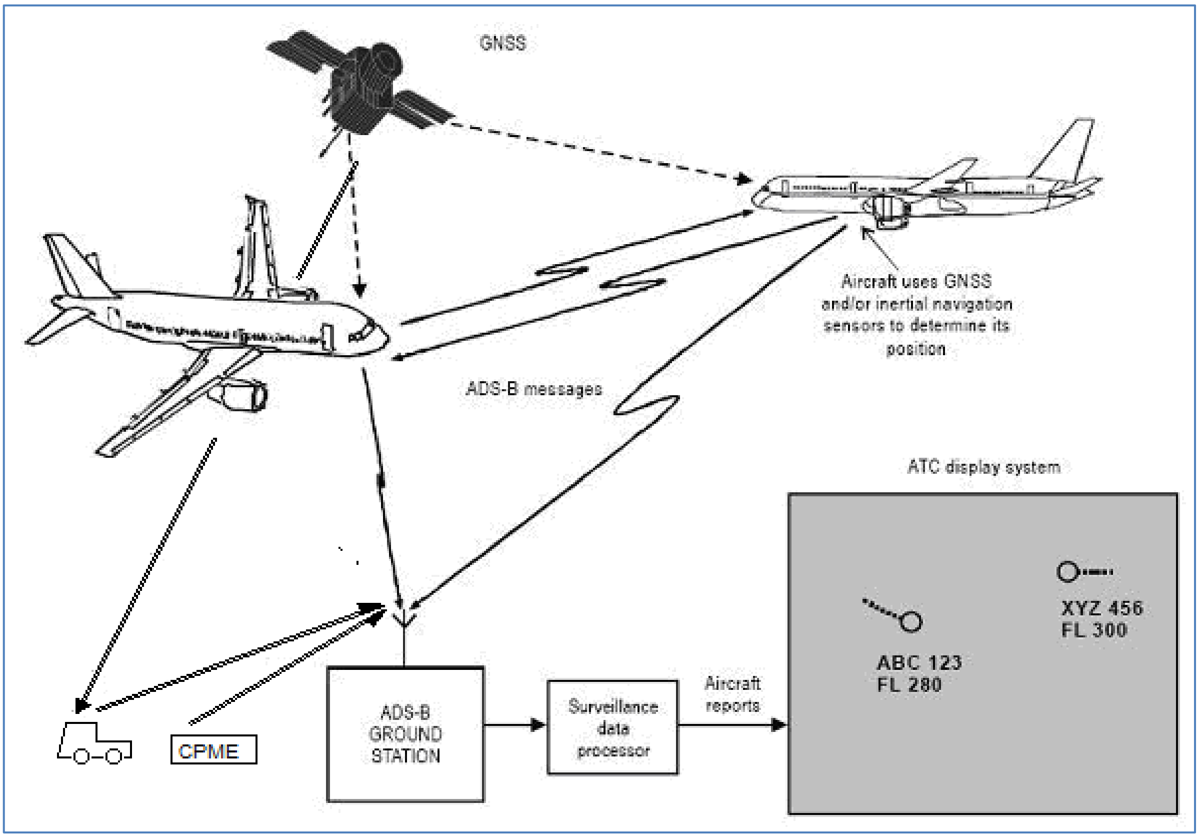
NOTE: Figure 3 represents a measured antenna pattern of an ADS-B transmitter installed on an aircraft.

Existing standards mandate that all aircraft with a maximum take-off weight of more than 5 700 kg, as well as smaller aircraft capable of maximum cruising speed of 324 km/h (175 kts) or greater and/or cruising altitudes of 15 000 feet (4.6 km) or higher, carry two antennae transmitting the ADS-B signal at 1 090 MHz (one placed on the bottom and one placed on top of the fuselage) in order to enjoy the benefits of antenna discrimination.

Terrestrial use of ADS-B is shown in Fig. 4.

FIGURE 4

Terrestrial automatic dependant surveillance – broadcast message broadcasting



NOTE: CPME= Calibration and performance monitoring equipment.

A limitation of terrestrial ADS-B is that aircraft transmissions cannot be received by a ground station beyond line-of-sight. Much of the oceanic airspace, transpolar and other remote regions cannot be practically covered using terrestrial ADS-B stations to receive aircraft transmissions.

2 Description of automatic dependent surveillance – broadcast reception by satellite

A space-based system with space-qualified ADS-B receivers on a low earth orbit (LEO) polar orbiting satellite system, or other types of non-geostationary orbit systems, can provide the opportunity for extending ADS-B coverage for aircraft equipped with ADS-B transmitters / 1090 ES ADS-B and so overcome the aforementioned limitations of terrestrial ADS-B ground stations.

In the case of aircraft equipped with an antenna placed on the bottom only (refer to § 1), the attenuation and diffraction due to the fuselage will affect the reception of ADS-B messages by the receiver on board the satellite. Such effects would impact the technical feasibility of satellite reception of ADS-B for aircraft without a top mounted antenna.

An example of the implementation of satellite-based ADS-B capability is described in Fig. 5. ADS-B receivers located on each satellite would receive the signals broadcast from each aircraft within line-of-sight. The successfully received ADS-B data from aircraft would be routed and down-linked to a control and processing system, and aggregated.

In this example, the feeder links and cross links used to route the ADS-B data to the ground, operate in the fixed-satellite service (FSS) and inter-satellite service (ISS), respectively. ISS and FSS feeder link frequency bands that may support ADS-B reception at 1 090 MHz would not require any special status, special coordination procedures or additional protection.

Once downlinked and aggregated, the pre-processed data from the control and from the initial processing system could be integrated into existing ADS-B ground infrastructure for further processing and analysis, and then forwarded on to the appropriate air traffic management (ATM) centres and airline operators.

FIGURE 5

Example of an integrated terrestrial and satellite automatic dependant surveillance - broadcast system

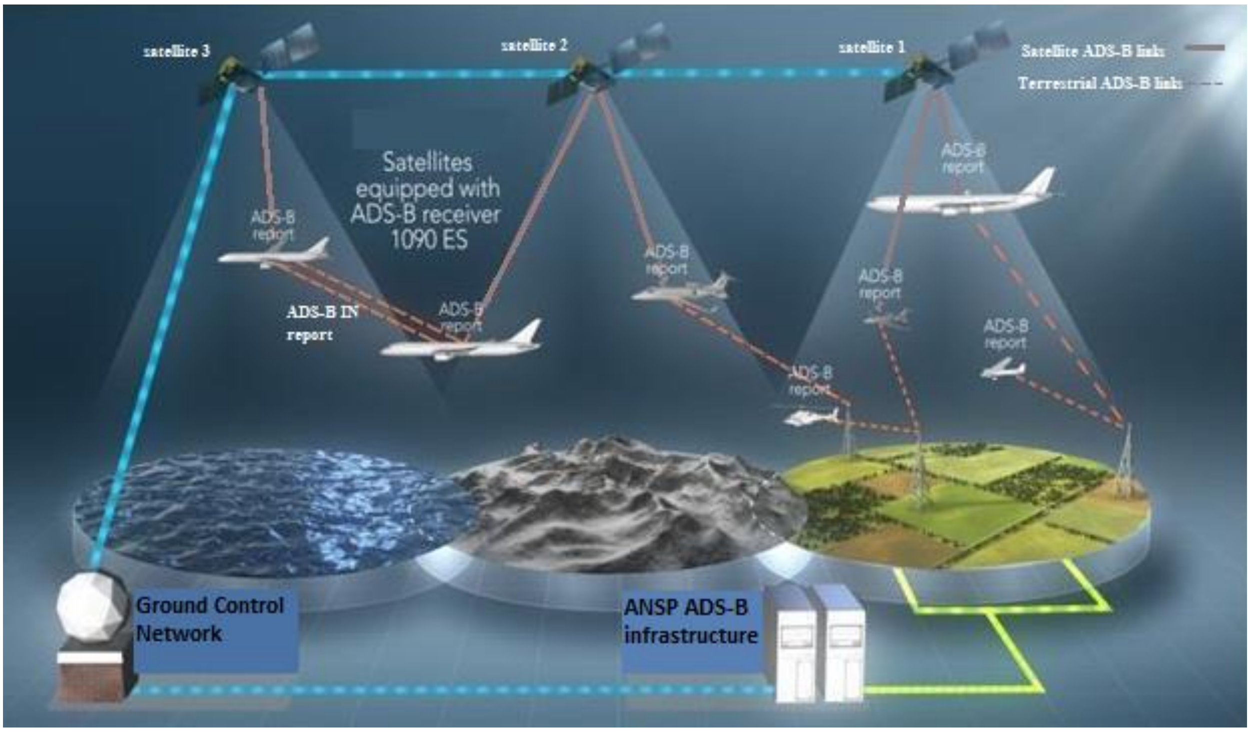


Figure 5 depicts an integration example of terrestrial and satellite ADS-B systems. In this example, satellite 1 receives the ADS-B transmission from aircraft flying over areas with terrestrial ADS-B coverage. Satellite 2 receives ADS-B transmissions from aircraft flying over areas with terrestrial ADS-B coverage as well as remote areas without terrestrial coverage. Satellite 3 receives ADS-B transmissions over oceanic regions.

Trials of reception of ADS-B via satellite have been conducted by the European Space Agency with its PROBA-V satellite. This satellite carried a hosted ADS-B receiver payload and has collected ADS-B data for the past two years, at the altitude of about 800 km. This experiment shows the feasibility of the reception of ADS-B signals via satellite under a certain level of probability of detection (see Annex 3). It has been considered that the design and the performance parameters of the experimental system at hand do not fulfil the requirements of an operational surveillance system. This can be explained mostly due to the influence of the antenna pattern of the ADS-B receiver and its placement onboard of PROBA-V, pointing vertically down in the cone of silence of the aircraft air traffic control (ATC) antenna or its vicinity. Better results could be expected by a slant pointing satellite ADS-B antenna, but such configuration was not possible on PROBA-V due to the restrictions for the hosted payload.

Assumed ADS-B satellite receiver characteristics are provided in Table 2.

TABLE 2

Example automatic dependent surveillance – broadcast satellite receiver characteristics

Typical parameter		
Satellite antenna gain and beamwidth *	**Minimum gain (dBi)**	**Approx. 3 dB beamwidth (degrees)**
	21.5	10
	19.0	13.5
	15.5	20
	13.5	25
	11	33
Non-geostationary orbit altitude	500 – 1 500 km	
System noise temperature	400 K	

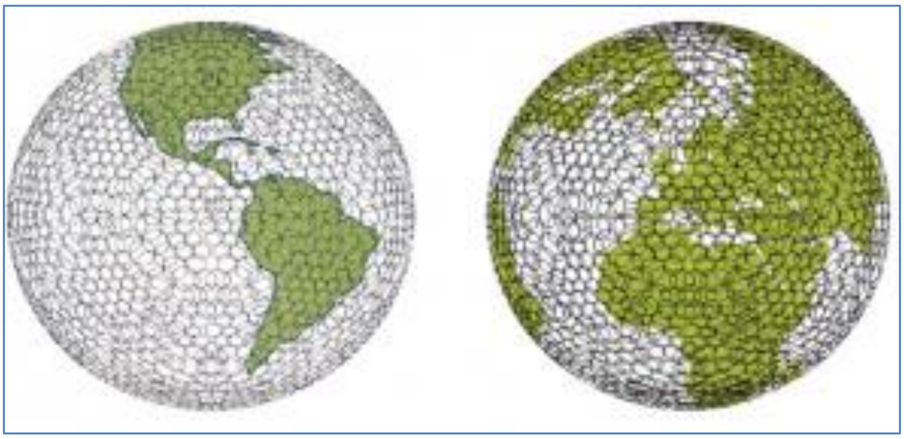
NOTE – Minimum gain represents the 3 dB beam edge value.

* A range of possible antenna characteristics are shown – these may be linked to specific orbits. Mobile satellite systems commonly employ an array of spot beams in order to provide continuous coverage of the visible Earth. These characteristics apply to individual spot beams.

When deploying non-geostationary orbit (NGSO) satellites to expand reception of ADS-B signals on a global basis, the NGSO constellation will use multi-spot beam configurations with beam characteristics resembling those in Table 2 and consistent with its planned orbital parameters. Various examples of orbit parameters for NGSO systems that operate or planned to operate at frequencies below 3 GHz can be found in Recommendation ITU-R M.1184-2 – Technical characteristics of mobile satellite systems in the frequency bands below 3 GHz for use in developing criteria for sharing between the mobile satellite service (MSS) and other services. Some additional information is also available in Report ITU-R M.2149-1 – Use and examples of mobile-satellite service systems for relief operation in the event of natural disasters and similar emergencies, and in the ITU-R Handbook on Mobile Satellite Service and its supplements 1, 2, 3 and 4. Figure 6 depicts one MSS satellite constellation beam configuration providing complete coverage of Earth.

FIGURE 6

An example mobile satellite service satellite constellation spot beam configuration with complete coverage of Earth



The following link budget calculation estimates the ADS-B signal level associated with different classes of aircraft transponders at the satellite receiver on either a low earth orbit or geostationary satellite:

$$P_{rx} = P_{tx} - FL_{tx} + G_{tx} - PL + G_{rx} - FL_{rx} \quad (1)$$

where:

P_{rx}: Power at the satellite receiver

P_{tx}: Transmitter power

FL_{tx} : Feeder loss in transmission chain

G_{tx}: Gain of the transmit antenna

PL: path loss (free space assumed)

G_{rx}: Gain of the receive antenna

FL_{rx}: Feeder loss in the receiver chain.

NOTE – The use of a free-space loss propagation model was assumed in these calculations. The use of the Rec. ITU-R P.618-12/P.682-3 propagation model may provide more accurate results but the impact on the results would not be significant.

Figure 7 presents the carrier-to-noise performance for Class A1, A2 and A3 transponder signals received by a satellite placed in non-geostationary orbits of 500 km, 800 km or 1 500 km, for different values of minimum satellite antenna gain as per Table 2. A carrier-to-noise objective is shown for reference, corresponding to the performance of standard terrestrial ADS-B receivers. (The full results are tabulated in Annex 2.)

FIGURE 7

Carrier-to-noise performance of satellite automatic dependent surveillance – broadcast link (noise temperature = 400 K)

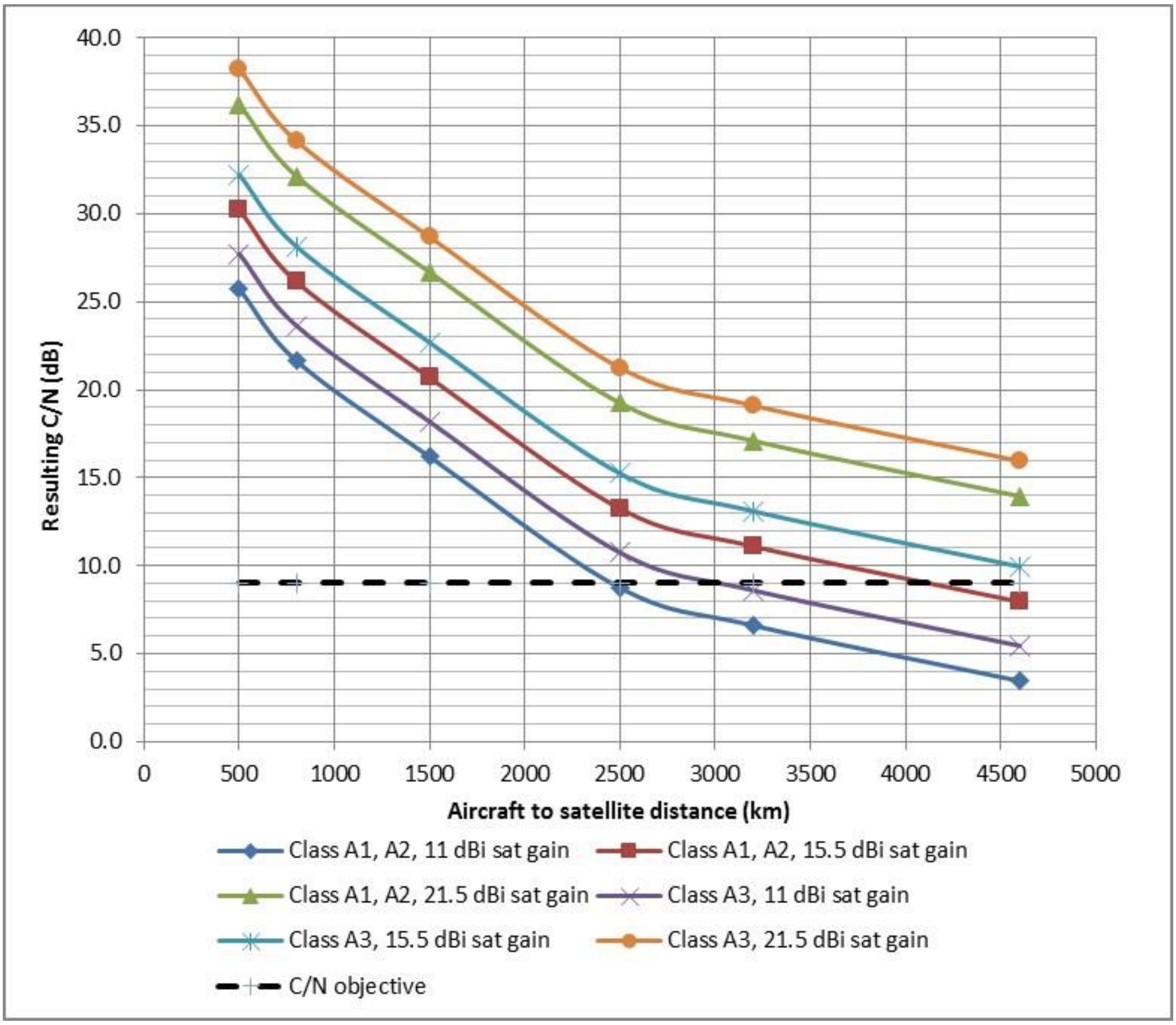


Figure 7 was derived using free-space propagation loss.

3 Operational environment for the reception of automatic dependent surveillance – broadcast via satellite

There are some operational considerations related to reception of ADS-B signal at the satellites. These are distinguishing the ADS-B signals from other aeronautical systems signals operating in the frequency band (undesired signals), such as replies to secondary surveillance radar (SSR) interrogations, DME and tactical air navigation system (TACAN).

3.1 Operational environment

First, in the global, remote and oceanic regions areas where the satellite component can provide surveillance coverage by receiving ADS-B signals from aircraft, it is expected that the satellites would be receiving mostly desired signals from aircraft that traverse oceanic, polar, and remote regions of the world.

However, there can be significant undesired signals density which impact satellite reception of ADS-B signals over areas of high air traffic activity, number of aircraft- and ground-transmitters and interrogations as well as replies to interrogation-modes transmitted on 1 030 MHz whenever the satellite’s antenna main beam and side lobes cover transitional areas adjacent to areas of high air traffic activity. As shown below, the presence of undesired signals may be mitigated through application of different techniques.

In the co-channel case, the sources of signals in the band come from:

− SSR and non ICAO systems equipped aircraft responding on 1 090 MHz to interrogations.

− Calibration and performance monitoring transponders, used to monitor performance of ground-based SSR receivers.

− Airborne collision avoidance system (ACAS).

− Ground-based 1090 ES ADS-B transmissions by airport ground vehicles fitted with “Squitter Boxes”, 1090 ES ADS-B transmitters. These are generally lower power and low in numbers and lower in transmission rate compared to other sources of interference signals in the 1090 MHz band.

− 1090 ES ADS-B transmissions from aircraft on the ground and in the air.

− DME and TACAN:

  – aircraft interrogators;

  – ground transponder replying to interrogations;

  – aircraft interrogator transponder replying to interrogations.

− Non-ICAO aeronautical radionavigation systems (ARNS) described in Recommendation ITU-R M.2013-0 Annex 2.

  The density of replies generated by interrogations on 1 030 MHz depends on the number of interrogators and their characteristics, from;

  – ground based ICAO and non ICAO standard SSR interrogators;

  – multilateration sensors;

  – airborne non ICAO standard SSR interrogator.

In the adjacent band/channel, other sources may also create interference when using high power transmissions. The impact of such interference depends on the unwanted emission source and the ADS-B receiver selectivity performance. It is expected that there would be few such sources in oceanic and remote areas.

Aircraft antenna gain varies as a factor of azimuth and flight orientation (roll, yaw, pitch) of an aircraft. The aircrafts flight orientation defines the effective antenna gain towards a satellite during the transmission of replies to SSR interrogations and ADS-B messages.

The e.i.r.p. of ADS-B transmissions towards the satellite receiver, the satellite receiver mask and satellite receiver antenna gain toward desired and interfering sources will have an impact on the decoding of desired signals received by the satellite.

3.2 Techniques to improve automatic dependent surveillance – broadcast signal discrimination and detection

There are various techniques to improve the reception of ADS-B signals in areas of high interrogator density. These include signal processing and spatial filtering.

– Signal Processing: an advanced receiver design uses a non-coherent matched filter with bit decision algorithms.

  By sampling at a much higher rate than a standard terrestrial ADS-B receiver, it is possible to detect bit collision and to significantly increase the probability of successful demodulation.

This may be effective in the presence of non-ICAO signals that have a much shorter pulse duration than ADS-B signals, and can be filtered out using this technique.

– Spatial Filtering/isolation: it may be possible to position the beam coverage in such a way as to reduce reception from aircraft in areas with a high density of interrogators. In addition, the beams may also be dynamically deactivated or reshaped to accomplish the same purpose. Areas of high numbers of interference sources, such as high density airport areas which are covered by terrestrial ADS-B and/or SSR surveillance, may be blanked out if necessary.

4 Current use of the frequency band

The frequency band 1 087.7-1 092.3 MHz is currently part of a larger frequency band allocated to the aeronautical mobile (route) service (AM(R)S) and the ARNS on a primary basis. WRC-15 made an allocation to the aeronautical mobile-satellite (route) service (AMS(R)S) for the purpose of satellite reception of ADS-B signals:

TABLE 3

Current Article 5 table of allocations entry for the frequency band 960–1 164 MHz

Allocation to services		
Region 1	**Region 2**	**Region 3**
960-1 164	AERONAUTICAL MOBILE (R) 5.327A AERONAUTICAL RADIONAVIGATION 5.328 5.328AA	

5.328AA The frequency band 1 087.7-1 092.3 MHz is also allocated to the aeronautical mobile – satellite (R) service (Earth-to-space) on a primary basis, limited to the space station reception of Automatic Dependent Surveillance-Broadcast (ADS-B) emissions from aircraft transmitters that operate in accordance with recognized international aeronautical standards. Stations operating in the aeronautical mobile-satellite (R) service shall not claim protection from stations operating in the aeronautical radionavigation service. Resolution **425 (WRC-15)** shall apply.

The aircraft ADS-B transmissions use 4.6 MHz of bandwidth centred on the frequency 1 090 MHz and operate under the AM(R)S and AMS(R)S in Article **5** of the Radio Regulations.

ICAO standardised systems

In addition to ADS-B, other global aeronautical systems operating within the frequency band 960-1 164 MHz with which compatibility needs to be considered are terrestrial DME, SSR, and ACAS. These systems are standardised to meet ICAO technical standards and interoperability requirements to ensure their global operation without any in-band or adjacent band interference or compatibility issues. Global interoperability and technical compatibility of these aeronautical systems are assured by ICAO standards and recommended practices.

It has also been noted that future AM(R)S systems are under study in ICAO.

A full description of the operation of terrestrial ADS-B systems is given in standardisation documents such as ICAO Convention on International Civil Aviation, Annex 10, Vol. IV, "Surveillance and Collision Avoidance Systems"[4].

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[4] ICAO Convention on International Civil Aviation, Annex 10, Vol. IV, "Surveillance and Collision Avoidance Systems", ICAO 2014.

Non-International Civil Aviation Organization systems

Non-ICAO ARNS systems are identified in *considering e)* and *f)* of Resolution **417 (Rev.WRC-12)** and Recommendation ITU-R M.2013-0. There are additional systems that have functionality similar to SSR which also operate in the same frequency band 1 087.7-1 092.3 MHz and are considered in some countries operating under ARNS. The operation of all the systems above should be considered when assessing the performance of satellite reception of ADS-B.

Feeder and Inter-Satellite Links

ADS-B signals received by the satellites are linked to the ground through feeder and inter-satellite links in other frequency bands. Feeder links in the FSS are being used in at least two other satellite networks to support similar AMS(R)S safety service applications without the need for protection requirements for the feeder link operations beyond that afforded to FSS feeder links not supporting safety services.

For both current and future systems, no change in regulatory status for the feeder link band is needed and no special protection for the feeder links is required. Fixed-satellite and inter-satellite allocations are currently used for safety services including AMS(R)S without the need for a special status.

5 Sharing and compatibility studies

5.1 Characteristics of incumbent services

International Civil Aviation Organization standardized systems

One study assumed characteristics of the ICAO standardized systems terrestrial DME, SSR, and ACAS as shown in Annex 4.

Non-International Civil Aviation Organization systems

The assumed characteristics of non-ICAO systems can be found in Annex 1.

5.2 Assumptions

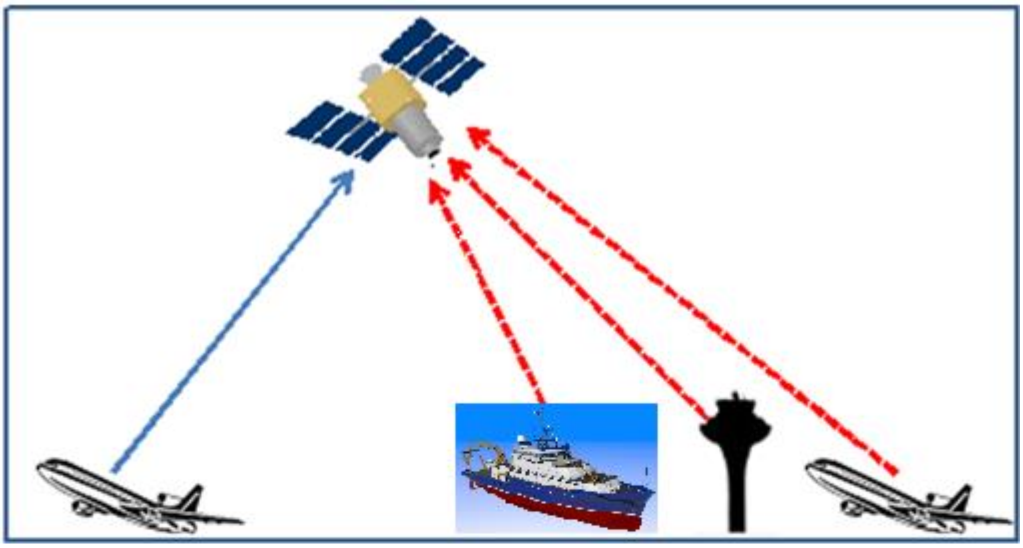
a) The satellite footprint based on a non-geostationary orbit altitude of 1 000 km and a 33 degree beamwidth antenna as per Table 2 is similar to the line of sight area of an aircraft flying at 6 875 m, approximately 296 km. Therefore, an aircraft flying at an altitude of 6 875 m will be subject to the same sources of undesired signals as a NGSO satellite with an altitude of 1 000 km and 33 degree beamwidth antenna.

b) Taking into account the existing sharing arrangements between ICAO and non-ICAO systems, it is assumed that these systems do not operate co-channel on 1090 MHz in the same geographic area as described in assumption a).

The sharing environment with non-ICAO systems can be summarised as presented in Fig. 8:

FIGURE 8

Sharing environment with non- ICAO systems and automatic dependent surveillance – broadcast satellite receiver



An ADS-B receiver located on a satellite will receive both desired signals (shown in blue) and one or more interfering signals (shown in red), when such interfering signals are present, as depicted in Fig. 8.

5.3 Static calculation of carrier to interference ratios of undesired non-International Civil Aviation Organization signals and desired automatic dependent surveillance – broadcast signals

For the worst-case analysis, it is assumed that the source of the desired ADS-B signal lies in the same satellite receive beam as each of the interference (non-ICAO system) signal sources and that the path loss and receive antenna gain for each signal are the same. In this case, the carrier-to-interference (*C/I*) ratio can be calculated by simple comparison of the e.i.r.p. values of the ADS-B signal and each of the interference sources.

TABLE 4

Carrier-to-interference impact to satellite reception of automatic dependent surveillance - broadcast signal

ADS-B		**Class A1/A2 ***					
Tx e.i.r.p.	**dBW**	**21 ***					
ARNS:		**TACAN Forward link**	**TACAN Return link**	**ARNS Forward link #2**	**ARNS Return link #2**	**ARNS Forward link #3**	**ARNS Return link #3**
Tx e.i.r.p.	dBW	45	33	54.6	36	40	34.5
C/I	dB	–24	–12	–33.6	–15	–19	–13.5

* ADS-B Class A3 has an e.i.r.p. of 23 dBW, increasing the *C/I* by 2 dB.

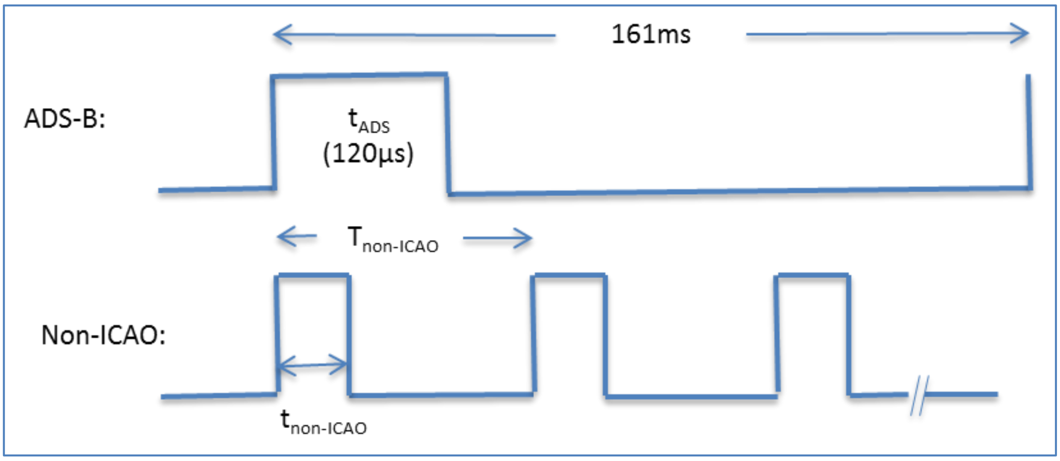
In these worst-case scenarios, the resulting *C/I* values for ADS-B reception assuming simultaneous transmission of desired and undesired signals are all negative. In order to further consider the coexistence environment between ADS-B and the systems in Table 4, the pulse characteristics of the signals may then be analysed using a probabilistic approach.

5.4 Calculations of the probability of pulse collisions based on the pulse nature and characteristics of some non-ICAO systems

As a first approximation, it was assumed that any collision of two pulses would result in the loss of both pulses, and not taking into account the inherent error correction capability of the ADS-B system made possible through availability of the cyclic redundancy checks at the receiver. The probability of interference due to collision of simultaneously transmitted signals can be calculated by examining the pulse duration and duty cycle (period) for each. Figure 9 presents the ADS-B and non-ICAO systems pulses and duty cycle. Annex 1 provides detailed information on non-ICAO systems pulse duration and duty cycles.

FIGURE 9

Example of pulse characteristics of automatic dependent surveillance – broadcast signal and non-ICAO systems



As can be seen from Fig. 9, if the period of the non-ICAO system is less than the pulse duration of the ADS-B signal, the probability of collision would be 100%. The non-ICAO system pulse characteristics shown in Table 5 were obtained from Annex 1.

Both signals are continuously transmitted, and the period of the ADS-B signal is much greater than the period of the non-ICAO signal, so the probability of collision can be calculated from the potential overlap of the two pulses thus:

$$P(single\ collision) = \frac{t_{non-ICAO}+t_{ADS}}{T_{non-ICAO}} \tag{2}$$

Assuming that: $T_{ADS} > T_{non\text{-}ICAO}$ and $t_{ADS} > t_{non\text{-}ICAO}$

where:

$t_{non\text{-}ICAO}$: pulse duration of non-ICAO interfering signal

t_{ADS} : pulse duration of ADS-B desired signal

$T_{non\text{-}ICAO}$: period of non-ICAO interfering signal

T_{ADS} : period of ADS-B desired signal.

and:

$$P\ \text{(multiple collision)} = 1 - (1 - P(single\ collision))^m$$

where:

m = number of independent co-frequency non-ICAO systems within the same beam interfering simultaneously with the ADS-B receiver on board the satellite.

The probability of single pulse collisions can thus be determined for each case as shown in Table 5:

TABLE 5

Probability of pulse collision with non-ICAO systems

		TACAN (ground* to air)	**TACAN** (air to ground*)	**ARNS #2** (ground* to air)	**ARNS #2** (air to ground*)	**ARNS #3** (ground* to air)	**ARNS #3** (air to ground*)
Pulse t	µs	3.5	3.5	5.5	1.5	1.7	1.7
Duty cycle	%	2.52	0.105	0.3	0.00765	0.04	0.009
Period T	µs	139	3 333	1 833	19 608	4 250	18 889
P(collision)	%	88.9	3.7	6.8	0.6	2.9	0.6

* May include ship-borne.

The study assumed that any collision of pulses resulted in complete loss of the desired ADS-B signal. However, ICAO, in response to an ITU-R liaison statement, has indicated that non-ICAO signals, such as TACAN and similar signals, are not considered significant as an interfering source since they typically do not occur near 1 090 MHz and/or their short pulse duration (1.5 to 3.5 µs relative to 120 µs ADS-B) is not enough for them to be considered highly destructive for 1 090 MHz ADS-B reception because of error correction.

It was noted that under multi-entry interference scenario into the ADS-B channel the probability of pulse collision would be higher than single interference case.

5.5 Detailed dynamic simulation of sharing environment including both ICAO and non-ICAO systems (Annex 3)

In order to evaluate the sharing and compatibility of satellite reception of ADS-B with the incumbent services described in § 4, including multiple sources of interference, Study#1 followed the steps:

a) identify characteristics of incumbent services

b) identify assumptions

c) perform basic calculations of the carrier to interference ratios of undesired non-ICAO signals and desired ADS-B signals

d) perform calculations of the probability of pulse collisions based on the pulse nature and characteristics of some non-ICAO systems

e) perform a detailed dynamic simulation of sharing environment considering both ICAO and non-ICAO systems

The simulation is based on the premise that the greatest source of undesired signals that would impact the satellite reception of ADS-B comes from the ICAO systems identified in § 3 operating co-channel on 1 090 MHz:

– aircraft responding to ground based SSR interrogations such as Mode-S;

– air traffic control radar beacon system;

– traffic collision avoidance system (TCAS) interrogations;

– other 1 090ES ADS-B signals.

The objective of the analysis was to model the successful reception of ADS-B messages in the overall environment of the systems mentioned above. The model begins with the assumption that undesired signals have the effect of a Poisson Arrival Rate because they arrive independently of each other. The probability model was built from the probability of successful reception in the presence of a number of undesired signals as documented in other ADS-B studies. With real world flight data from a 24-hour period, aircraft counts were then categorized according to link type and transmit power. For example, 15% of aircraft were assumed to be transmitting ADS-B messages with a transmit power of 250 W with half of these transmissions from the top antenna and half from the bottom antenna. To be close to real flight data, aircraft counts are not uniformly distributed in time and space. A phased array beam gain antenna pattern was applied to the satellite receiver and taken into account over each geographical area of aircraft counts. This study indicated that the resulting probability of successful reception was portrayed in areas surrounding the 17 busiest airports of the given flight data. Near real time surveillance performance of an update interval of every 15 seconds was met better than 95% of the time and every 30 seconds better than 97% of the time.

List of assumptions used in Study #1:

– The simulation is based on the premise that the greatest source of undesired signals that would impact the satellite reception of ADS-B comes from ICAO and non-ICAO systems operating co-channel on 1 090 MHz.
– Undesired signals have the effect of a Poisson Arrival Rate because they arrive independently of each other.
– Real world flight data from a 24 hour period have been used and aircraft counts categorized according to link type and transmit power.
– The model assumes that both desired and undesired signals from the bottom antenna can be seen at the satellite, taking into account an attenuation factor dependent on the geometry of the satellite to the aircraft.
– It was assumed that TACAN systems are primarily operated at least 5 MHz away from 1 090 MHz and do not pose a significant co-frequency interference concern.
– Aircraft transmitter message categorization assumptions are provided in Tables A3-2 and A3-5 for years 2015 and 2030, respectively.
– The three classes of interfering signal (Mode S, SSR and non-ICAO systems are assumed to arrive independently of each other.
– Since there are many instances of beam overlap and satellite-to-satellite overlap, the simulation model calculates the Update Interval relative to position message updates and accounts for the mix of position messages of the ADS-B 1090 ES position reporting algorithm.

Detailed discussion of Study # 1 can be found in Annexes 3 and 4.

5.6 Statistical simulation of sharing environment including both ICAO and non- ICAO systems (Annex 5)

A second statistical study (Study # 2) used a proprietary computer modelling software package to simulate pulse collisions at a non-geostationary satellite. The study modelled a fixed density of aircraft, and considered ICAO systems and some non-ICAO systems.

The results of this study indicate that smaller beams provide better performance and, based on the assumptions used and a satellite antenna beamwidth of 20 degrees, estimated that an ADS-B signal can be received from an aircraft within 15 seconds with a probability of nearly 100%. With a satellite antenna beamwidth of 33 degrees, it was estimated that an ADS-B signal can be received from an aircraft within 15 seconds with a probability of more than 93.8%.

List of assumptions used in Study #2:

– Study modelled a fixed density of aircraft, and considered ICAO systems and some non-ICAO systems.

– The most important assumption taken to develop the simulation model was that every transmission signal in coverage area would be received by the satellite in orbit. False replies unsynchronized in time (FRUIT) is not taken into account, but may be easily modelled by incrementing SSR transmissions (replies) rate.

– Message reception validity is done by modelling message collisions caused by interference from various radar interrogation replies and messages at 1 090 MHz. A message collision occurs when the broadcast time interval from two separate messages or replies overlap partially or completely.

Detailed discussion of Study # 2 can be found in Annex 5.

5.7 Statistical and dynamical simulation of sharing environment including both ICAO and non-ICAO systems (Annex 6)

A third study (Study # 3) evaluates, dynamically and statistically, the ADS-B pulse frames received and decoded by the satellite when emitted by aircraft in its line of sight.

This simulation is dynamic in that it considers not only satellite trajectories but also the world air routes used by commercial aircraft. It is statistical in that the instants in time defining the calculation area are selected randomly. In other words, at each time ‘t’, the satellite position and the positions of all the aircraft throughout the world are drawn randomly, noting however that the aircraft are distributed over all known air routes. The conclusion from Study # 3 is that the reception probability of ADS-B messages in ocean areas or over isolated land masses is close to 100% during more than 43% of the time, and always at least 57%. Nevertheless, this reception is significantly affected over areas with particularly dense air traffic, notably over a large part of Europe, the eastern part of North America and the whole of eastern Asia, where reception quality may fall to around 60% but in which the maximum of located aircraft never exceed 90%.

List of assumptions used in Study #3:

– The satellite position and the positions of all the aircraft throughout the world are drawn randomly, noting the aircraft are distributed over all known air routes.

– It is considered that, at a given time, there is always one aircraft on an air route, then we may consider that, at every instant in time, there are approximately 59 000 aircraft circulating around the globe.

– Table A6-1 presents the assumed distribution of different types of transponders over the global aircraft fleet for ICAO and non ICAO type aircraft.

– The simulation results are based on the following hypotheses:

  • ICAO-type aircraft are distributed on the world air routes.

  • Non-ICAO type aircraft are distributed in satellite line of sight.

  • The simulations are performed during 10s. During this time, the satellite motion is considered whereas the aircraft are considered fixed (taking into account that satellite speed is around 30 times greater than the speed of aircraft) – See Figs A6-3, A6-4 and A6-5.

  • The number of non-ICAO type aircraft in the global area described by the displacement of the satellite spot beam during 10s is taken randomly between one and 10.

- For each aircraft, the total emissions (Mode A/C, Mode S, ADS B and SSR) are modelled during 10 seconds. Each second the simulation considers all samples of one second from aircraft emissions in visibility of the satellite (see Table A6-5 for more details).
- The simulation considers that beyond an angle of 30° between the satellite and the aircraft, the aircraft are no longer detected and do not contribute to interference in the satellite receiver.
- The simulation is based on the receiver sensitivity.
- The time increment in the pulse frames of each aircraft emission is 1 µs.
- The number of pulses of each emission for each aircraft is taken randomly in the range provided in Table A6-2.
- All emissions other that ADS-B are considered as interference (Mode A/C, SSR, Mode S with or without long message).
- ICAO emissions responding to an interrogation are considered to be present solely above land masses or within a maximum distance of coastlines. These hypotheses do not apply to non-ICAO emissions, which are considered to transmit anywhere.
- Due to fuselage attenuation, the simulation considers that only message emitted by the top antenna could be received by the satellite. Then, for each aircraft, only 40% of the total number of interfered message per second are emitted in direction of the satellite
- The simulation takes into account that one ADS-B message containing the position information is sent every second in direction of the satellite.
- The simulation takes account of the propagation time of messages to the satellite.
- The simulations do not take into account terrestrial stations transmitting in the 1 090 MHz band.
- The simulations consider that an ADS-B message that is partially or totally drowned in interference is lost and cannot be decoded by the receiver.

Detailed discussion of Study # 3 can be found in Annex 6.

6 Summary

Augmentation of ADS-B using satellite-based receivers permits to extend the surveillance technology globally under the allocation made at WRC-15. The definition of operational conditions for the use of satellite ADS-B data is the responsibility of ICAO and aeronautical standards organisations.

Message update rate is a function of the density of aircraft as shown in the results of the studies. When assessing the performance of satellite reception of ADS-B messages, an operational environment including both ICAO and non-ICAO systems should be considered. The studies have highlighted that in areas with high density of aircraft, short message update periods may not be supportable. It will be the responsibility of ICAO and national administrations to determine the necessary performance and appropriate use of data from satellite reception of ADS-B messages.

Annex 1

Typical transmitter characteristics of non-ICAO systems

TABLE A1-1

Characteristics of the tactical air navigation system stations[5]

Purpose	Units	Radio systems for air navigation (960-1 215 MHz)		
Radio transmission direction		Earth-aircraft	Aircraft-Earth	Aircraft-aircraft
Operating frequency range	MHz	962-1 213	1 025-1 150	1 025-1 151
Operation range	km	up to 600	up to 600	up to 740
Transmitted information		Range and bearing response signals, Identification	Range and bearing request signal	Range and bearing response signals, Identification
Transmitter characteristics				
Station name		Beacon	Interrogator	Beacon
Height above the ground	m	3	up to 18 288	up to 18 288
Signal type		Pulsed	Pulsed	Pulsed
Channel spacing	MHz	1	1	1
Type of modulation		Pulse form and pulse pair spacing	Pulse form and pulse pair spacing	Pulse form and pulse pair spacing
Transmitter power (pulsed)	dBW	39 (max)	33 (max.)	33 (max)
Pulse length	µs	3.5 ± 0.5 (50% amplitude)	3.5 ± 0.5 (50% amplitude)	3.5 ± 0.5 (50% amplitude)
Typical duty factor	%	2.52	0.105	0.735
Antenna type		Circular array	Omnidirectional	Circular array
Typical antenna gain	dBi	6	0	6

5 Recommendation ITU-R M.2013-0.

TABLE A1-2

Typical characteristics of non-ICAO systems at 1 090 MHz
(additionally to ICAO standardized characteristics for secondary surveillance radar)

Purpose	Units	Radio systems
Transmitter characteristics		
Station name		Transponder
Radio transmission direction		Aircraft-terrestrial station and aircraft–aircraft
Operating frequency	MHz	1 090
Operation range (limited to RLOS)	km	up to 400
Transmitted information		Response signal
Height above the ground	m	From ground/sea level to up to 18 288 (60 000 ft)
Type of modulation		Pulse form
Transmitter power (pulsed)	dBW	29
Message length	µs	35
Typical duty factor	%	1
Antenna type		Omnidirectional
Typical antenna gain	dBi	10

TABLE A1-3

Characteristics of non-ICAO stations operating in the aeronautical radionavigation service in the countries referenced in RR No. 5.312

ARNS system characteristics	Units	Type 2		Type 3	
Purpose		**Radio systems of short-range navigation**		**Radio systems of approach and landing**	
Operating frequency range	MHz	960 – 1 164			
Radio transmission direction		“Earth-aircraft”	“aircraft-Earth”	“Earth-aircraft”	“aircraft-Earth”
Operation range	km	up to 400	up to 400	up to 45	up to 45
Transmitted information		Transmission of azimuthal signals, range response signals and request to indication	Transmission of range request signal and indication response signal	Transmission of signals in glide path and course channels and range response signals	Transmission of range request
Transmitter characteristics					
Station name		Airport and en-route path ground stations	Aircraft station	Airport ground station	Aircraft station
Class of emission		4M30P1N	4M30P1D	700KP0X; 4M30P1N	700KP0X; 4M30P1N
Channel spacing	MHz	0.7	0.7	0.7	2

TABLE A1-3 (*end*)

ARNS system characteristics	**Units**	**Type 2**		**Type 3**	
Purpose		**Radio systems of short-range navigation**		**Radio systems of approach and landing**	
Type of modulation		Pulsed	pulsed	pulsed	pulsed
Transmitter power (pulsed)	dBW	29-39	27-33	3-30	5-33
Duty factor	%	0.064 - 0.3	0.00765	0.04; 0.025	0.009
Mean output		7.1/13.8	−8.2	−4/−6	−7.5
Pulse length	ms	1.25; 1.5; 5.5	1.5	1.7	1.7
Antenna type		array antenna	omnidirectional	array antenna	omnidirectional
Max/min antenna gain	dBi	15.6	3/−10	10/0	1.5/−3
Height above the ground	m	10	up to 12 000	10	up to 12 000

Annex 2

Tables of carrier-to-noise performance for satellite automatic dependent surveillance – broadcast link

TABLE A2-1

Satellite receive antenna gain = 11 dBi, receiver noise temperature = 400 K

	Units	**Class A1 and A2 Transponder**					
Transmitter e.i.r.p. [1]	dBm	51	51	51	51	51	51
Satellite orbit	km	500	800	1 500	500	800	1 500
Elevation angle	degree	90	90	90	0	0	0
Distance between satellite and surface of earth	km	500	800	1 500	2 500	3 200	4 600
Free space path loss [2]	dB	147.2	151.3	156.7	161.1	163.3	166.4
Gain of satellite receive antenna	dBi	14	14	14	11	11	11
Feeder loss in the receive chain [3]	dB	0.5	0.5	0.5	0.5	0.5	0.5
Received signal power	dBm	–82.7	–86.8	–92.2	–99.6	–101.8	–104.9
System noise [4]	dBm	–108.4	–108.4	–108.4	–108.4	–108.4	–108.4
C/N	dB	25.7	21.6	16.2	8.8	6.6	3.5
C/(N+I) required [5]	dB	9.0	9.0	9.0	9.0	9.0	9.0

NOTE: Possible polarisation mismatch between transmitter and receiver has been considered.

TABLE A2-2

Satellite receive antenna gain = 15.5 dBi, receiver noise temperature = 400 K

	Units	**Class A1 and A2 Transponder**					
Transmitter e.i.r.p. [1]	dBm	51	51	51	51	51	51
Satellite orbit	km	500	800	1 500	500	800	1 500
Elevation angle	degree	90	90	90	0	0	0
Distance between satellite and surface of earth	km	500	800	1 500	2 500	3 200	4 600
Free space path loss [2]	dB	147.2	151.3	156.7	161.1	163.3	166.4
Gain of satellite receive antenna	dBi	18.5	18.5	18.5	15.5	15.5	15.5
Feeder loss in the receive chain [3]	dB	0.5	0.5	0.5	0.5	0.5	0.5
Received signal power	dBm	–78.2	–82.3	–87.7	–95.1	–97.3	–100.4
System noise [4]	dBm	–108.4	–108.4	–108.4	–108.4	–108.4	–108.4
C/N	dB	30.2	26.1	20.7	13.3	11.1	8.0
C/(N+I) required [5]	dB	9.0	9.0	9.0	9.0	9.0	9.0

TABLE A2-3

Satellite receive antenna gain = 21.5 dBi, receiver noise temperature = 400 K

	Units	**Class A1 and A2 Transponder**						
Transmitter e.i.r.p. [1]	dBm	51	51	51	51	51	51	51
Satellite orbit	km	500	800	1 500	500	800	1500	GSO
Elevation angle	degree	90	90	90	0	0	0	90
Distance between satellite and surface of earth	km	500	800	1 500	2 500	3 200	4 600	36 000
Free space path loss [2]	dB	147.2	151.3	156.7	161.1	163.3	166.4	184.3
Gain of satellite receive antenna	dBi	24.5	24.5	24.5	21.5	21.5	21.5	21.5
Feeder loss in the receive chain [3]	dB	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Received signal power	dBm	–72.2	–76.3	–81.7	–89.1	–91.3	–94.4	–112.3
System noise [4]	dBm	–108.4	–108.4	–108.4	–108.4	–108.4	–108.4	–108.4
C/N	dB	36.2	32.1	26.7	19.3	17.1	14.0	–3.9
C/(N+I) required [5]	dB	9.0	9.0	9.0	9.0	9.0	9.0	9.0

TABLE A2-4

Satellite receive antenna gain 11 dBi, satellite height = 1 500 km, receiver noise temperature = 400 K, Potential impact of measured aircraft antenna pattern null

	Units	Class A1 and A2 Transponder								
Transmitter power at aircraft antenna input	dBm	51	51	51	51	51	51	51	51	51
Aircraft antenna Sidelobe angle to the satellite	degrees	0	2.04	4.08	6.12	8.16	10.21	12.26	14.32	14.89
Aircraft antenna gain	dBi	−16	−7.94	−5.12	−3.12	−1.8	−1.06	−1.07	−1.5	−1.33
Distance between satellite and surface of the earth	km	1500	1501	1503	1507	1512	1519	1528	1539	825
Free space path loss	dB	156.7	156.7	156.7	156.7	156.7	156.8	156.8	156.9	151.5
Gain of the Satellite receive antenna at sub-satellite point	dBi	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
Feeder loss in the receiver chain	dB	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Received signal power	dBm	−108.2	−100.14	−97.32	−95.32	−94	−93.36	−93.37	−93.9	−88.33
System noise	dB	−108.4	−108.4	−108.4	−108.4	−108.4	−108.4	−108.4	−108.4	−108.4
C/*N*	dB	0.2	8.26	11.08	13.08	14.4	15.04	15.03	14.5	20.07
Required *C*/*N*	dB	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0

Notes to Tables A2-1 to A2-4

[1] For Class A3 transponders the computed *C*/*N* values would improve by 2 dB, as the transmit power for Class A3 is 53 dBm. The e.i.r.p. is based on an omnidirectional antenna of typical gain of 0.0 dBi.

[2] Based on Maximum distance between satellite and surface of earth assuming coverage at 0° elevation angle.

[3] Based on integrated antenna and ADS-B receiver on-board satellite.

[4] Based on noise temperature of 400 K and noise bandwidth of 2.6 MHz.

[5] The measure of *C/(N+I)* is not a useful approach for this band, due to the time-shared nature of the 1 090 MHz channel. Protection criteria are defined in ICAO and other standards in terms of probability of reception in a shared channel within a predefined time period.

Annex 3

Analysis of compatibility of space-based reception of automatic dependent surveillance – broadcast signals at 1 090 MHz[6] (Study # 1)

A3.1 Introduction

This Annex provides compatibility studies in the frequency 1 090 MHz which is widely used by ICAO-standardised and some non-ICAO aeronautical applications. The assumed bandwidth at –3 dB of the receiver fitted on satellite is 4.6 MHz centred on 1 090 MHz, corresponding to the ADS-B transmission bandwidth[7] (terrestrials ADS-B signals receivers can normally be successfully decoded if the interfering signal is at least 3 dB below the desired signal[8]). Doppler shift is expected to be less than ±25 kHz (for thelow earth orbit (LEO) satellite constellation considered) with respect to the aircraft and therefore not a significant contributor to the receiver bandwidth.

ADS-B avionics broadcast messages on 1 090 MHz and successful reception of these messages depends on the signal to noise ratio and the channel occupancy which is affected by ADS-B and other 1 090 MHz signals above the receiver's sensitivity. This Study focuses on the latter of these two factors since it is more challenging to predict its impact on an example Space Based ADS-B performance.

The non-ICAO systems described in Annex 1 are not each specifically modelled in this analysis. The aeronautical systems described in Annex 1 Table A1-2 have a low probability of pulse collisions with ADS-B, demonstrating their minor potential impact relative to other sources of interference. It was assumed that TACAN systems are primarily operated at least 5 MHz away from 1 090 MHz and do not pose a significant co-frequency interference concern.

A3.2 Automatic dependent surveillance – broadcast co-channel interference

The maximum transmission rate of ADS-B messages from an aircraft is 6.2 messages/second. ADS-B position Messages are transmitted uniformly randomly every 0.5s ± 0.1s (this leads to the random access channel affect and provides independence of message arrivals at a receiver). Aircraft transmit from a bottom-mounted antenna, and aircraft that are diversity equipped (with a top and bottom antenna) are required to alternate top vs. bottom antenna for successive position message transmissions.

The 1 090 MHz band is shared with a number of ICAO standardized system, as well as other non-ICAO systems. ICAO analysis has been conducted on the compatibility of various systems, and defined the term FRUIT to refer to co-channel interference from a mixture of avionics and devices operating in bands overlapping 1 090 MHz. The following aircraft avionics are considered significant contributors to a FRUIT (i.e. co-channel interference) environment:

1 SSR both civil and non-civil modes.

2 Mode S.

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6 ICAO defines the band used by ADS-B as 1 087.7-1 092.3 MHz (at the –3 dB point), which includes a transmitter frequency tolerance of ±1 MHz.

7 ICAO Convention on International Civil Aviation, Annex 10, Vol. IV, Surveillance and Collision Avoidance Systems, 2014

8 V. A. Orlando and W. H. Harman, "GPS-Squitter Capacity Analysis", No. ATC-214, 1994, https://www.ll.mit.edu/mission/aviation/publications/publication-files/atc-reports/Orlando_1994_ATC-214_WW-15318.pdf.

3 1 090ES ADS-B.

Each of these avionics link technologies has different characteristics individually, yet typically combines together with the others as an aggregate to degrade the reception of desired ADS-B aircraft messages. Although there are other link technologies near 1 090 MHz, these three groups are considered to have the most impact on ADS-B reception[9].

Secondary surveillance radar

International Civil Aviation Organization systems

Secondary surveillance radar (also known as air traffic control radar beacon system (ATCRBS) is one of the oldest aircraft surveillance link communication schemes, and consists of a number of different modes used for various operational purposes. ATC radars interrogate SSR-equipped aircraft using calling signals at 1 030 MHz and the SSR avionics will reply on 1 090 MHz with a pulse amplitude modulated (PAM) signal that has a duration of 20.3 µs. Each SSR message only tells the recipient either the four digit octal identifier (Mode 3/A reply) or the altitude (Mode C reply) of the aircraft.

Modes with interrogations (1 030 MHz) and replies (1 090 MHz)

Many SSR surveillance systems end up requesting multiple replies from aircraft using doublet and triplet schemes in order to improve the reliability of the receptions and correlations of aircraft replies at the radars. In a densely populated area with multiple radars operating within a few 100 nautical miles of each other: several radars, multi-lateration systems, and other aircraft-based surveillance systems such as the TCAS will make their own independent requests for SSR replies, resulting in escalating 1 090 MHz transmission rates. The high density interrogation and reply environment led to the development of other secondary surveillance radar technologies.

Mode S - Interrogation (1 030 MHz)/reply (1 090 MHz)

Mode S was introduced in the 1960s as an update to SSR avionics. The link scheme was greatly improved from SSR including CRC, increased number of bits per message (112 or 56, instead of 12), and the use of pulse position modulation instead of PAM.

Additionally, every Mode S message contains a globally unique 24-bit ID of the aircraft known as the ICAO target address, vastly improving message-to-message correlation. This permitted radar and aircraft surveillance systems to lower their overall rates of interrogations and thus reduce congestion in the band. However, all of these ATC radar and aircraft systems were still independent of each other and thus still resulted in a large amount of redundant messaging per aircraft.

Mode S - Acquisition squitter (1 090 MHz)

Mode S provides also broadcasted 64µs duration messages at a rate of 1 per s alternatively on each antenna. Mode 1 090ES (Extended Squitter) called Automatic dependent surveillance-broadcast (ADS-B).

Mode 1 090ES ADS-B was introduced and developed in the 1990s largely based on the Mode S messaging scheme. The key difference being that neither ground nor airborne systems could request transmissions from these avionics, but rather the avionics would automatically broadcast their messages based with pseudorandom time intervals between each message. These long messages (112 bits) also contain aircraft state vector information that conveys the aircraft’s navigation information from its on-board GNSS directly to any 1 090 MHz ADS-B receivers. The communication of state vector information practically eliminates the need for any interrogation since the plane has determined

[9] The National Telecommunications and Information Administration, “Compendium for 960-1 164 MHz”, 2014, http://www.ntia.doc.gov/files/ntia/publications/compendium/0960.00-1164.00_01MAR14.pdf.

its own position via GNSS and is conveying that to the ADS-B 1090 ES receivers. Where necessary, the aircraft's encoded position can be verified through methods such as time difference of arrival from multiple ground stations and/or low frequency interrogation surveillance. Therefore, the ADS-B protocol has a relatively static, per-aircraft channel occupancy rate and increased adoption of ADS-B will eventually reduce the Mode S and SSR reply rates exhibited today[10].

Summary of ICAO standardized Secondary Surveillance Radar Mode Replies (1 090 MHz)

Mode S Level 1	**Interrogation**	Mode A	Mode C	Mode A/C/S All-call	Mode S only All-call	
	Reply	4096	Altitude code	Mode S short (Downlink Format 11)	Mode S short (Downlink Format 11)	
	Duration of reply	20.3µs	20.3µs	64µs	64µs	
Mode S Level 2	**Interrogation**	Mode A/C Mode A	Mode A/C Mode C	Mode A/C/S All-call	Uplink Format(UF)=4, UF=5, UF11, UF=20,UF=21	
	Reply	4096	Altitude code	Mode S short (Downlink Format 11)	Downlink Format (DF)=4 or DF=11 or DF=5	Downlink Format (DF)=20 or DF=21
	Duration of reply	20.3µs	20.3µs	64µs	64µs	120µs
Mode S Acquisition squitter	**Interrogation**	No				
	Reply	Broadcast, period 1s±0.2s, Mode S short				
	Duration of reply	64µs				
Mode S Extended squitter	**Interrogation**	No				
	Reply	Broadcast, period 161µs, Mode S long (Downlink				
	Duration of reply	120µs				

Non-ICAO systems

In addition to ICAO systems characteristics, non-ICAO systems are described in Annex 1. For the purposes of this study, representative characteristics were chosen.

According to ICAO Convention on International Civil Aviation, Annex 10 Vol. IV, § 3.1.2.3.2.4, non-ICAO applications must be provisioned to ensure that they do not exceed the RF power and reply/squitter rate requirements levied on the ICAO systems.

A3.3 Automatic dependent surveillance – broadcast adjacent channel interference

DME, TACAN were not included in Tables A3-2 and A3-3 for the following reasons:

– By ICAO standards, DME channel assignments are generally 5 MHz separated from 1090 MHz, but can be as close as 3 MHz. Some protection practices being applicable to TACAN include:

- SSR and TCAS operate on frequencies in the 1 030±10 MHz and 1 090±10 MHz ranges, so DME channels lying within those ranges, and the corresponding ground reply frequencies are not used. Note this frequency plan is also valid for the TACAN system.
- Even if two TACAN systems were set within the 3 dB bandwidth of an ADS-B receiver, their peak rates (7200 pulse pairs/s combined) would still negatively impact the ADS-B probability of detection by 30% (see Fig. A3-3). Any more than two nearby TACANs or DMEs within this band would begin to impact civil operations and would also likely start interfering between TACAN or DME signals.

– The transmit profile of DMEs and TACANs can be described in Table A3-1 (see Eurocontrol B-AMC 2007 Report). Therefore, if the 3 dB edge of the ADS-B receiver is at 1087.7 MHz and the closest DME channel is set to transmit at 1 085 MHz, the DME's energy within the ADS-B receiver's 3 dB edge is ~2 mW and is substantially below the 125W aircraft 1 090 MHz ADS-B transmitters. This is without even taking into account the DME

[10] Eurocontrol, "1 090 MHz Capacity Study – Final Report," Eurocontrol, 2006, http://docslide.us/documents/1090-interference-study-final-report-v26.html.

antenna pattern, which has its highest gain (normalized to 0 dB) at the horizon but ≤ –10 dB for elevation angles ≥ 15°.

TABLE A3-1

Distance measuring equipment/TACAN transmitter profile

Offset from center frequency (MHz)	DME e.i.r.p. Power during transmission	TACAN e.i.r.p Power during transmission
0	67 dBm (5 kW)	75 dBm (32 kW)
0.8	36 dBm	26 dBm (400 mW)
2.0	16 dBm	6 dBm (4 mW)

In ICAO Convention on International Civil Aviation, Annex 10, Vol IV is a recommendation in § 3.1.2.3.2.4.1 stating: "Through investigation and validation, States should ensure that military applications do not unduly affect the existing 1 030/1 090 MHz civil aviation operations environment"[11], which today includes ACAS, radar, multilateration and ADS-B receiver systems which would be at least as vulnerable as a satellite system to high in-band channel occupancy. Therefore, it was assumed that this existing provision for civil systems provides an umbrella of protection to Space-Based ADS-B systems since it is applicable where civil aviation is applicable.

A3.4 Modelling of 1 090 MHz interference environment

NOTE – Due to the complexity of the model and associated parameters and assumptions, the equations have been expanded in Annex 4.

In order to produce an interference environment model that is not overly-conservative nor overly-optimistic this study used a bottom-up approach to model the interference environment from historical global flight plan data. The central question to which this study provides an answer was:

> "If a Space-based ADS-B (SBA) receiver has a phased array beam pointed at a particular place on the globe at a particular time and the spatial gain contours of the beam are known, how will FRUIT (i.e. all interference sources) impact the expected probability of successful reception and decoding of an ADS-B message, P_d , from a given aircraft location?"

The approach, which has been used to evaluate the RF environment for terrestrial ADS-B studies, when modelling FRUIT is to assume that its effect corresponds to a Poisson Arrival Rate behaviour[12]. The assumption of a Poisson Arrival Rate system is that the messaging scheme corresponds to that of a random access channel. A random access channel is a relatively cheap and efficient means of communication since time-synchronization is not required of the transmitter or the receiver. For the case of a channel with perfect reception of non-interfered messages and zero reception of overlapping messages: as the offered load, *G*, increases, the detection probability of a message decreases exponentially, i.e. $P_{msg} = e^{-K*G}$ (see Fig. A3-1).

$$G = (message\ rate)\ x\ (message\ duration)$$

[11] ICAO Convention on International Civil Aviation, Annex 10, Vol. IV, Surveillance and Collision Avoidance Systems, 2014.

[12] V. A. Orlando and W. H. Harman, "GPS-Squitter Capacity Analysis", No. ATC-214, 1994, https://www.ll.mit.edu/mission/aviation/publications/publication-files/atc-reports/Orlando_1994_ATC-214_WW-15318.pdf

where (message rate) has the unit of *messages per second*

(message duration) as the unit of *seconds*

$$K = \frac{t_{interferer\ signal\ duration} + t_{ADS\ signal\ duration}}{t_{ADS\ signal\ duration}}$$

Factor K represents the ratio of the combined message duration to the duration of the ADS-B message (see Annex 4). Mode S (K = 1.53=(64+120)/120), SSR (K = 1.17=(20.3+120)/120), non-ICAO system Mode short pulse (K = 1.03=(3.2+120)/120) all have shorter message durations than ADS-B (K = 2=(120+120)/120), hence the improved ADS-B probability-of-detection P_d in those environments as it relates to the co-channel load factor.

In order to account for the complexity specific to ADS-B message reception as it relates to SSR, Mode S, and other 1090 ES ADS-B transmissions, we start with P_R, the probability of successful reception of an ADS-B message in a "Clear Sky" environment (i.e. without FRUIT).

Then we make assumptions about the probability of successful reception in the presence of given number n of interfering messages of the various types. For Mode S and ES messages, it is assumed that only zero overlap is tolerable for the ADS-B message and that "room" in time must be created for it. This is a fairly conservative assumption given the known ADS-B message bit error correction techniques, but this conservative assumption allows for additional unknown short-burst error quantities to be left out of the calculation (e.g. in-band DME/TACAN transmissions).

The study considered that the probability of reception given n interfering arrivals is:

$$P_{Mode\ S,ES}(R|n) = \begin{Bmatrix} P_R & n = 0 \\ 0 & n > 0 \end{Bmatrix}$$

Where (n = number of overlapping messages)

and for SSR we assume the minimal probability of reception for A1 class receivers with zero to three overlapping SSR messages as specified by the standards, specifically:

$$P_{SSR}(R|n) = \begin{Bmatrix} P_R & n = 0 \\ 0.89P_R & n = 1 \\ 0.64P_R & n = 2 \\ 0.52P_R & n = 3 \\ 0 & n > 3 \end{Bmatrix}$$

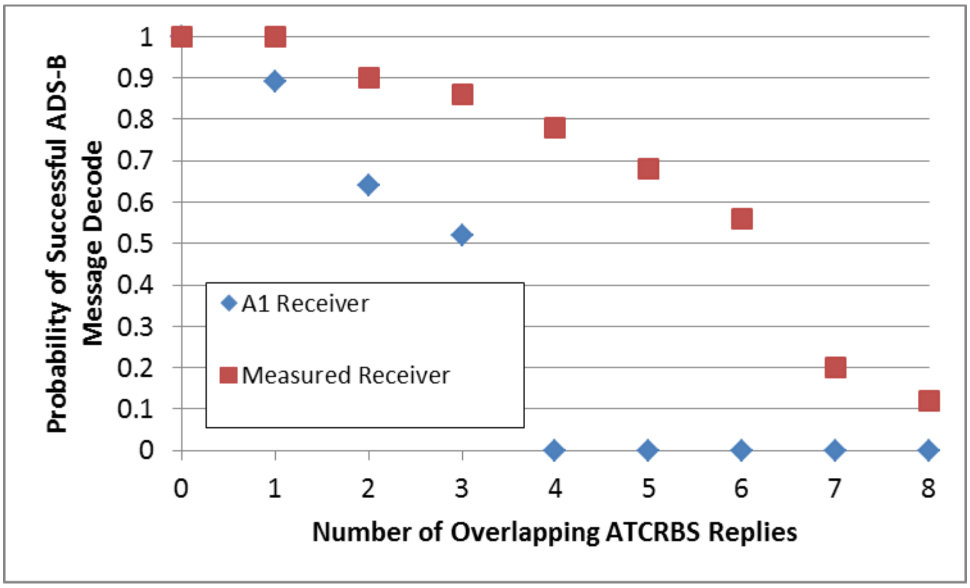
where:

n : number of overlapping messages.

The basis for these assumptions is from the ADS-B avionics standard for A1 receivers described in aviation standards. Figure A3-1 shows a demonstration of a measured ADS-B receiver, which exceeds the aviation standard performance requirements and validates the assumption that the standard can be achieved. The measured performance near the interference levels can be summarized in Table A3-6.

FIGURE A3-1

Comparison of A1 stations operating in the aeronautical radionavigation service automatic dependent surveillance – broadcast receiver vs. measured receiver performance



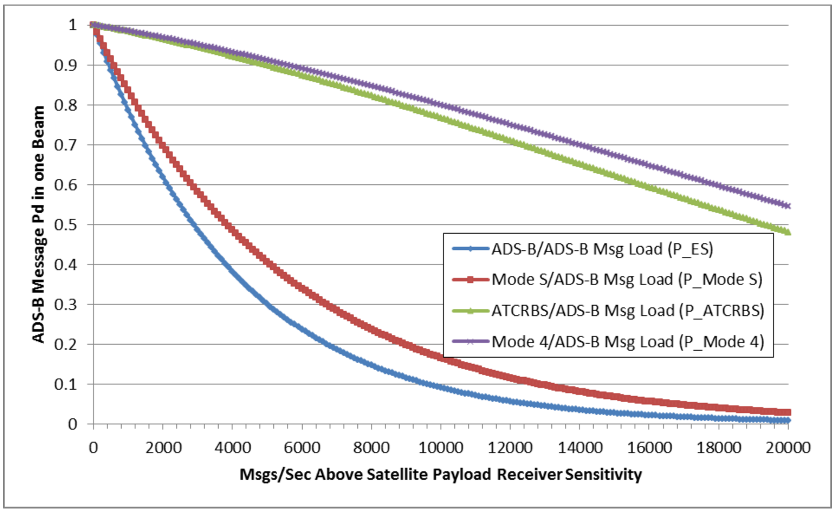
As mentioned above, we assume that the arrivals of each interfering message follow a Poisson arrival process. For such a process with parameter λ, the number of arrivals is

$$P_\lambda(n) = \frac{\lambda^n}{n!} e^{-\lambda} \tag{3}$$

Finally, we assume that the three classes of interfering signal arrive independently of each other, such that $P_d = P_R \cdot P_{SSR} \cdot P_{ES} \cdot P_{ModeS}$. The effects of these message loads on ADS-B P_d in one beam can be viewed in isolation in Fig. A3-2.

FIGURE A3-2

Automatic dependent surveillance – broadcast probability of detection vs. message arrival rate above receiver sensitivity



Putting all these assumptions together leads to equation (4) which is the basis of this model:

$$P_d = P_R \cdot \left(1 + 0.89\lambda_{SSR} + \frac{0.64}{2}\lambda_{SSR}^2 + \frac{0.52}{6}\lambda_{SSR}^3\right) \cdot \tag{4}$$

$$e^{-(\lambda_{ICAO-SSR} + \lambda_{long\ message\ mode\ S} + \lambda_{short\ message\ modeS} + \lambda_{non-ICAO-SSR(shortpulse)} + \lambda_{Mnon-ICAO-SSR(longsignal)})}$$

Equation (4) can be summarized as $P_d = P_R \cdot P_{env}$

– The λ terms are the offered load values for each respective link technology.

– For example, $\lambda_{\text{shortmessagemodeS}}$ is the expected offered load of the short Mode S messages as the ADS-B message of interest where $\lambda_{\text{shortmessagemodeS}} = \varphi_{\text{shortmessagemodeS}} \cdot \tau_{\text{shortmessagemodeS}}$,, and $\varphi_{\text{shortmessagemodeS}}$ is the Mode S arrival rate (messages/sec) within the signal reception range of the space-based ADS-B receiver and $\tau_{\text{shortmessagemodeS}}$ is the duration of each Mode S message plus the duration of a 1090 ES message (64 + 120 µs)

The duration values are assumed to be as follows: $\tau_{ICAO-\text{SSR,non-ICAO-SSR(shortpulse)}} = 141$ µs, $\tau_{nonICAO-\text{SSR}\,(long\_signal)} = 156$, and $\tau_{\text{shortmessagemodeS}} = 184$ µs, and $\tau_{\text{longmessagemodeS}} = 240$ µs.

An attenuation penalty is also applied as a function of aircraft elevation, α, in order to determine the relative gain from a bottom antenna squitter versus a top antenna (for a typical aircraft antenna, $\beta_{bottom} = \beta_{\text{top}} - 0.373\alpha$ in dB, where α is in degrees). In particular, this bottom antenna squitter attenuation penalty seems to have been overlooked by several other analysis papers on SBA.

Aircraft antenna characteristics

The top and bottom-mounted aircraft antenna patterns are derived as follows:

$$g(\theta) = \frac{360}{\pi \cdot BW} \exp\left(-1.66 \left(\frac{\theta - \theta_0}{BW} \right)^2 \right) \tag{5}$$

where θ is in degrees, $BW = 45°$

Therefore, converting to dB

$$\begin{aligned} G(\theta) &= 10\log_{10}(g(\theta)) = 10\log_{10}\left(\frac{360}{\pi \cdot BW}\right) - \frac{10 \times 1.66}{\ln(10) \cdot BW^2}(\theta - \theta_0)^2 \\ &= C_1 - C_2(\theta - \theta_0)^2 \\ &= C_1 - C_2\left(\theta^2 - 2\theta_0\theta + \theta_0^2\right) \\ &= 2\theta_0 C_2 \theta - C_2\left(\theta^2 + \theta_0^2\right) + C_1, \end{aligned}$$

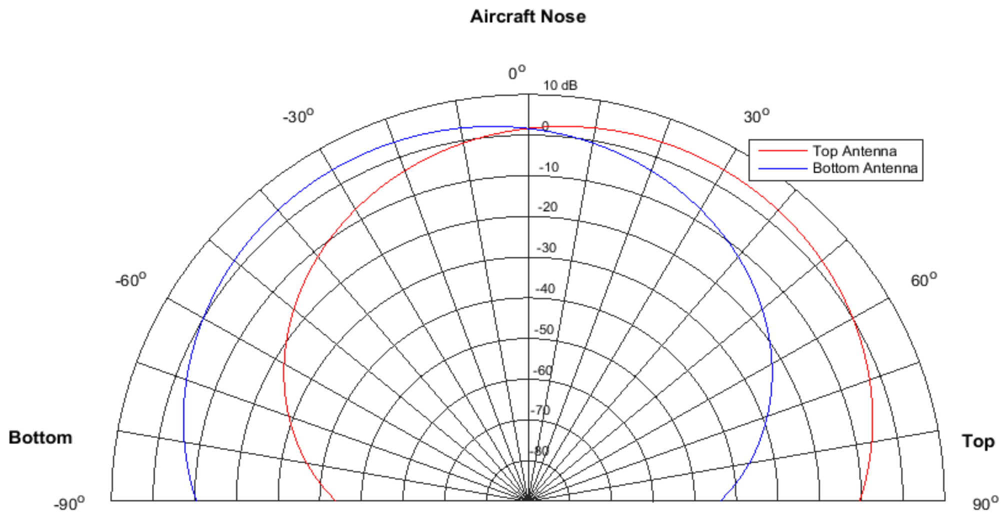
where $C_1 = 10\log_{10}\left(\frac{360}{\pi \cdot BW}\right)$, and $C_2 = \frac{16.6}{\ln(10) \cdot BW^2}$.

$G(\theta) - G(-\theta) = 4\theta_0 C_2 \theta = 0.373103\theta$, and therefore:

$$G(-\theta) = G(\theta) - 0.373103\,\theta$$

FIGURE A3-3

Technical link assessment team aircraft antenna pattern gain as a function of elevation from horizon (Antenna gain pattern shown for top-mounted and bottom-mounted antenna relative to the satellite, inverted pattern assumed for bottom-mounted antenna)



NOTE: The model assumes that both wanted and unwanted signals from the bottom antenna can be seen at the satellite, but applies an attenuation factor dependent on the geometry of the satellite to the aircraft.

The only unknowns in this equation are the φ values (effective aggregate arrival rate). It is assumed that FRUIT has an independent "field effect" on each SBA receiver beam. This means that each beam can be handled such that the combined effect of the FRUIT impacts any and all other received ADS-B messages with the same "penalty" (P_{env}). This assumption is rooted in the idea that φ can be calculated using a tile/grid based approach over the earth's surface with the beam gain contours applying a respective weight to each grid point. In this way, an *effective* arrival rate can be calculated as such:

$$\varphi_{ModeS}(h) = \sum_{i=1}^{n} \varphi_{ModeS}(h, t_i) \cdot \gamma_{t_i} \tag{6}$$

where h is the hour in the simulation (this model assesses peak aircraft density on an hourly basis), and t_i is the i^{th} tile of the observable n tiles during simulation hour h. The gain or weighting factor γ_{t_i} is based on the SBA receiver's message error rate relationship to the energy per bit relative to the noise floor (E_b/N_0) calculated at the i^{th} tile for a particular beam during hour h.

Typically, the E_b/N_0 link budget will be calculated to a tile from the satellite as a function of range, azimuth and elevation to a 125 W aircraft transmitter. An increase in transmitter power improves the E_b/N_0 by 3 dB (250 W) or 6 dB (500 W). The reason for the deviation from the minimum e.i.r.p requirement for a Class A3 transponder (200 W) in this evaluation is that a typical installation is equipped with a 250 W transmitter or higher (400 W or 600 W) in order to compensate for some cable losses, which results in an average e.i.r.p. of 250 W or higher. In this example, the 50 W delta in power wouldn't materially change the performance results for 250 W vs. 200 W.

A3.4.1 Description of model structure and assumptions

Spatial/Temporal Aircraft Counts

In alignment with the ATM industry approach, this model has some core elements and assumptions[13]. The central element is a spatial-temporal distribution of aircraft counts, since aircraft are not uniformly distributed in space or time. The approach taken to appropriately distribute these counts

[13] Eurocontrol, "1 090 MHz Capacity Study – Final Report", Eurocontrol, 2006.

was to use flight plan data containing departure times, origins, and destinations of nearly every aircraft in the world grouped in universal co-ordinated time (UTC) hourly files to reconstruct the spatial-temporal distribution of aircraft. The primary assumption here is that aircraft do not generally spontaneously appear into the airspace, but are rather coming from some known airport and travelling to another one.

Additionally, planes can be modelled as flying great circle routes (shortest distance over the earth). The expected airspeed of the aircraft can be estimated as a function of the distance between the two airports such that the greater the distance, the higher the expected average aircraft velocity. With virtual aircraft in the simulation departing at defined times to defined places using expected velocity and trajectories from a global fight plan database containing 3 579 world-wide airports, the spatial-temporal aircraft counts can simply be “measured” over a global grid. The grid spacing used in this model is 1 degree by 1 degree over the WGS-84 earth model. Although these 1 degree dimensions have varying lengths by latitude, it is a relatively simple and effective grid to use.

The aircraft counts are such that any aircraft that passes near or through a grid point (rounding the decimal coordinates to the nearest value) are counted in one minute time window bins.

The peak 1 minute “instantaneous aircraft count” then becomes associated with a given UTC hour at that grid point location. One minute time windows were chosen since although many aircraft may pass over a grid point within an hour, only those that are there within one minute of each other should be considered “clustered” in time and space where transmitted messages can be assumed to be coming from a group. The UTC hour count is set to the worst-case minute so that within a region, for every tile, there is an assigned worst minute for that tile (inherently a conservative estimate).

The result of this aggregated aircraft count can be seen in Fig. A3-4 where tile index (t_i), given by:

$$t_i = 360 \cdot (90 + \Phi_i) + \Lambda_i \tag{7}$$

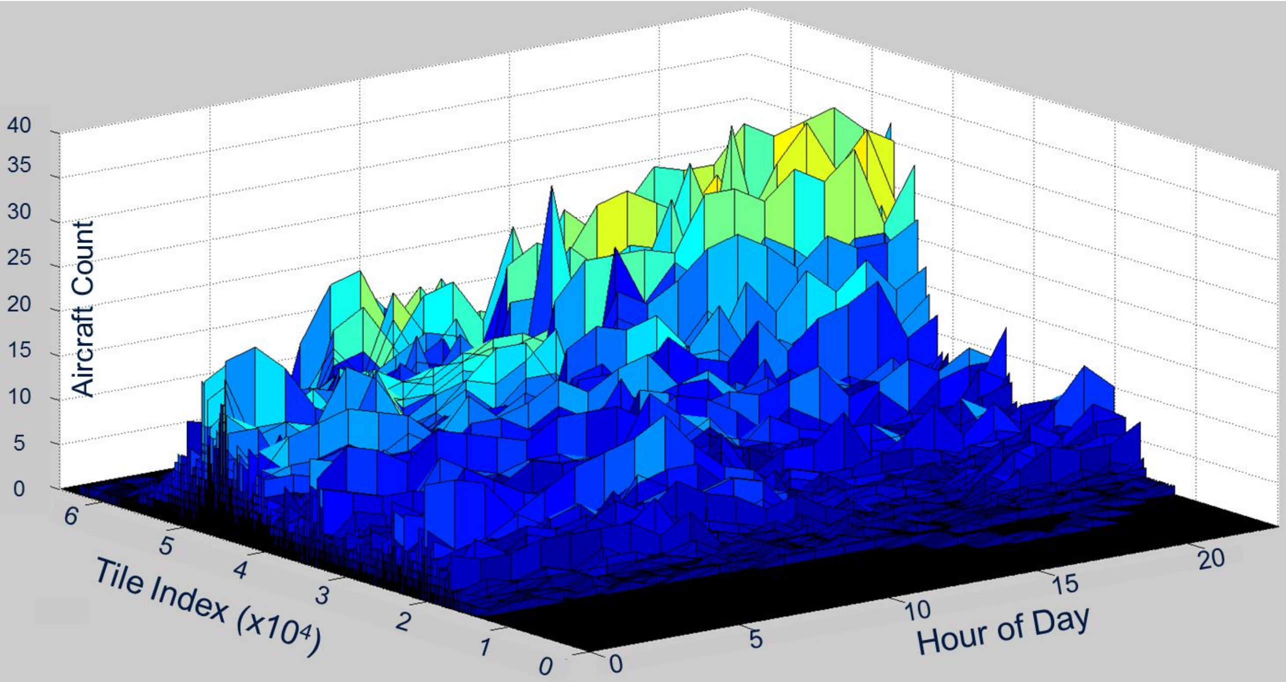
where:

$-90 \leq \Phi_i \leq 90$	latitude
$0 \leq \Lambda_i \leq 360$	eastward longitude of the i^{th} tile.

The tile index is along the left horizontal axis and the UTC hour of the day is on the right horizontal axis and the 1 minute peak aircraft counts in each hour is the vertical axis. The peak tile in Fig. A3-4 (t_i = 47 446, Φ_i = 41°, Λ_i = 286°), correlates with the same aircraft density hotspot observed in prior work (near JFK Airport) where the density was measured with archived ADS-B aircraft data. The numbers in this model have been validated against the Eurocontrol Capacity Study referenced above where in § 2.1.2.4 it was projected that the peak instantaneous aircraft count within 300 nautical miles (555.6 km) of Brussels would be between 1463 and 1611. The model used in this study shown in Fig. A3-4 in combination with the 1.4 scalar multiple described in Table A3-2 calculates 1485 aircraft near Brussels during the 16:00Z hour and thus falls within the predicted range by the independent study. In addition to modelling the 2015 environment, a second aircraft traffic profile was also considered, with increased traffic corresponding to a traffic scenario projected for 2030.

FIGURE A3-4

Spatial-temporal counts of aircraft over the Earth based on 5 July 2013 flight plans



Avionics transmit message rates

Now that the aircraft counts are distributed in space and time in the model, the next step is to convert aircraft counts to categorized expected transmitted message rates. This step is typically performed during an applicable hour of analysis such that the spatial profile is two-dimensional and is assumed not to vary appreciably over time within the hour. This assumption accounts for the fact that the model applies the worst-cast traffic in each tile (e.g. a max-max case is held steady over the simulation hour). For example, if the interference analysis is being assessed at 12:23Z, then the 12th hour aircraft count profile, $\kappa(t_i, h)$, would be used.

The aircraft counts in this profile need to be categorized by link type and transmit power. Furthermore, the transmitted messages must also be distributed between a top and bottom antenna where applicable. Tables A3-2, A3-3 and A3-6 describe this model's assumptions of aircraft transmissions that enable a mapping from aircraft counts to message rates in each respective category. These values were determined through a careful analysis of the aircraft population in the northeast region of the United States of America in combination with assumptions about TCAS and SSR reply rates[14] given the average aircraft density and radar density in that region. Furthermore, the assumptions in Tables A3-2 and A3-3 are consistent with results from other studies[15].

[14] V.A. Orlando and W. H. Harman, "GPS-Squitter Capacity Analysis", No. ATC-214, 1994, https://www.ll.mit.edu/mission/aviation/publications/publication-files/atc-reports/Orlando_1994_ATC-214_WW-15318.pdf.

[15] Eurocontrol, "1 090 MHz Capacity Study – Final Report," Eurocontrol, 2006,

TABLE A3-2

Aircraft transmitter message categorization assumptions (2015)

Parameter	Symbol	Value
Fraction SSR	ν_{SSR}	0.1
Fraction Mode S	$\nu_{Mode\ S}$	0.9
Fraction of Mode S that has ADS-B	ν_{ADS-B}	0.3
ADS-B msgs/s/aircraft	ω_{ADS-B}	6
Mode S short msgs/s/aircraft	$\omega_{Mode\ S}$	6
SSR msgs/s/aircraft	ω_{SSR}	60
ADS-B fraction of top transmissions	α_{ADS-B}	0.5
Mode S fraction of top transmissions	$\alpha_{Mode\ S}$	0.5
SSR fraction of top transmissions	α_{SSR}	0
Aircraft Count Scalar Multiplier	ξ	1.4

The composition of the replies relative to 1 030 MHz interrogation sources is conveyed in Table A3-3, where there could be 3-4 asynchronous terminal radars interrogating an aircraft.

TABLE A3-3

Case 1 of secondary surveillance radar replies to 1 030 MHz interrogations

Interrogation Source	ATCRBS Replies (msgs/s)	Mode S Short Replies (msgs/s)	Mode S Long Replies (msgs/s)
Ground	60	1	1
Squitter	0	1	1
ACAS	0	4	6
Total	60	**6**	**8**

TABLE A3-4

Aircraft transmitter power assumptions

Link Tech	Symbol	125W	250W	500W
ADS-B	η_{ADS-B}	0.25	0.5	0.25
Mode S	$\eta_{Mode\ S}$	0.54	0.3	0.16
SSR	η_{SSR}	1	0	0

A second simulation was undertaken with modified assumptions and the alternative traffic profile mentioned earlier. The update interval (UI) performance of the center tile of each en-route flight information region (FIR) was evaluated over Europe and parts of northern Africa. For this simulation, the parameters in Table A3-5 show the changes in the parameters used in this scenario in order to evaluate a traffic situation projected for the year 2030. This environment will certainly have higher ADS-B equipage due to airspace rules and an estimated ~30% growth in aircraft counts from the year 2015. Technology advancements such as a hybrid ACAS system are also assumed to be implemented to reduce the number of interrogations and thus Mode S and SSR replies.

TABLE A3-5

Aircraft Assumptions for 2030 Traffic Model

Parameter	Symbol	Value
Fraction SSR	ν_{SSR}	0.05
Fraction Mode S	$\nu_{Mode\ S}$	0.95
Fraction of Mode S that has ADS-B	ν_{ADS-B}	1
ADS-B msgs/s/aircraft	ω_{ADS-B}	6
Mode S short msgs/s/aircraft	$\omega_{Mode\ S}$	4
SSR msgs/s/aircraft	ω_{SSR}	20
ADS-B fraction of top transmissions	α_{ADS-B}	0.5
Mode S fraction of top transmissions	$\alpha_{\text{Mode S}}$	0.5
SSR fraction of top transmissions	α_{SSR}	0
Aircraft Count Scalar Multiplier	ξ	1.8

Although these parameters will have their own spatial and temporal distribution, this model uses these values for "worst case" purposes. Over the ocean, there will certainly be a lower percentage of SSR and low power transmitters, but there will also be a lower aircraft count and redistributing the categorization would therefore have a negligible effect.

These tables are assumed to be representative of the populations in high aircraft density regions where the model would have more impact on SBA P_d. In order to find the transmitted message count in a particular category, one must simply multiply the respective coefficients together. For example, the following equations show how to assess the expected number of transmitted messages per second at the lowest level of categorization using the variables in Tables A3-2, A3-3 and A3-6 with κ being the aircraft count profile and ξ being the scalar multiple:

$$\varphi_{ADS-B,Top,125W}(t_i,h) = \xi \cdot \kappa(t_i,h) \cdot \nu_{ModeS} \cdot \nu_{ADS-B} \cdot \omega_{ADS-B} \cdot \alpha_{ADS-B} \cdot \eta_{ADS-B,125W} \quad (8)$$

$$\varphi_{ADS-B,Bottom,125W}(t_i,h) = \xi \cdot \kappa(t_i,h) \cdot \nu_{ModeS} \cdot \nu_{ADS-B} \cdot \omega_{ADS-B} \cdot (1-\alpha_{ADS-B}) \cdot \eta_{ADS-B,125W} \quad (9)$$

A3.4.2 Aggregation of parameters for instantaneous P_{env} calculation

Once the aircraft counts profile has been translated to transmitted messages per second in each respective category, the SBA receiver model can apply a phased array beam gain pattern over an area and determine the environmental impact to P_d. Figure A3-5 shows an example of a notional SBA receiver beam "footprint" (extent of E_b/N_0 gain above required link margin) overlaid on the tile grid space. The beam was modelled on the characteristics for the 11 dBi antenna in Fig. A3-3. When evaluating the impact of unwanted signals to the ADS-B aircraft of interest in this beam during a particular hour of the day, the methods described in § 3 can be used to determine the categorized transmitted message rates for each grid point within the beam's footprint. To determine the effective message rates that would be "received" by the beam and have impact on the ADS-B messages of interest, equation (10) can be expanded to account for each λ value (when combined with the appropriate τ) in equation (4) as follows:

$$\varphi_{ModeS}(h) = \sum_{i=1}^{n}\left[\sum_{j=125W,250W,500W}\left(\varphi_{ModeS,Top,j}(t_i,h)\cdot\gamma_{Top,j} + \varphi_{ModeS,Bottom,j}(t_i,h)\cdot\gamma_{Bottom,j}\right)\right] \quad (10)$$

This is calculated similarly for φ_{SSR} and φ_{ES} in order to populate P_{env} which is the scaling factor of equation (4). The value of P_{env} can be used to determine the effective P_d of any given ADS-B message that was transmitted in that beam during a given time window where the ADS-B message's clear sky probability of successful reception is P_R.

An example of how these calculations might combine to effect an SBA receiver as a function of aircraft count is shown in Fig. A3-6 for the configurations described in Table A3-3 and Table A3-5, respectively. The red line versus the blue line shows a clear impact from the presence of increased ADS-B equipage from 30% in 2015 to 100% in 2030. However, if there are 2 beams with similar environments overlapping the same aircraft (either from the same satellite or from an adjacent one) then this neutralizes some of the effects of co-channel interference resulting in a higher aggregate probability of successful reception.

FIGURE A3-5

Example of space-based automatic dependent surveillance - broadcast beam footprint over tiles

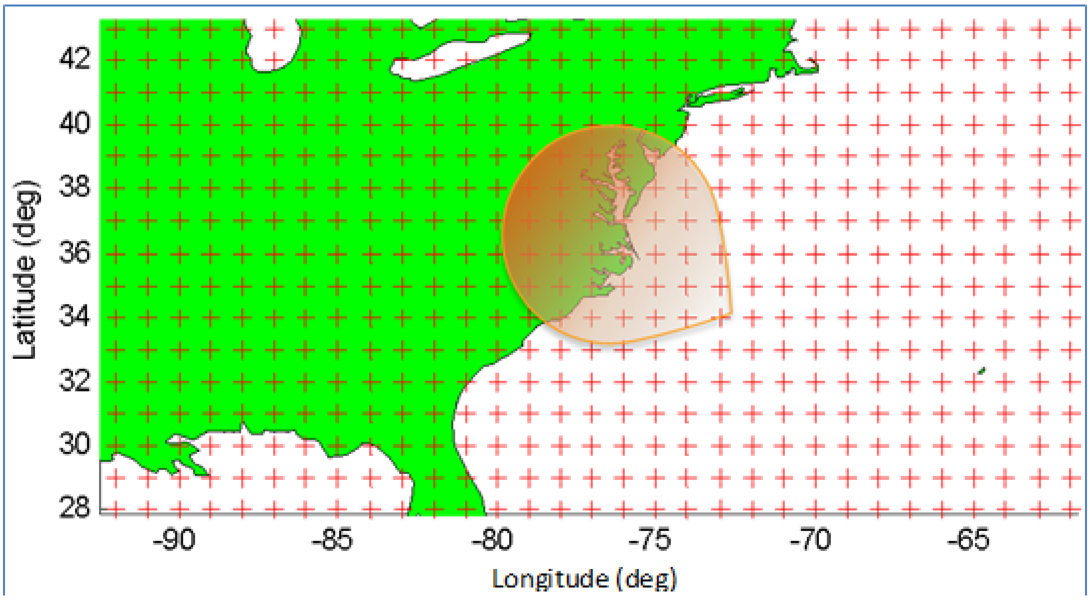
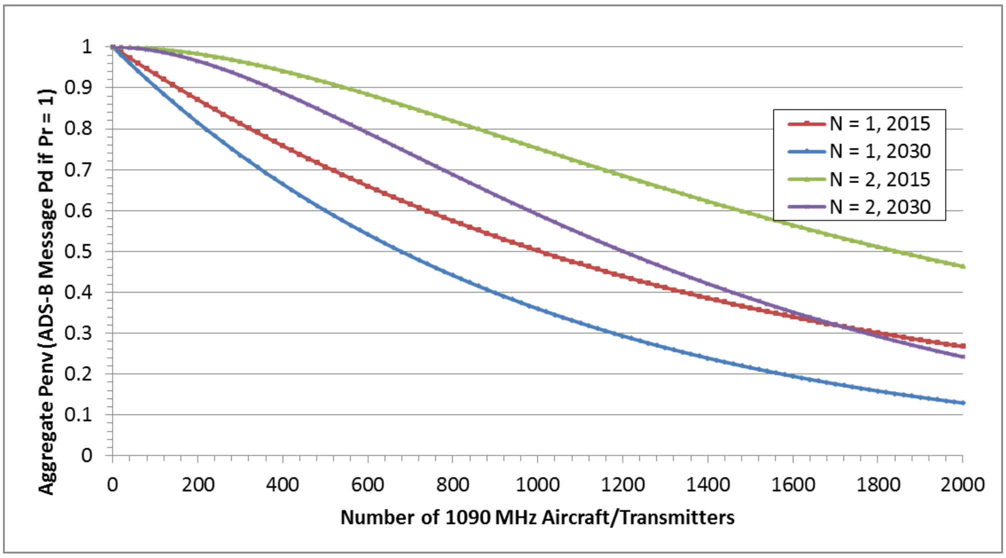


FIGURE A3-6

Example of space-based automatic dependent surveillance - broadcast beam footprint over tiles



A3.5 Results of modelling of space-based automatic dependent surveillance – broadcast

Performance evaluation criteria

The performance criteria for an SBA system receiving 1 090 MHz in-band signals depends on the level of surveillance/tracking service that one is attempting to achieve. ICAO, civil aviation authorities, and/or air navigation service providers will ultimately determine the performance criteria for satellite reception of ADS-B.

From the ADS-B signals captured by the PROBA-V hosted ADS-B payload receiver during March 2014, the system measured an average probability of detection of 13.5% (ranging from 10.7% in Europe to 22.4% in Australia), noting that an average probability of detection of 9.5% provides for 15 second position update intervals.

The performance criteria for the purpose of this evaluation are continuous, near real-time surveillance with a 15 second UI greater than or equal to 95% of the time for oceanic and low-density aircraft environments. Notionally, with proper communications and navigation performance available, this 15 second UI performance could support 10 nautical miles (18.5 km) or less separation services depending on the outcome of the ICAO and regional air navigation service provider safety case assessments. Currently, Eurocontrol describes terrestrial en-route (5 nautical miles / 9.3 km) and terminal (2-3 nautical miles / 3.7-5.6 kms) surveillance applications requiring 8s and 5s UIs, respectively[16]. However, there are also applications currently using longer UIs for 5 nautical miles (9.3 km) separations (the FAA uses 12 seconds long range radars) and others being developed, such as pairwise trajectory management, that may support en-route separation, given proper equipage, with significantly less stringent ATC UI requirements than those Eurocontrol described[17].

ICAO expects that the criterion for the evaluation of performance of the example SBA of the 15s UI to be met greater than or equal to 95% for 125W equipped aircraft with a top-mounted or diversity antenna (diversity antennas are required for TCAS operations and aircraft that operate above 18 000 ft (5 486 m)).

Performance evaluation tool and results

Since LEO satellite motion and beam positions rapidly change over time, ~3.6 nautical miles per second (6.7 km/s), a stochastic simulation program was created. This simulator accounts for the dynamic aspects of the system for a higher fidelity assessment of the expected UI performance. (Characteristics of the LEO satellite system is shown in Table A3-6.)

[16] Eurocontrol, "Safety & Performance Requirements Document on a Generic Surveillance System Supporting ATC Services", Brussels, Belgium, 2015 (Pending), https://www.eurocontrol.int/sites/default/files/publication/files/20123003-esassp-spec-vol1-v1.0.pdf.

[17] K. Jones, "Pair-Wise Trajectory Management-Oceanic CONOPS", NASA, 2014, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140005336.pdf.

TABLE A3-6

Satellite constellation characteristics

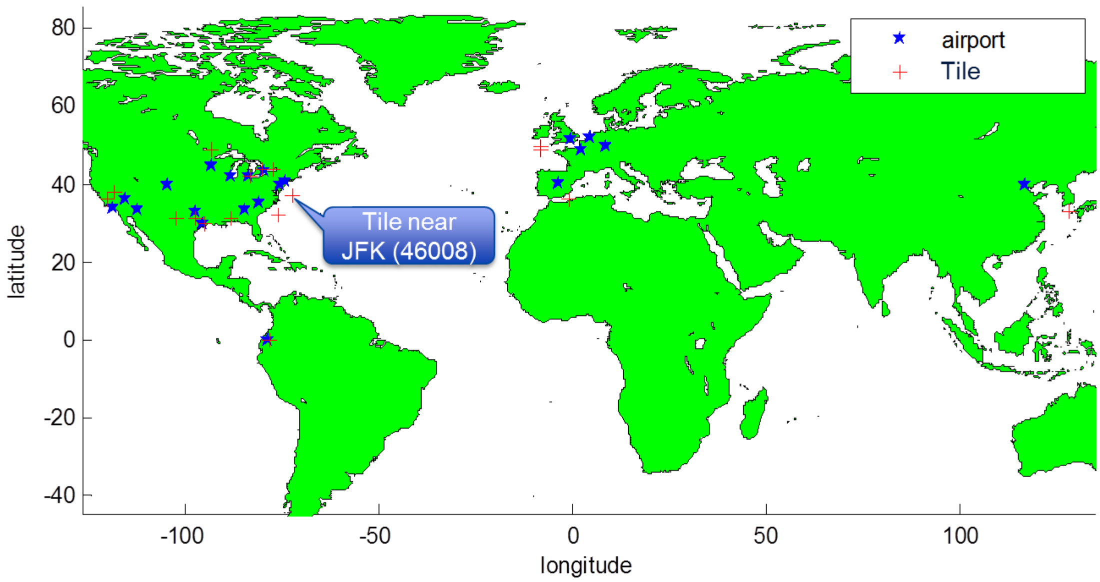
Parameter	Value
Satellite constellation type	Non-geostationary LEO in 780 km circular orbit
Number of satellites	66
Number of planes	6
Orbital inclination	86.5°

The simulation program was configured to apply the unwanted signals model described in the earlier sections of this paper and to place "test" aircraft at specific fixed locations (each location gets a 125 W and a 250 W equipped aircraft) with a conservative antenna pattern. Using this configuration the simulation program calculated the UI statistics over a 24-hour period for each tile and each transmit power type.

Although any and every point on the earth could be evaluated, the test aircraft were placed in oceanic/low-density airspace most proximate to the 20 busiest airports in the world (see Fig. A3-7) according to Wikipedia (data provided by Airports Council International). It was expected that one or more of these tiles would be subject to beams with significantly high aircraft density and thus unwanted signals impacts and would represent the worst case UIs for ADS-B surveillance services. The tiles were chosen to be close to but not directly overlapping with the major airports, to measure performance of the space-based ADS-B system as aircraft potentially leave the coverage of ground-based surveillance systems. Since this example SBA is a LEO system and has a high degree of inclination and less overlapping coverage near the equator, a test aircraft was also added near airports in Ecuador.

FIGURE A3-7

Highest density airports and neighbouring tiles



For the second simulation, the tile centers of en-route FIRs throughout most of Europe and Northern Africa were tested to evaluate their performance.

ASIM evaluates the instantaneous probability of detection of each aircraft message for each beam. For several SBA systems, there are many instances of beam overlap and satellite-to-satellite overlap, particularly north of the Tropic of Cancer and south of the Tropic of Capricorn. The UI is calculated relative to position message updates and ASIM accounts for the mix of odd and even parity position messages using the ADS-B 1090 ES compact position reporting algorithm. The theoretical minimum aggregate average P_d necessary to support a 15s UI at 95% can be computed as follows:

$$(1 - P_{UI}) = (1 - P_d)^{(T_{UI} * f_{position\_tx})} \tag{11}$$

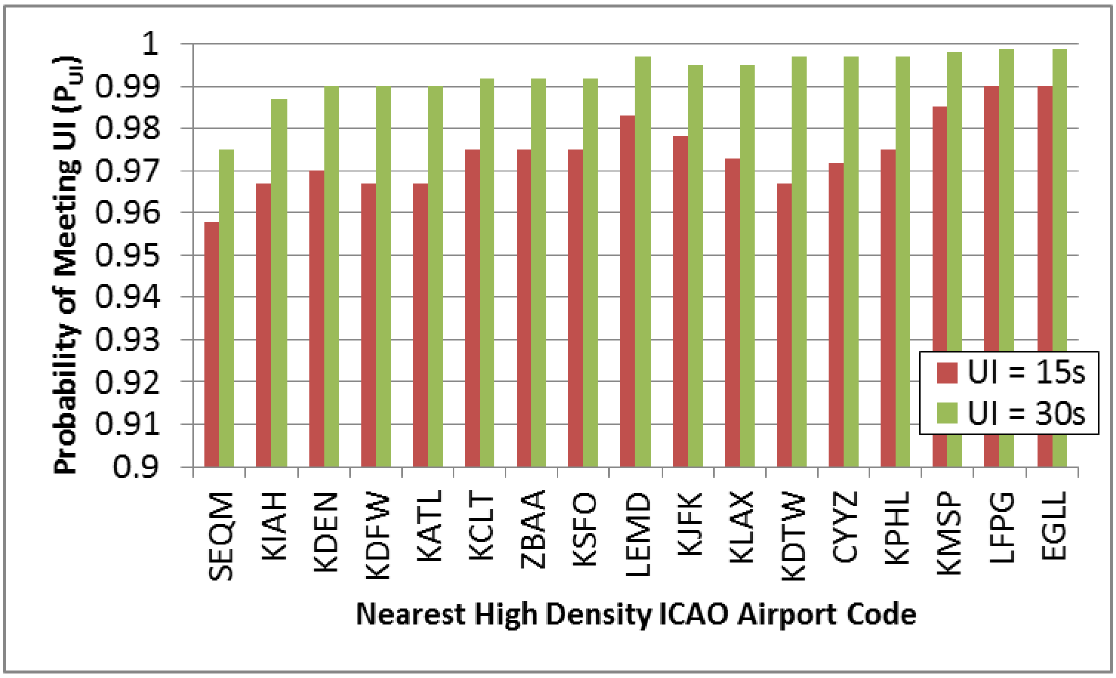
where:

- P_{UI} : 0.95 (required P_d of the position message within the UI timeframe)
- T_{UI} : 15s (required UI timeframe)
- $f_{position\_tx}$: 2 Hz (rate of position information transmitted from the aircraft).

Solving this equation for P_d gives a value of 0.095, which is the minimum average P_d of any given ADS-B message. Indeed, such P_d has been exceeded with observations from a prototype SBA receiver with a single beam[18]. Some SBA systems have the capability to support multiple simultaneous beams to support wide coverage areas. Figures A3-8 and A3-9 show the UI results for the 17 test tiles for the 125W and 250W aircraft, respectively, for the first simulation. Although the transmit power of the ADS-B aircraft makes a substantial difference in the results, all 15s UI percentages are above 95%, thus meeting the stated criterion for the example SBA and demonstrating its performance and compatibility with the 1 090 MHz in-band environment (FRUIT) model.

FIGURE A3-8

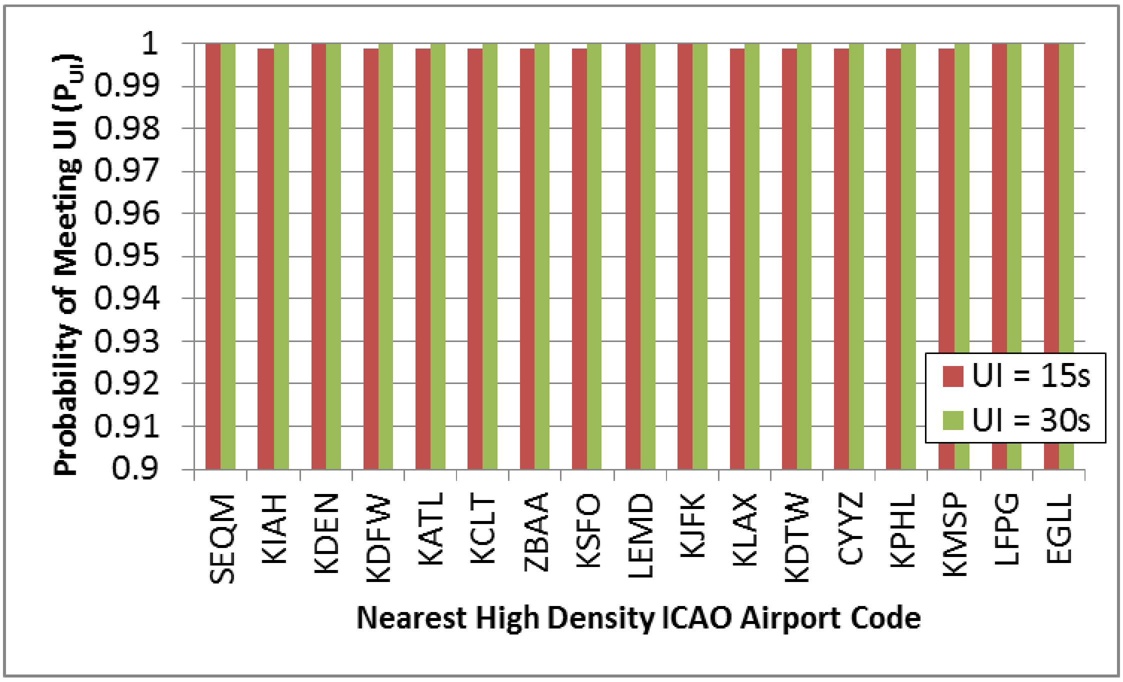
Automatic dependent surveillance – broadcast update interval results for 125W equipped aircraft in the top 17 high density tiles



[18] K. Werner, J. Bredemeyer and D. T., "ADS-B over Satellite", Proceedings of ESAV, p. 55, 2014, http://elib.dlr.de/91303/1/Final-Paper_ESAV2014-AoS.pdf.

FIGURE A3-9

Automatic dependent surveillance – broadcast update interval results for 250W equipped aircraft in the top 17 high density tiles



The UI results for the second simulation are shown in Figs A3-10 to A3-12 for 125 W aircraft. Aircraft with higher transmitter power will certainly have even better results, however since all FIRs show performance that can meet 5 nautical miles (9.3 km) at 8 seconds safety surveillance needs for 125 W aircraft then this indicates significant margin with respect to the ICAO 15s UI guideline that was used in this compatibility analysis.

FIGURE A3-10

Automatic dependent surveillance – broadcast update interval results for 125 W equipped aircraft within Europe and North Africa with the color of the most stringent UI meeting 95% shown

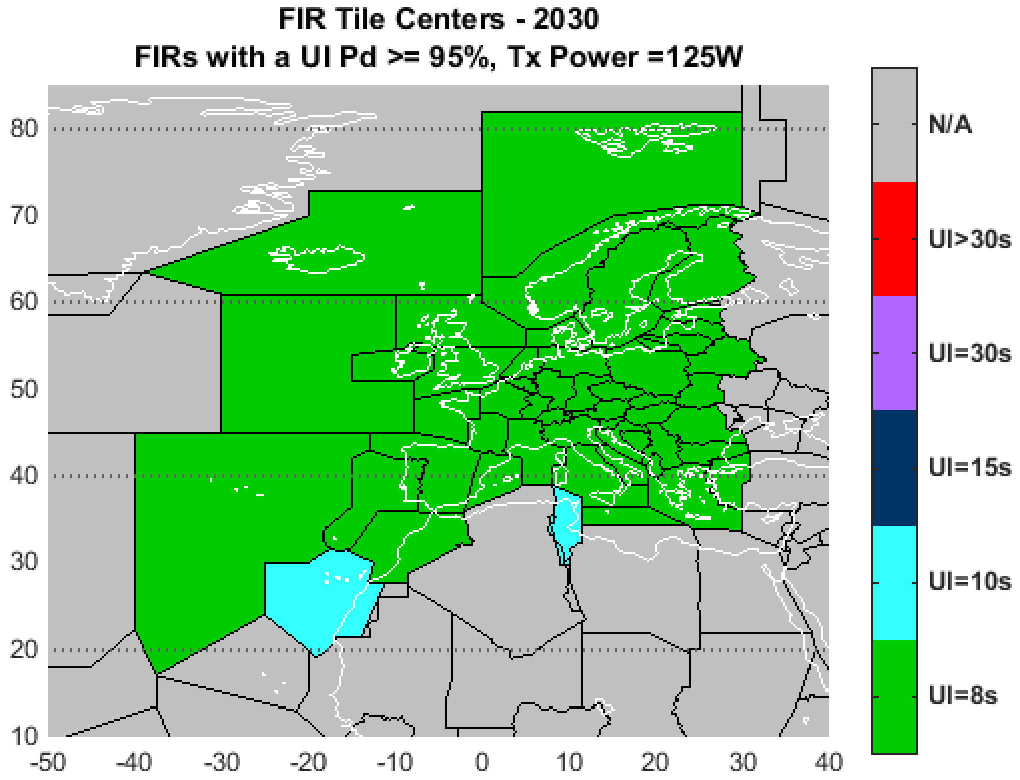


FIGURE A3-11

Automatic dependent surveillance – broadcast update interval results for 125 W equipped aircraft within Europe and North Africa

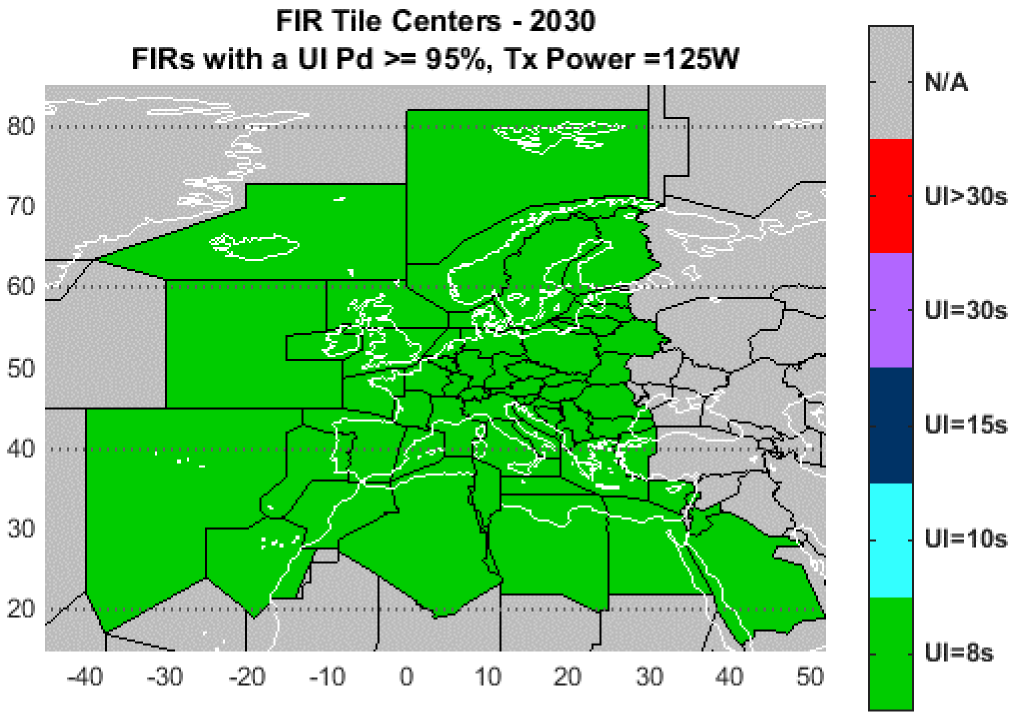
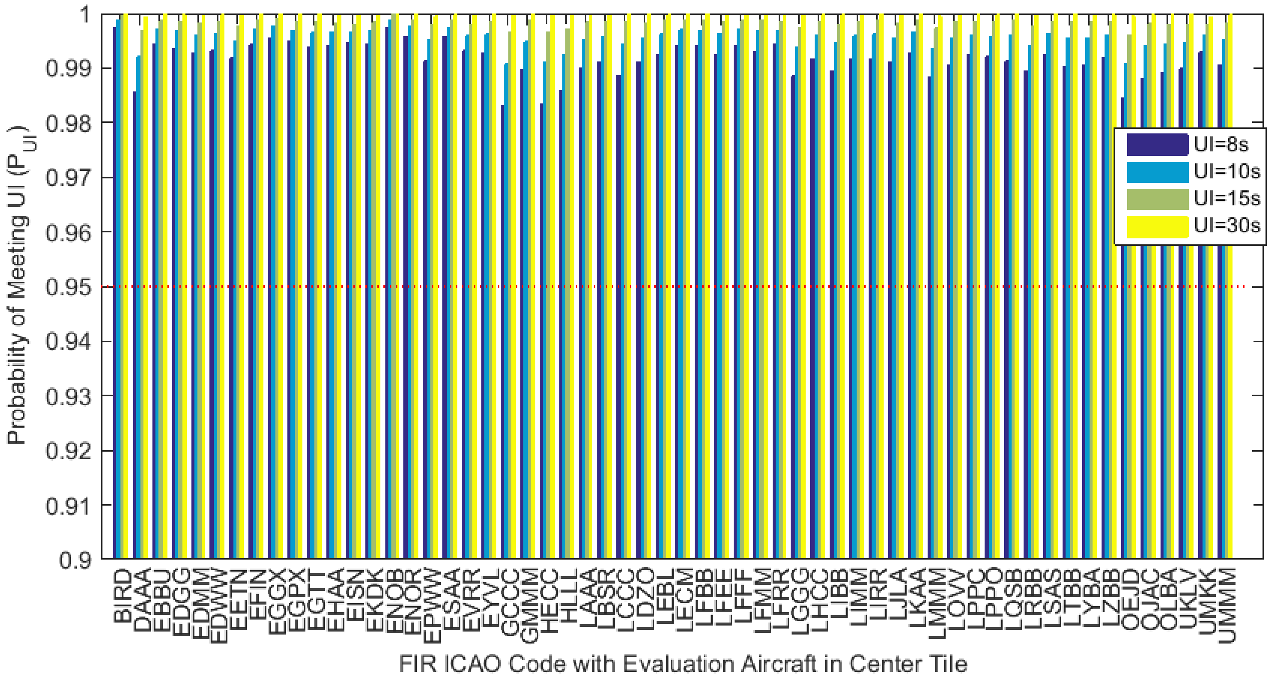


FIGURE A3-12

Automatic dependent surveillance – broadcast update interval results for 125 W equipped aircraft



A3.6 Conclusion

Although some of the assumptions could be fine-tuned for specific SBA systems in specific regions, the majority of assumptions in this Study are suitably conservative to allow for some unexpected errors. The results of this Study shown in Figs A3-7 to A3-11 demonstrate that 15 sec UI at 95% P_d should be achievable globally for Class A1 equipped aircraft (125W transmit power) with a top antenna, even in presence of co-channel unwanted signals. Shorter update intervals may also be achievable, but these would need to be studied separately. The actual update interval necessary for a given flight information region and other performance metrics would be a matter for ICAO and aviation standards bodies.

With respect to compatibility of space-based 1 090 MHz ADS-B receivers with existing services in the band, a co-primary allocation for the satellite reception of ADS-B (an AMS(R)S allocation) would require no additional restrictions on existing systems in either the ARNS or AM(R)S services in order to operate compatibly and support high-integrity flight surveillance on a global basis.

Annex 4

Assumptions, equations and system parameters presented in Study #1 of Annex 3

Section A3.3 – Modelling of 1 090 MHz unwanted signals environment

TABLE A4-1

Characteristics of various signals operating at 1 090 MHz

		SSR	**Mode S**	**ADS-B / 1090 ES**	**Mode 4**	**Mode 5**	**TACAN / DME**	**Non-ICAO ARNS**
Max message duration	µs	20.3	64	120	3.6	15 or 35	3.5	1.25-5.5

– Probability of successful detection against channel loading ($P_{msg} = e^{-K*G}$)

- G = Channel occupancy offered load (unit-less)
- K = Ratio of combined message duration to ADS-B message duration (unit-less)
  – $K_{ADS\text{-}B}$ = (120 µs + 120 µs)/120 µs = 2
  – $K_{Mode\ S}$ = (64 µs + 120 µs)/120 µs = 1.53
  – K_{SSR} = (20.3 µs + 120 µs)/120 µs = 1.17 (representative of SSR and Mode 5 values)
  – $K_{Mode\ 4}$ = (3.5 µs + 120 µs)/120 µs = 1.03 (representative of Mode 4, TACAN/DME, and non-ICAO ARNS values)

– Probability of successful reception with n unwanted signal arrivals

- $P_{Mode\ S,ES}(R|n) = \begin{Bmatrix} P_R & n = 0 \\ 0 & n > 0 \end{Bmatrix}$
  – Assumption is that one or more overlapping replies results in the ADS-B message not being received, due to long message duration (64-120 µs)
  – This is applicable for ADS-B, Mode S, and SSR/Mode 5 (Level 2B)
  – P_R = probability of successful reception in clear sky
- $P_{SSR}(R|n) = \begin{Bmatrix} P_R & n = 0 \\ 0.89P_R & n = 1 \\ 0.64P_R & n = 2 \\ 0.52P_R & n = 3 \\ 0 & n > 3 \end{Bmatrix}$
  – This calculation applies for all messages with short duration (< 35 µs), which includes ATCRBS (SSR/Modes 3A & 3C), SSR/Modes 1, 2, 4, and 5 (Level 1 and 2A), DME, and TACAN.
  – For simplicity, these messages are all estimated to have the same duration (20 µs) even though some have less and some have more, in the aggregate they have the same effect on ADS-B. For example, since Mode 5 can operate with either 15 or 35 µs message duration, it was assumed to be similar to SSR with a value of 20 µs. An average message duration value of SSR, Mode 4, Mode 5, TACAN/DME, and non-ICAO ARNS would result in less than 20 µs which would make this formula overly pessimistic.

  – This calculation method assumes that up to 3 overlapping replies from these types of messages can be tolerated for successful ADS-B message decode due to bit error correction techniques that are available because of the 24 bit cyclic redundancy check at the end of the ADS-B message. (Measured results indicate that this is conservative, and that practical receivers can achieve much higher multiple-signal performance)

– Poisson arrival process $P_\lambda(n)$, probability of n arrivals in unit time. The transmissions assumed in this study (SSR, Mode S, ADS-B 1090 ES, Mode 4, Mode 5) can be characterized as a random access channel because the messages are not synchronized or scheduled and thus collisions occur between multiple messages. Since all the transmissions assumed in the analysis represent random, mutually independent message arrivals the Poisson arrival process is an appropriate model:

- $P_\lambda(n) = \frac{\lambda^n}{n!} e^{-\lambda}$
  – λ = offered load for each respective link technology (unit-less)
  – n = number of overlapping messages on an ADS-B message

– Probability of reception/detection considering all sources of unwanted signals P_d:

- $P_d = P_R \cdot P_{SSR} \cdot P_{ES} \cdot P_{ModeS}$
  – $P_{ES} = e^{-\lambda_{ES}}$
  – $P_{Mode\ S} = e^{-\lambda_{Mode\ S}}$
  – $P_{SSR} = \left(1 + 0.89\lambda_{SSR} + \frac{0.64}{2}\lambda_{SSR}^2 + \frac{0.52}{6}\lambda_{SSR}^3\right) \cdot e^{-\lambda_{SSR}}$
  – P_R = "Clear Sky" Probability of reception/detection without unwanted signals. This is based on the ADS-B receiver's performance relative to the message energy per bit to noise power spectral density ratio (E_b/N_0)

– Offered load λ (average arrivals within an ADS-B message) for each technology:

- $\lambda_{ES} = \varphi_{ES} \cdot \tau_{ES}$
- $\lambda_{Mode\ S} = \varphi_{Mode\ S} \cdot \tau_{Mode\ S}$
- $\lambda_{SSR} = \varphi_{SSR} \cdot \tau_{SSR}$
  – where φ = arrival rate in messages per second for a given beam at a particular measurement instant (time can and should be sampled during the simulation to balance accuracy with efficiency of the simulation run-time), *d*
  – τ = duration of the signal type plus ADS-B message (e.g. for Mode S: 64 µs + 120 µs)
    - τ_{ES} = 240 µs
    - $\tau_{Mode\ S}$ = 184 µs
    - τ_{SSR} = 141 µs

– Deriving the effective aggregate arrival rate φ for each message type in a given beam at a given sample time is a convolution of the raw arrival rate and a weighting factor Υ (representing receiver response of message error rate to E_b/N_0), over the tiles visible within that beam:

- $\varphi_{ES} = \sum_{i=1}^{n} \varphi_{ES}(h, t_i) \cdot \gamma_{t_i}$
- $\varphi_{ModeS} = \sum_{i=1}^{n} \varphi_{ModeS}(h, t_i) \cdot \gamma_{t_i}$
- $\varphi_{SSR} = \sum_{i=1}^{n} \varphi_{SSR}(h, t_i) \cdot \gamma_{t_i}$
  – where *h* is the hour in the simulation (this model assesses peak aircraft density on an hourly basis), and t_i is the i^{th} tile of the observable n tiles during simulation hour *h*.

– The gain or weighting factor γ_{t_i} is based on the SBA receiver's E_b/N_0 calculated at the i^{th} tile for a particular beam during hour h.

– γ_{t_i} typically falls into a range that depends on the ADS-B receiver's design. However, for this analysis the worst case would be for it to be in the range of 0.7 to 0.9 at the receiver sensitivity from the aircraft's top antenna since this will result in more co-channel interference.

– γ_{t_i} for messages from the aircraft's bottom antenna is assumed to be in the range of 0.1 to 0.3 which is a highly conservative worst case average since most messages from the bottom antenna will not have enough signal to be above the satellite receiver's noise floor.

– Antenna gain β towards satellite, including attenuation penalty (for both wanted and unwanted signals) due to aircraft shielding of bottom antenna, $\beta_{bottom} = \beta_{top} - 0.373\alpha$

- β_{bottom} = gain from lower antenna relative to the satellite (dBi)
- β_{top} = gain from upper antenna relative to the satellite (dBi) (*see Fig. A3-3*)
- α = elevation angle from aircraft to the satellite (degrees)

Section A3.3.1 Description of model structure and assumptions

The following contains the primary assumptions made for deriving the numbers of likely unwanted signals at 1090 MHz.

– Aircraft densities: A model of civil air traffic movements was derived from a global flight plan database and the locations of 3 579 major worldwide airports. Modelling the globe as a series of tiles of dimension 1 × 1 degrees, aircraft were assumed to fly great-circle routes from origin to destination and placed in the nearest tile, with a time resolution of one minute. The peak traffic tile in the model was close to JFK Airport, USA, with 32 flights per hour. The actual simulation allowed for traffic growth by multiplying these numbers by a factor of $\xi = 1.4$

– Raw arrival rate $\varphi_{(source)}(h, t_i)$ is derived separately for signals arriving from top and bottom-mounted antennas, for each signal type and for each power. The equations for 125 W avionics are shown below (the equations are the same for 250 W and 500 W avionics but the η values are different):

- $\varphi_{ES,Top,125W}(h, t_i) = \xi \cdot \kappa(h, t_i) \cdot \nu_{ModeS} \cdot \nu_{ADS-B} \cdot \omega_{ADS-B} \cdot \alpha_{ADS-B} \cdot \eta_{ADS-B,125W}$
- $\varphi_{Mode\ S,Top,125W}(h, t_i) = \xi \cdot \kappa(h, t_i) \cdot \nu_{ModeS} \cdot \omega_{Mode\ S} \cdot \alpha_{Mode\ S} \cdot \eta_{Mode\ S,125W}$
- $\varphi_{SSR,Top,125W}(h, t_i) = \xi \cdot \kappa(h, t_i) \cdot \nu_{SSR} \cdot \omega_{SSR} \cdot \alpha_{SSR} \cdot \eta_{SSR,125W}$
  – ξ = scalar multiple of the aircraft count (used for traffic growth modeling)
  – $\kappa(h, t_i)$ = aircraft count for time t, tile i, hour h
  – $\nu_{signal\ type}$ = fraction of signals of signal type, of all signals from that aircraft

TABLE A4-2

Assumption of fraction of signals by signal type

Symbol	Parameter	Value
ν_{SSR}	Fraction SSR	0.1
$\nu_{Mode\ S}$	Fraction Mode S	0.9
ν_{ADS-B}	Fraction of Mode S that has ADS-B	0.3
ξ	Aircraft Count Scalar Multiplier	1.4

– $\omega_{signal\ type}$ = messages per second of signal type

TABLE A4-3

Number of messages per second by signal type

Symbol	Parameter	Value
ω_{ADS-B}	ADS-B msgs/s/aircraft	6
$\omega_{Mode\ S}$	Mode S short msgs/s/aircraft	6
ω_{SSR}	SSR msgs/s/aircraft	60

(A breakdown of these values is shown in Table A3-3)

– $\alpha_{signal\ type}$ = fraction of transmissions broadcast from top antenna

TABLE A4-4

Fraction of top antenna transmissions by signal type

Symbol	Parameter	Value
α_{ADS-B}	ADS-B fraction of top transmissions	0.5
$\alpha_{Mode\ S}$	Mode S fraction of top transmissions	0.5
α_{SSR}	SSR fraction of top transmissions	0

– $\eta_{signal\ type,power}$ = proportion of signals of signal type transmitted with power (125W, 250W, 500W)

TABLE A4-5

Fraction of signals by signal type and transmit power

Symbol	Signal type	125W	250W	500W
η_{ADS-B}	ADS-B	0.25	0.5	0.25
$\eta_{Mode\ S}$	Mode S	0.54	0.3	0.16
η_{SSR}	SSR	1	0	0

Similarly, for the bottom-mounted antenna:

– $\varphi_{ES,bottom,125W}(h, t_i) = \xi \cdot \kappa(h, t_i) \cdot \nu_{ModeS} \cdot \nu_{ADS-B} \cdot \omega_{ADS-B} \cdot (1 - \alpha_{ADS-B}) \cdot \eta_{ADS-B,125W}$

– $\varphi_{Mode\ S,bottom,125W}(h, t_i) = \xi \cdot \kappa(h, t_i) \cdot \nu_{ModeS} \cdot \omega_{Mode\ S} \cdot (1 - \alpha_{Mode\ S}) \cdot \eta_{Mode\ S,125W}$

– $\varphi_{SSR,bottom,125W}(h, t_i) = \xi \cdot \kappa(h, t_i) \cdot \nu_{SSR} \cdot \omega_{SSR} \cdot (1 - \alpha_{SSR}) \cdot \eta_{SSR,125W}$

Exclusions: DME, TACAN, Modes 4/5 and Non-ICAO systems not considered separately:

– DME channel assignments must be 5 MHz or greater from 1 090 MHz (defined in ICAO standards). Out-of-band power from DME falls rapidly to a negligible level at ADS-B band edge, likely to be undetectable at the satellite if centre frequency is no less than 5 MHz from 1 090 MHz:

TABLE A4-6

Distance Measuring Equipment e.i.r.p. values

Offset from centre frequency (MHz)	**DME e.i.r.p. (max) at offset**
0	67 dBm
0.8	23 dBm
2.0	3 dBm

Antenna discrimination from the transmitting DME ground antenna may reduce the potential of receiving unwanted signals even further.

– DME channel assignments must be 5 MHz or greater from 1 090 MHz (defined in similarly, international TACAN channel plans preclude use of channels within ±10 MHz of 1 090 MHz (except on a secondary national basis). Out-of-band power from TACAN transmitters are unlikely to be detectable at the satellite if centre frequency is 10 MHz from 1 090 MHz:

TABLE A4-7

Tactical air navigation system e.i.r.p. values

Offset from center frequency (MHz)	**TACAN E.I.R.P. (max) at offset**
0	75 dBm (see Annex 1)
0.8	26 dBm
2.0	6 dBm

Even if two TACAN/DME systems are operated within the 3 dB bandwidth of the satellite receiver (1 087.7-1 092.3 MHz), at the maximum message rate of 7 200 messages/s, the probability of detection of ADS-B is only reduced by 30%.

– Modes 4/5 various duration messages (3.5, 15, and 35 µs) are likely to be insignificant in number compared to the much greater numbers of civilian-mode (20 µs duration) SSR (“ATCRBS”) replies.

– Other non-ICAO systems identified in Recommendation ITU-R M.2013-0 have short-duration pulse characteristics (up to 5.5 µs) very similar to those of Mode 4, and are therefore conservatively modelled by the very high numbers of civil-mode SSR (“ATCRBS”) replies.

Annex 5

Simulation of Automatic Dependent Surveillance System - Broadcast Message Collision Onboard Satellites (Study # 2)

Introduction

Study presented in § 5.4 of this Report calculated the probability of message collision received on-board a satellite constellation. Having observed that there was no simulation model of the proposed scenario, a first approach is presented in this Annex.

Many countries and regions already mandate the use of ADS-B and many others will soon establish the deadline for airlines to implement ADS-B on their fleet.

In every estimation or parameter used or calculated, the worst case is evaluated, giving a result that represents an unreal situation that is very unlikely to happen.

Results are preliminary and may be modified with more accurate input data, but in a first attempt, shows that interference in 1 090 MHz due to congestion will not avoid reception of ADS-B messages onboard satellites.

Discussion

ADS-B operates at 1 090 MHz, which is shared with other ICAO and non-ICAO standardised aeronautical applications. Extending the coverage of existing terrestrial receptors of ADS-B signal by a satellite network needs different analysis from different perspectives and using as many methods as possible.

The study presented in this contribution is based on simulations of the channel occupancy by ADS-B messages and many others. The main aim is to determine roughly if collisions that ADS-B messages suffer in orbit will allow to achieve the objective of having a real-time aircraft position information.

The simulator tries to outcome to an approximate collision probability of position messages sent from civil aircrafts. Many of the values or parameters used in the simulation were estimated and may not be completely accurate, anyhow a flexible simulator was developed, which is available to run as many tests as needed.

Simulator

The simulator builds a signal that models the different transmissions that are received on-board the satellite. They are all uncorrelated in time and is only modelled the state of the source transmitter (transmitting or standby). The power received is not modelled and a collision state is considered in any case that any signal is received in the same period of time that an ADS-B pulse is being received. In that case, the ADS-B message is considered completely lost (even though that many bibliography[19] states that some recovery is possible).

The scenario modelled is very conservative and always will consider the worst case.

Assumptions

The most important assumption taken to develop the simulation model was that every transmission signal in coverage would be received by the satellite in orbit. FRUIT is not considered, but may be easily modelled incrementing SSR transmissions (replies) rate.

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[19] "Techniques for Improved Reception of 1 090 MHZ ADS-B Signals" W. Harman, J. Gertz, A. Kaminsky, 1998 IEEE. https://www.ll.mit.edu/mission/aviation/publications/publication-files/ms-papers/Harman_1998_DASC_MS-13181_WW-18698.pdf.

Message reception validity is done by modeling message collisions caused by interference from various radar interrogation replies and messages over 1 090 MHz. A message collision occurs if the broadcast time interval from two separate messages or replies overlap partially or completely.

Number of aircraft on sight

The number of airplanes inside the footprint of a satellite is difficult to estimate. The worst case scenario would be the one with the greatest density of aircraft/square nautical mile. Two possible scenarios were considered: the first one is LA2020, which is an estimation of the air traffic in Los Angeles Basin for the year 2020, and the other one is Core Europe (CE2015) developed by EuroControl, which represents air traffic in Core Europe in 2015.

For each scenario, the number of airplanes is estimated within a circular area with different density values depending on its radius. These values are limited to a specific radius, therefore, for greater radiuses, the value is extrapolated. This means that the number of airplanes within the entire footprint of the satellite is calculated according to the density of the most congested area.

– As for the LA2020, the density of airborne aircraft is taken to be:
  - 5.25 aircraft per nautical mile (0.00742 aircraft/square nautical mile or 0.00216 aircraft/km^2) from the center of the area up to 225 nautical miles (416.7 km).
  - 0.00375 aircraft/square nautical mile (0.00109 aircraft/km^2) from 225-400 nautical miles (416.7-740.8 km).
  - For greater radiuses, the density is considered to be 0.00375 aircraft/square nautical mile (0.00109 aircraft/km^2) as well.

– Besides an amount of 225 ground aircraft is considered to be within the area of 400 nautical miles (740.8 km) radius circle. This density of 0.00044 aircraft/ square nautical mile (0.00013 aircraft/km^2) is used for any radius value.

– As for the CE2015, the density of aircraft is taken to be:
  - 1356 airborne aircraft plus 125 ground aircraft within a radius of 200 nautical mile (370.4 km). This is a density of 0.01178 aircraft/square nautical mile (0.00343 aircraft/km^2).
  - 585 airborne aircraft plus 25 ground aircraft within a radius from 200 to 300 nautical miles (370.4 – 555.6 km). This is a density of 0.00388 aircraft/square nautical mile (0.00113 aircraft/km^2).
  - For greater radiuses, there is a density of 0.00388 aircraft/square nautical mile (0.00113 aircraft/km^2).

For example, considering the LA2020 scenario and a radius of 450 nautical miles (833.4 km), the amount would be those from the circle of 225 (416.7 km) nautical miles plus those from the ring between 225 and 450 nautical miles (416.7 & 833.4 km). In addition, ground aircraft should be considered. That would be:

$$7.42 \times 10^{-3}\pi(225)^2 + 3.75 \times 10^{-3}\pi(450^2 - 225^2) + 440 \times 10^{-6}\pi(450)^2 = 3250\, airplanes$$

On the other side, considering the CE2015 scenario and a 450 nautical mile (833.4 km) radius, the amount would be those from the circle of 200 nautical miles (370.4 km) plus those from the ring between 200 and 450 nautical miles (370.4 & 833.4 km). In this case, the number of ground planes is included in the values of density for each radius.

$$11.78 \times 10^{-3}\pi(200)^2 + 3.88 \times 10^{-3}\pi(450^2 - 200^2) = 3462\, airplanes$$

Since the number of airplanes is greater for the CE2015 scenario this is the one that will be considered for the simulation.

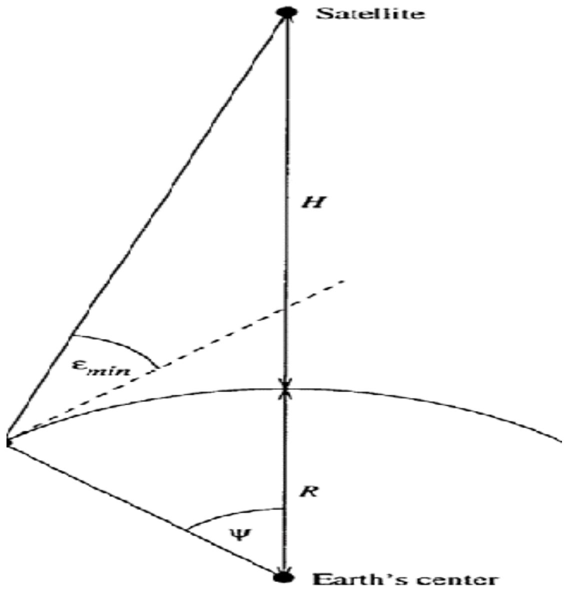
Low earth orbit satellite coverage

The scenario simulated the reception of ADS-B signals aboard LEO satellites. The satellite's coverage area on the Earth depends on orbital parameters. Ground stations can communicate with LEO satellites only when the ground station is under the coverage area (satellite footprint). The two main parameters to determine the area of the footprint are the altitude H and the minimum elevation angle ε.

Consequently, it is necessary to know the coverage of a single LEO satellite. The geometric model[20] that is used in the simulation is shown in Fig. A5-1. The largest coverage area is achieved when the elevation in the edge, ε, is 0º, which is the worst case when modelling. In Fig. A5-1, R is the radius of the earth ($R = 6378\ km$) and $H$the altitude of the satellite above the surface of the Earth.

FIGURE A5-1

Geometric satellite coverage scheme



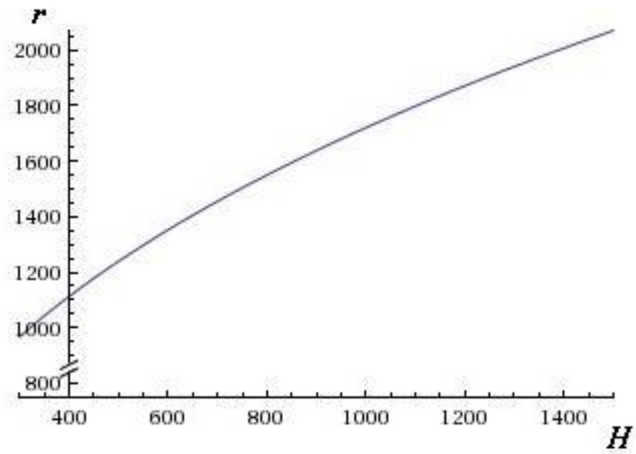
Through information taken from previous studies and operating mathematically, it obtained the following equation, from which it can obtain r, radius of satellite's footprint.

$$r = \frac{H \cdot R}{\sqrt{(R+H)^2 \ - R^2}}$$

[20] "The Coverage Analysis for Low Earth Orbiting Satellites at Low Elevation", S. Cakaj, B. Kamo, A. Lala, A. Rakipi – Polytechnic University of Tirana, Tirana, Albania. http://thesai.org/Downloads/Volume5No6/Paper_2-The_Coverage_Analysis_for_Low_Earth_Orbiting_Satellites_at_Low_Elevation.pdf

FIGURE A5-2

Relationship between radius and altitude of the satellite



For the simulation, 800 km is used as satellite's altitude. Due to the fact that Iridium constellation is positioned at 780 km of altitude, a conservative model was considered and estimated a mean altitude of 800 km.

The radius of the coverage of a satellite at that height is:

$$r = 1549.4\ km = 836.6\ NM$$

This result differs from the case where an antenna with a beamwidth of 30° is used. Again, worst case is used for the simulation.

Transmission types

Transmission types depends on the type of flight and how is that airplane equipped. Information from United States define this ratios:

- 33% Commercial.
- 31% General Aviation.
- 28% Air Taxi.
- 06% Military.
- 02% Cargo.

Depending on the type of flight, aircraft and other variables, are the type of signals that an aircraft will transmit. In every case, the average is used for parameters not defined as an exact value.

Secondary surveillance radar

Secondary Surveillance Radar has many functioning modes. There are some characteristics that are shared between modes, but some particular considerations have to be made in each case.

The ATCRBS interrogator periodically interrogates aircraft on a frequency outside the bandwidth of ADS-B, at 1 030 MHz. Although this frequency is outside the bandwidth of ADS-B transmissions, the replies of those interrogations are centered in 1 090 MHz. This is done through a rotating scanning antenna sending signals at the radar's assigned pulse repetition frequency (PRF). Little information was found regarding the interrogation frequency. However, it was found that typical values are 450-500 interrogations/seconds. In the simulator 500 Hz is taken as is the worst case scenario.

All transmission modes parameters are considered separately below.

Mode A/C

SSR was a mode of interrogate, commonly referred as mode A/C. When the transponder receives an interrogation request it sends back a transponder's squawk code. This is referred to as Mode 3A. A transponder code can be paired with pressure altitude information, which is called Mode C[21]. Mode 3A and C are used to help air traffic controllers to identify the aircraft on a radar screen and to maintain separation, but does not provide information on the position encoded in the digital data. For that reason, is not useful and considered as interference in the simulator.

The interrogation are done with the same frequency of PRF, but only a portion of the aircraft will be in the range due to the directional antenna. Typically the beamwidth is 2.5° [22], so a constant of 25/3600 is used to calculate the real number of mode A/C replies.

Also when mode S is used in the same radar site, only ⅓ of the time the radar is interrogating for A/C mode[23]. So, a factor of ⅓ must be applied to the number of mode A/C replies.

Mode S

Mode S has two different interrogations signal, one that makes an 'all-call' and another that interrogates only to one particular aircraft at any given time. The later mode is used only ⅔ of the time. So, this mode, will have a ⅔ factor, and because not every aircraft will reply at the same time, a factor estimated in 1/10 is used in this type of transmission.

Mode 4 and 5

These modes are only used by military aircrafts. Only a small portion of flights are military, about 6%. Not having the information about the how many use mode 4 or 5, it is assumed 3% of total flights will use mode 4 and 3% will use mode 5.

Distance measuring equipment/tactical air navigation system

It is assumed that TACAN systems are primarily operated at least 5 MHz away from 1 090 MHz and do not pose a significant co-frequency interference/concern. But, if the worst case is taken into account, the probability of message collision is not zero.

The rate of interrogation (or PRF) is nominally 30 pulse pairs per second. In that case, depending on the channel used, the probability of collision is not zero. From the DME frequency table, it can be seen that only one channel of 126 may interfere with ADS-B messages.

Although is not completely realistic, a factor of 1/126 is used in the mean of DME messages transmitted. In that way, the number of DME messages simulated in the same bandwidth than ADS-B, will be representative of DME interference.

Accurate information indicating the number of Aircraft using DME transponder system couldn't be found. However, it is estimated that it is a high value. Therefore, it is specified that 90% of all the aircraft use DME technology.

Automatic dependent surveillance - broadcast / 1 090 extended squitter

Mode Extended Squitter or ADS-B is a cooperative surveillance technology in which an aircraft determines its position via satellite navigation and periodically broadcasts it, enabling it to be tracked.

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21 "From the Ground Up: Training Manual for Pilots", Sandy A. F. MacDonald, 1997, I.L. Peppler.

22 "Radar Systems", Paul A. Lynn, 1987, Springer Science & Business Media.

23 "Principles of Mode S Operation and Interrogator Codes", 4.3 Defining A MIP. https://www.eurocontrol.int/sites/default/files/publication/files/surveillance-modes-principles-of-modes-operation-and-interrogator-codes-20030318.pdf.

The information can be received by air traffic control ground stations as a replacement for secondary radar. It can also be received by other aircraft to provide situational awareness and allow self-separation.

The probability of reception of this type of transmission without interference is the main objective in the simulation. The simulation calculates the ratio between the number of ADS-B messages transmitted and received on orbit.

In this particular case, it's important to consider collisions occurred between ADS-B signals and with all the other interfering signals.

Final probability

Even though getting a low probability of receive without interference an ADS-B message, the probability of receive at least one message of position in a five-minute period can be calculated.

The probability of not receiving an ADS-B message $P(collision)$ is known from the simulation. The probability of not receiving two messages, can be calculated as

$$P(collision) * P(collision)$$

or

$$P(collision)^2$$

assuming all collision are independent. Then the probability of receiving at least one of two messages (or the probability that both messages did not collided) is

$$P(at\ least\ 1\ of\ 2) = 1 - P(collision)^2$$

Using the same expression for n messages sent, the general equation is:

$$P(at\ least\ 1\ of\ n) = 1 - P(collision)^n$$

Knowing that the position is transmitted twice a second, it is possible to calculate the probability of receiving one position message at least in a five-minute period. The latter probability can be calculated as follows:

$$P(receive\ ADS - B)_{5min} = 1 - P(collision)^{2*60*5}$$

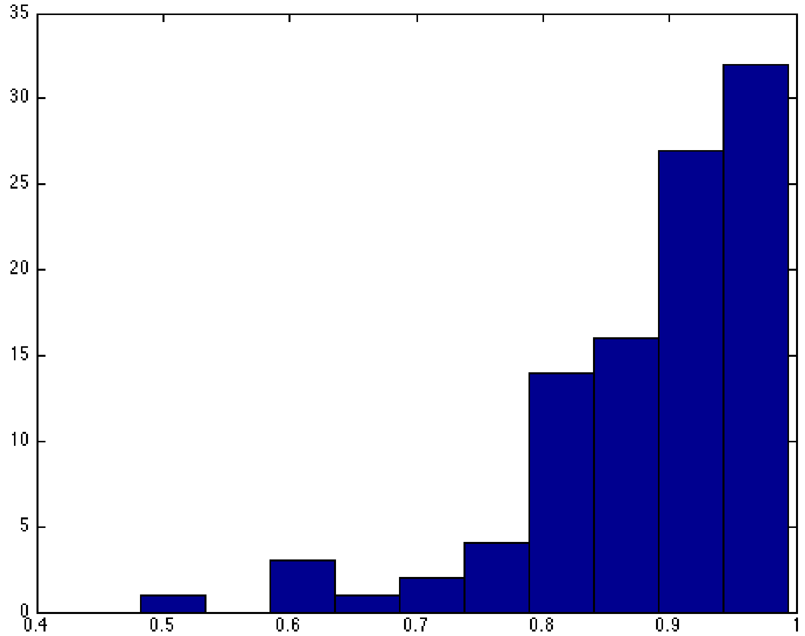
Results

Using the assumptions stated before, the simulation was run several times. The distribution of results are shown in a histogram in Fig. A5-3, using a simulation time of 2 seconds and running the scenario one hundred times. The results are placed in 10 bins, showing that 60% of the scenario simulations resulted that receiving a position message in a five-minute period has a probability of 90%.

Next figures shows the abscissa the probability of receive a position message in five minutes and the ordinate shows the number of simulations that fell in the same bin.

FIGURE A5-3

Histogram of 100 simulations run

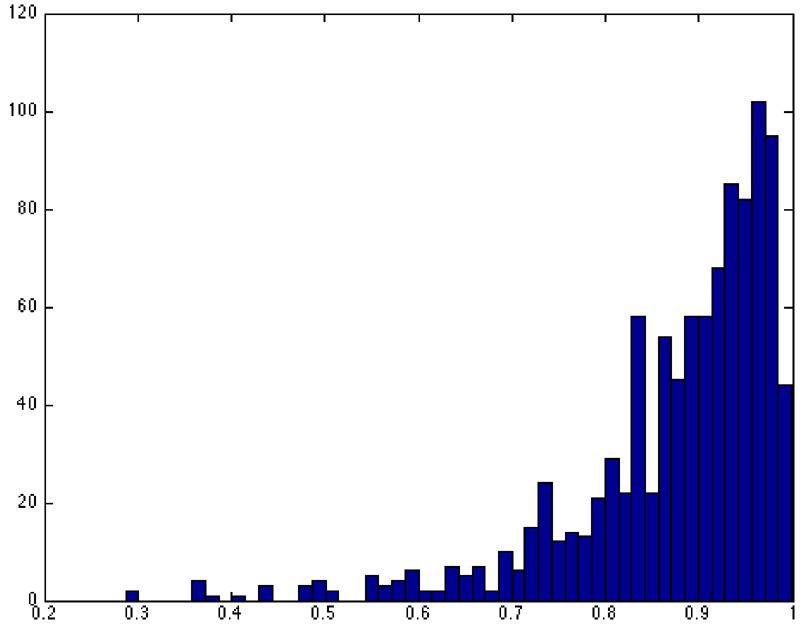


If the simulation time is changed to 1 second and the simulation is run 1 000 times, the results are very similar. The results are shown in Fig. A5-4, grouping the histogram in 50 bins.

Although the simulation shows an important dispersion of values, results are mainly above 90%.

FIGURE A5-4

Histogram of 1 000 simulations run



Summary

The objective of this study was to present a conservative simulation model to calculate the possible use of satellite reception of ADS-B messages in the worst case scenario. It is also assumed that very congested areas are over large cities, where terrestrial coverage of ADS-B is available. Even in the case of congestion similar to the evaluation above, results show that there should not be a problem in receiving message rates similar to existing ICAO standards.

It's important to note, that the results shown evaluates the probability to receive a position message in a timeframe of 5 minutes. If a timeframe of 15 minutes is used, which is an ICAO objective, the probability will be higher.

Annex 6

Dynamic statistical study on satellite reception of the automatic dependent surveillance - broadcast signal for global flight tracking for civil aviation (Study # 3)

A6-1 General information of the employed methodology

The methodology used consists in determining, dynamically and statistically, the ADS-B pulse frames received and decoded by the satellite when emitted by an aircraft in the satellite's line of sight. The simulation is dynamic because it takes into account actual satellite trajectories as well as world air routes used by commercial aircraft. The instants in time defining the calculation area are statistical, selected randomly. Indeed, at each instant "t", the satellite location and the positions of all aircraft throughout the world are chosen randomly, noting however that the aircraft are distributed over all known air routes. Figure A6-1 depicts the situation simulated. At each instant "t", the power level of ADS-B messages received from each aircraft by the satellite are compared with the sensitivity level of the satellite receiver, taking into account the additional interference power from the various messages transmitted by other aircraft in the satellite line of sight. The interference level from other aircraft may be summarized by the following equation:

$$I = 10\log\left(\sum_{n=1}^{n=N-1} 10^{[Pt_n + Gt_n + Gr_n - Loss_n]/10}\right)$$

with:

Pt_n: power level of the transponder *n*

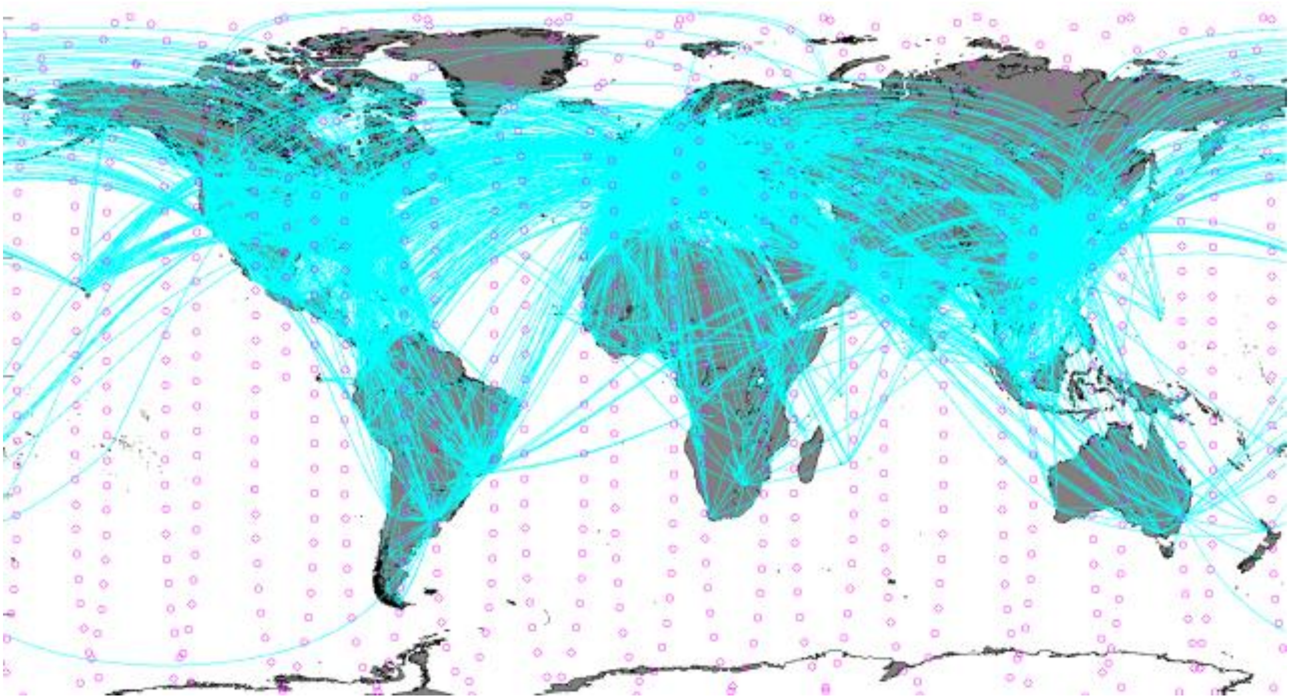
Gt_n: gain of the transponder, considered omnidirectional (0 dBi)

Gr_n: gain of the receiver, dependent on the angle between the aircraft and the satellite

$Loss_n$: free-space propagation losses.

FIGURE A6-1

Satellites locations and air routes used for the simulations
Blue lines: air routes. Pink circle: examples of satellites locations



A6-2 Characteristics of the aeronautical services

A6-2.1 Global aircraft count

Figure A6-1 is constructed on the basis of over 59 000 air routes worldwide. At a given time, there is always one aircraft on each air route, therefore at every instant, there are approximately 59 000 aircraft flying around the globe.

Statistics from the US National Air Traffic Controllers Association estimate that over 87 000 flights take place over the United States daily. One-third of these (i.e. around 28 500) are commercial (passenger) flights. About 27 000 are general aviation (private) flights, 24 548 are taxi flights (leased aircraft), and around 5 260 are military flights, 2 148 being cargo flights. At any time, there are more than 5 000 aircraft in the skies above the United Statesof America.

Eurocontrol estimates that, at any time in the European sky, within DME coverage in Europe, up to their radio horizon – around 505 km in standard atmospheric conditions for an aircraft at an altitude of 15 km (50 000 feet), there are 660 aircraft in flight. Eurocontrol estimates that this figure will rise to over 800 by 2020, i.e. a 30% increase in five years. This number takes into account all types of flights (commercial, cargo, private, tourism) except military ones.

Figures A6-2 to A6-5 show a possible configuration for the random distribution of aircraft by air route. On these Figures, blue points are ICAO aircraft in the line of sight of the satellite spot beam during a 10s period and red points are non ICAO aircraft in the line of sight of the satellite spot beam.

FIGURE A6-2

Locations of International Civil Aviation Organization aircraft on air routes at a given time of the simulation over Atlantic Ocean

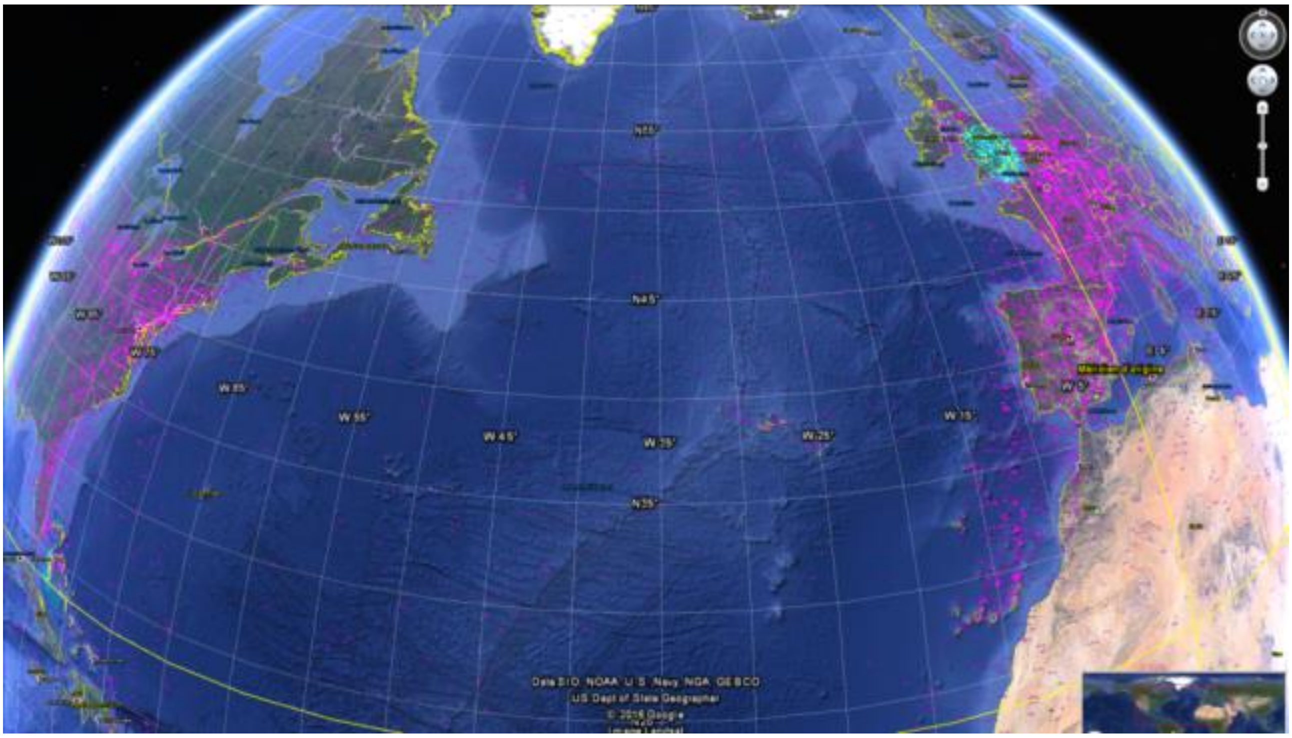


FIGURE A6-3

Locations of aircraft during a 10 second period considering the motion of the coverage area of the satellite. Orange circle: center of the satellite each second during the 10 second period

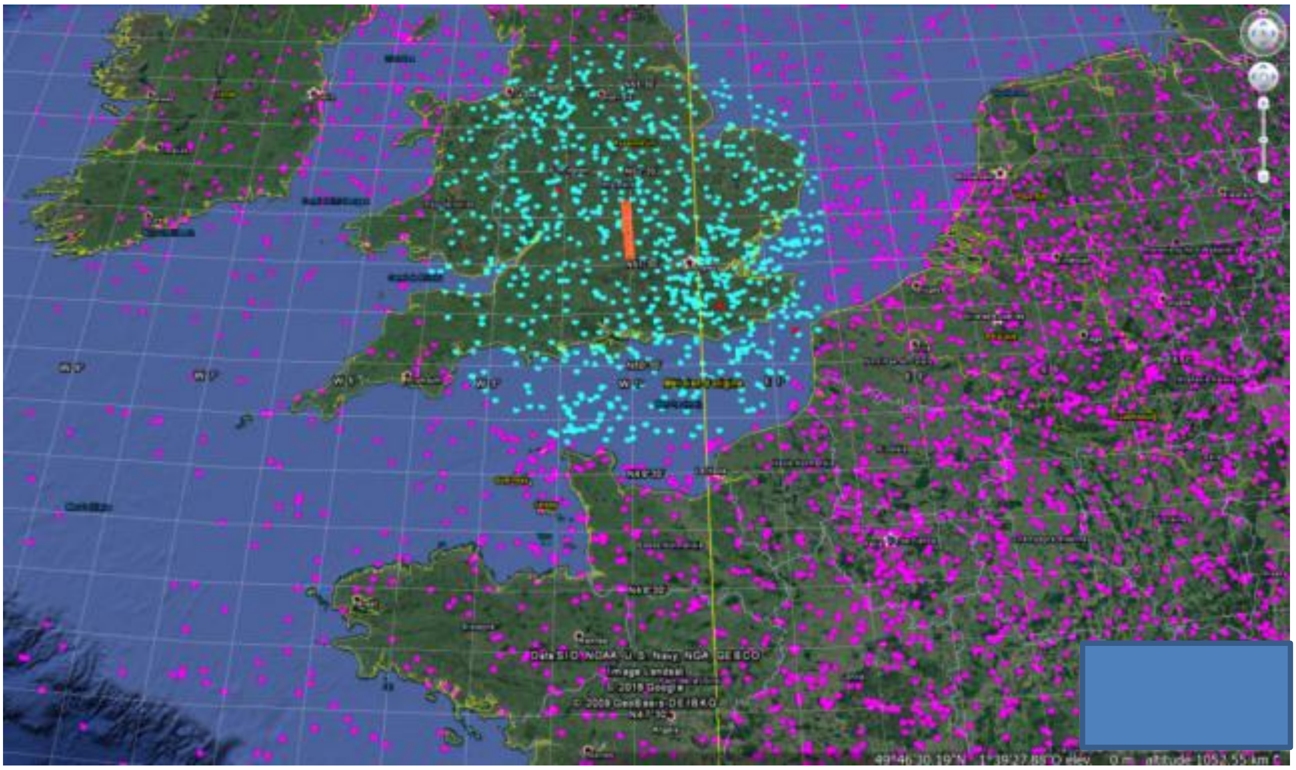


FIGURE A6-4

Locations of ICAO aircraft (orange points) in the line of sight of the satellite during the first second

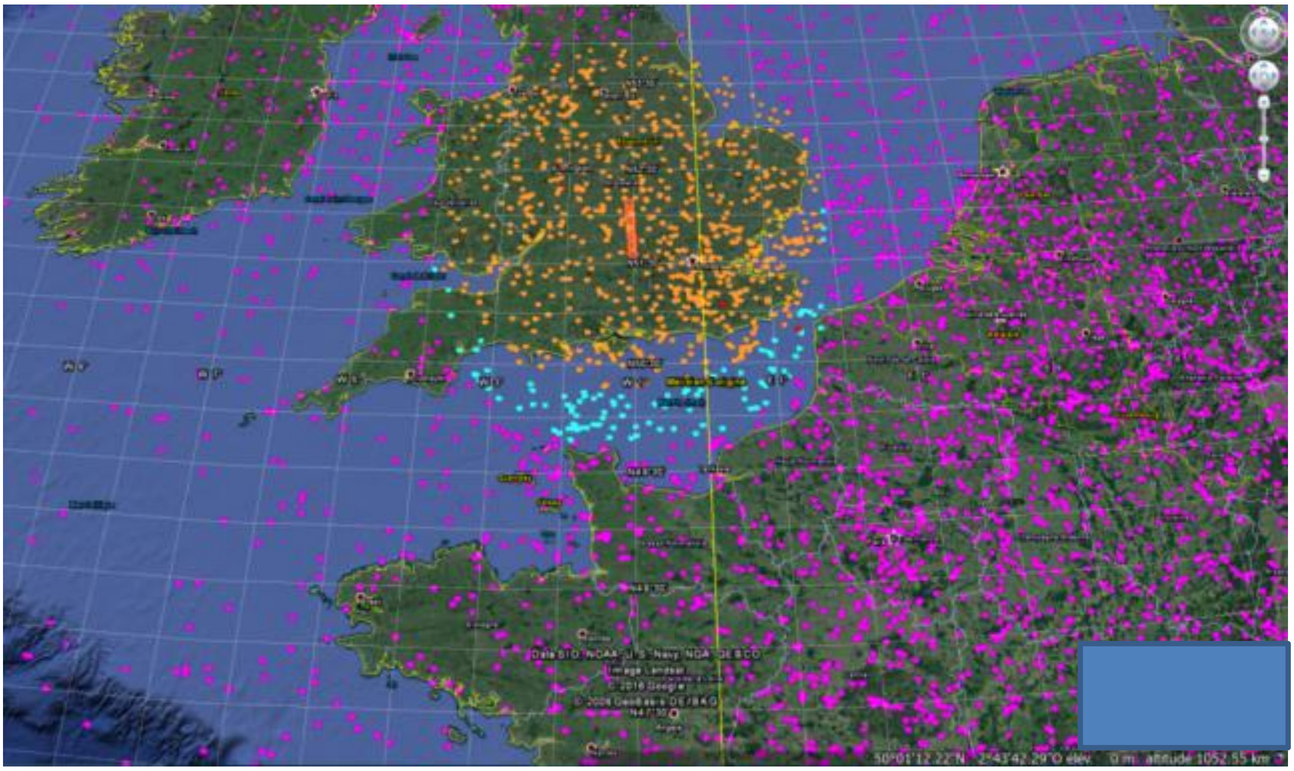


FIGURE A6-5

Locations of ICAO aircraft (yellow points) in the line of sight of the satellite during the 10th second

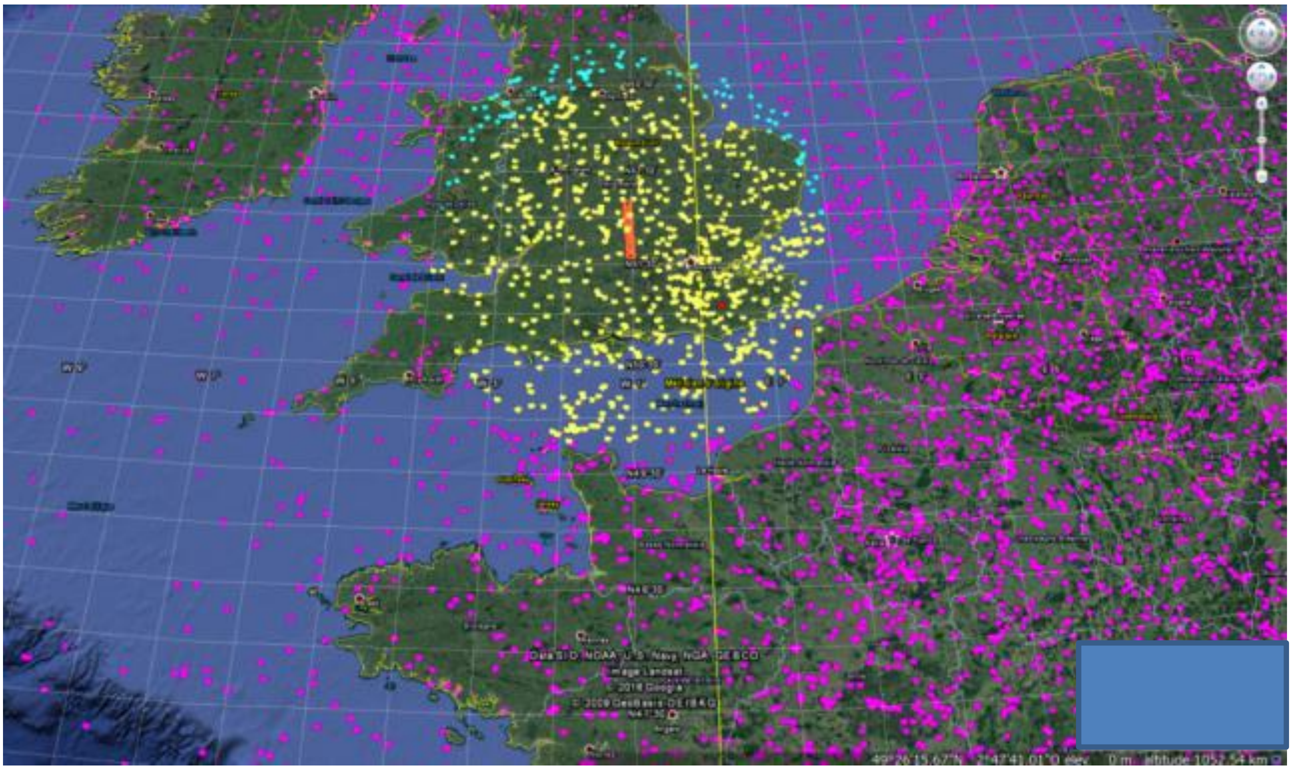


FIGURE A6-6

Estimation of aircraft over the United Kingdom at 1020 hours UTC on the 18th of October 2016 (retrieved from the Internet site)

It can be considered by comparison with Figs A6-3 to A6-5 that the simulation, and in particular the choice of the number of aircraft to be positioned on the air routes, is appropriately representative of the current actual level of air traffic.

Indeed, for Fig. A6-3, the total number of aircraft plotted is more than 1 000. The Fig. A6-6 does not allow a clear view due to the superimposition of aircraft in many areas.

It has to be noted that:

1) This information provided by public website is fairly approximate.

2) The transponders referenced are only those emitting in mode S or ADS-B. In other words, aircraft equipped solely with A/C mode transponders or non-ICAO ones are not considered.

Zooming in over the blue area in Fig. A6-6 gives an aircraft count of around 500 (to compare to the 600 aircraft represented in the simulation by yellow or orange points). This confirms that considering one aircraft per air route may be the appropriate estimation of aircraft distribution for the study.

A6-2.2 Characteristics of transponders

Table A6-1 gives the statistical distribution of the different types of transponders of ICAO and non-ICAO aircraft. This Table is based on Tables A4-1a and A4-2c in Annex 12 to Document R12-5B/883 (Report of the Chairman of ITU-R Working Party 5B on the July 2015 meeting).

The latter table statistically distributes types of transponders according to the types of transmitted messages.

TABLE A6-1

Distribution of different types of transponder over the global aircraft fleet

							Transponders			
							29 dBW	**21 dBW**	**24 dBW**	**27 dBW**
ICAO	**90%**									
		Mode A/C	10%				0%	100%	0%	0%
Aggregate percentage							0%	9%	0%	0%
		Mode S	90%							
				with ADS-B	80%		0%	25%	50%	25%
Aggregate percentage							0%	16.20%	32.40%	16.20%
				without ADS-B	20%		0%	54%	30%	16%
					with long message	80%	0%	54%	30%	16%
Aggregate percentage							0%	7%	3.89%	2.07%
					without long message	20%	0%	54%	30%	16%
Aggregate percentage							0%	1.75%	0.97%	0.52%
NON ICAO	**10%**									
		ADS-B	90%				0%	25%	50%	25%
Aggregate percentage							0%	2.25%	4.5%	2.25%
		SSR	10%				100%	0%	0%	0%
Aggregate percentage							1%	0%	0%	0%

For the simulation, in each satellite spot beam, the power distribution by aircraft observes the percentages expressed in Table A6-1.

Table A6-2 gives the number of messages emitted according to their type. It is important to note that, during the simulations, the number of types of messages emitted by a transponder is chosen randomly by aircraft within the range defined by the table. For example, an ICAO aircraft displaying emissions in mode S with ADS-B will have, in its pulse frame of duration 1 second towards the satellite, between 0 and 60 type A/C messages, between 6 and 40 short messages, between 6 and 20 long messages and six ADS-B messages. However, these hypotheses are based on emissions more or less alternating between top-mounted and bottom-mounted antennas on the aircraft's fuselage (hereinafter referred to respectively as top and bottom antennas). As shown in § A6-2.4 (Fig. A6-8), this study only took account of emissions from transmitters positioned on the top of the fuselage.

It is possible to assume that 60% of emissions to answer an interrogation are directed downwards (and 40% upwards). Thus, when a number of pulses per type of message is chosen randomly for a given aircraft, the number of pulses considered in the simulation is reduced by 60% in order to take into account only upward emissions in the frames.

On the basis of Table A6-2, it must be considered that ICAO emissions of type Mode A/C, Mode S All Call, Mode S long message and Mode S short message are responses to interrogations. Such interrogations are emitted from land-based stations. In these cases, only aircraft located above land masses or less than 400 km from the nearest coastline can be involved in this type of emission.

The distance from the coastline is based on a geometrical horizon for an aircraft at an altitude of approximately 11.5 km under standard atmospheric conditions (k = 4/3).

TABLE A6-2

Characteristics of aeronautical emissions

	ICAO					**Non-ICAO**	
Type of emissions	Mode A/C	Mode S All Call	Mode S Short message	Mode S Long message	ADS-B / 1090 ES	SSR Short pulse	SSR Long pulse
Maximum duration (µs)	20.3	64	64	120	120	3.5	35
Number of messages per second	0-120	0-60	6-40	6-20	6	6-40	6-20

Thereafter, the threshold distance is accurately calculated for reception of transmissions to answer secondary radar interrogation for each aircraft.

For non-ICAO aircraft, SSR short or long pulse type emissions are not subject to the rules quoted above, the use in this case being a type identification friend or foe (IFF) which does not necessarily require an interrogation.

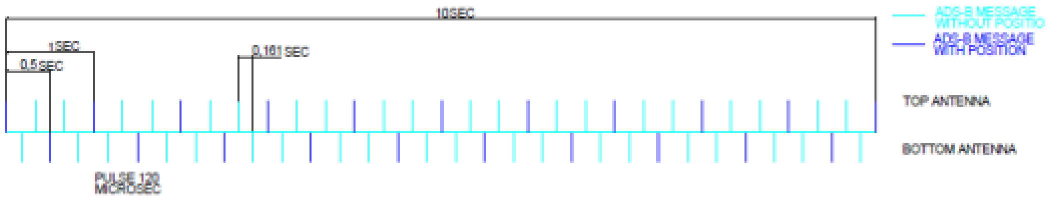
A6-2.3 Specific case of automatic dependent surveillance - broadcast emissions

Figure A6-7 presents a schematic representation of ADS-B pulse frames. In line with Table A6-2, within one second, six messages are transmitted by the two antennas. Three of these were emitted by the top antenna. However, it can be seen that, within one second, only one single message containing position information was emitted by this antenna. In the current study, this message will be called the “desired” message.

For each aircraft, the location of this “desired” message is taken randomly within the ADS-B frame, and can be found in the first, second or third position. Due to the random shift of the desired ADS-B message (±0.1 ms), each second could show zero, one or two desired messages (each second presenting zero desired message is always follows by a second presenting two messages – See for example Table A6-5).

FIGURE A6-7

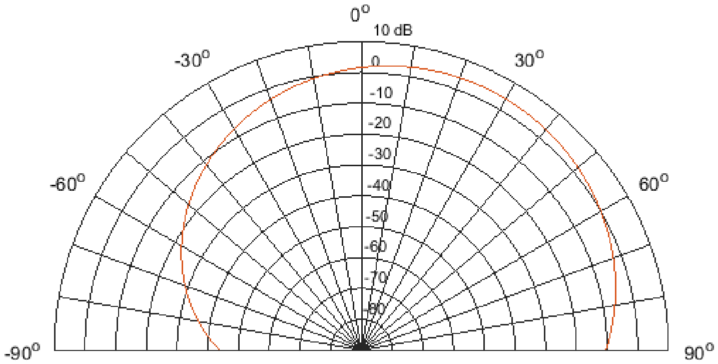
Time representation of automatic dependent surveillance - broadcast pulse frames



A6-2.4 Automatic dependent surveillance - broadcast antenna pattern

FIGURE A6-8

Time representation of automatic dependent surveillance - broadcast pulse frames



NOTE: The axis [90° - 90°] represents the vertical axis. For a downward-facing antenna, 90 represents the nadir and for an upward-facing antenna, it represents the zenith.

If we consider an aircraft in the coverage area, it may be deemed to see the satellite with an elevation angle of between 0° and 16.5° in relation to its zenith. It can be considered that the contribution of emissions from downward-facing antennas is entirely negligible in the aggregate interference. The studies are thus based solely on top antenna emissions and this antenna is considered omnidirectional in the current simulation.

A6-3 Characteristics of the receiving satellite

A6-3.1 Receiver sensitivity

The satellite is located at an altitude of 780 km on one of the orbits existing in the HIBLEO-2 constellation. The receiver sensitivity is taken to be −87 dBm or −117 dBW. As the liaison statement points out, ADS-B reception standards do not specify performance in terms of C/N or $C/(N+I)$.

Receiver performance is normally defined as the signal level at which 90% decode probability is achieved. The receiver sensitivity is specified in the absence of interference. This implies that the receiver noise figure is sufficiently low to provide the margin required for the decoder to overcome the noise amplitude.

Normally, the value of signal margin above the noise to achieve the required decode probability is beyond the scope of ICAO.

The actual sensitivity of ADS-B receivers used in global flight tracking is currently unknown. The studies undertaken are therefore based on the sensitivity defined by ICAO.

Nevertheless, it is worth noting that a sensitivity of −117 dBW with an on-axis antenna gain of over 21 dB would be more or less similar to a sensitivity of −127 dBW for an on-axis gain of 10 dB and 1 dB off-axis. These latter values are fairly similar to those that can be found on the system already deployed and in operation on the satellite PROBA-V (sensitivity of −96 dBm and maximum gain of 10 dB).

A6-3.1 Satellite antenna pattern

At present, the antennas of satellites seeking to receive ADS-B emissions are made up of flat antenna arrays. The studies carried out are based on the hypothesis that each antenna in the array has its own receiving and information processing system, but also that each antenna produces its own spot beam, as shown in Fig. A6-9. Table 2 of the main body of this Report contains gain characteristics for each spot beam for a −3 dB beamwidth (in relation to the nadir). Table A6-3 summarizes the data. It should be noted that beyond a 33° beamwidth, the simulations undertaken assume that signal reception is no longer possible. By way of example, this means that the overall circular coverage of a spot beam for a satellite at 780 km is around 460 km in diameter.

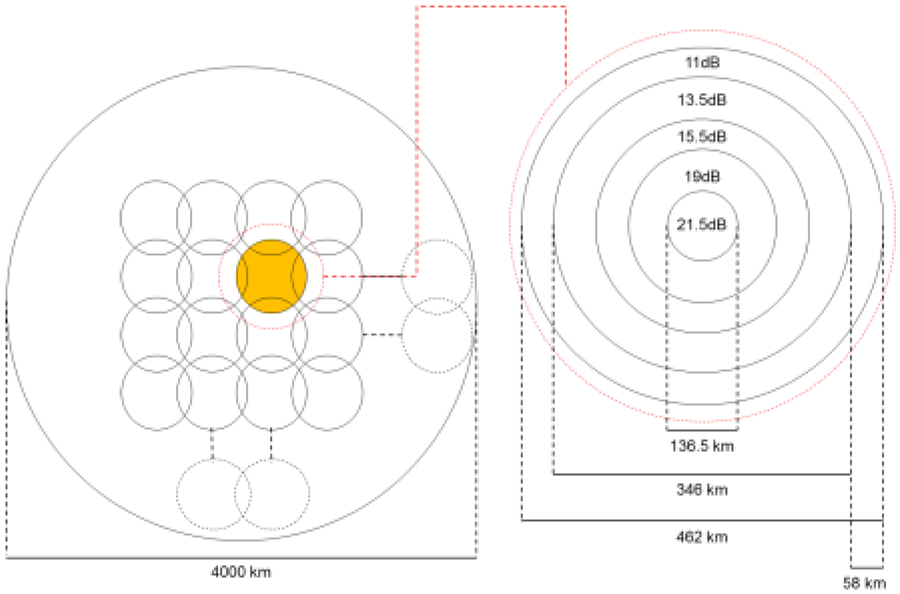
TABLE A6-3

Gain of a satellite antenna spot beam (taken from Table 2 of main body)

Minimum gain (dBi)	3dB beamwidth (°)
21.5	10
19.0	13.5
15.5	20
13.5	25
11	33

FIGURE A6-9

Schematic representation of the network of spot beams for a satellite. The orange portion represents one of the spot beams used in the simulations



The noteworthy difference between the modelled beam and an actual beam of a satellite of the current satellite network is that the modelling assumes an uniform overlap between all the beams in the array and each spot beam is perfectly circular and of uniform dimensions. In the modelled array, the spot beams are perfectly aligned and its diameter is equivalent to 8 spot beams.

A6-4 Determination of satellite reception

A6-4.1 Summary of hypothesis

The simulation results are based on the following hypotheses:

1 ICAO-type aircraft are distributed on the world air routes.

2 Their count is always the same worldwide and equal to more than 59 000 randomly distributed on the air routes.

3 Non-ICAO type aircraft are distributed in satellite line of sight.

4 The simulations are performed during a period of 10 s. During this time, the satellite motion is considered whereas the aircraft are considered fixed (taking into account that satellite speed is around 30 times greater than the speed of aircraft) – See Figs. A6-3, A6-4 and A6-5.

5 The number of non-ICAO aircraft in the global area described by the displacement of the satellite spot beam during the 10s period is taken randomly between one and 10.

6 For each aircraft, the total emissions (Mode A/C, Mode S, ADS B and SSR) are modelled during the 10 second period. For each second the simulation considers all samples from aircraft emissions in the visibility of the satellite (see Table A6-5 for more details).

7 The simulation assumes that beyond an angle of 30° between the satellite and the aircraft, the aircraft are no longer detected and do not contribute to interference in the satellite receiver.

8 The simulation is based on the receiver sensitivity.

9 The time increment in the pulse frames of each aircraft emission is 1 µs.

10 The number of pulses of each emission for each aircraft is taken randomly in the range provided in Table A6-2.

11 Table A6-1 presents the assumed distribution of different types of transponders over the global aircraft fleet for ICAO and non ICAO aircraft.

12 All emissions other that ADS-B are considered to be interference (Mode A/C, SSR, Mode S with or without long message).

13 ICAO emissions responding to an interrogation are considered to be present solely above land masses or within a maximum distance of coastlines. These assumptions do not apply to non-ICAO emissions, which are considered to transmit anywhere.

14 Due to fuselage attenuation, the simulation considers that only message emitted by the top antenna could be received by the satellite. Then, for each aircraft, only 40% of the total number of interfered messages per second to answer an interrogator are emitted in the direction of the satellite

15 The simulation takes into account that one ADS-B pulse containing position information is sent every second in the direction of the satellite.

16 The simulation takes account of the propagation time of messages to the satellite.

17 The simulations do not take into account terrestrial stations transmitting in the 1 090 MHz band.

18 The simulations consider that an ADS-B message that is partially or totally drowned in interference is lost and cannot be decoded by the receiver.

Figure A6-10 represents, over a time-frame of 10 ms, the cases when an ADS-B message exceeds the receiver’s aggregate noise level.

This aggregate noise level is a linear combination of the internal noise of the receiver, with the additional interferences due to other emissions (long message, short message or A/C) from the “desired” aircraft, and all the emissions of the other aircraft (Mode A/C or Mode S with or without ADS-B) present in the satellite’s spot beam. In this case, the “desired” aircraft ADS-B messages can be decoded by the satellite whereas, in the case of Fig. A6-11, it cannot be, since the received power level is lower than the aggregate noise level at the considered instant.

FIGURE A6-10

Typical automatic dependent surveillance-broadcast message exceeding the level of noise from other emissions in the spot beam of the satellite. Red line corresponds to an automatic dependent surveillance - broadcast pulse. Blue line corresponds to the satellite receiver noise level. The X axis represents time (in µs) and the Y axis represents the receiver noise sensitivity and interference level (in dBW)

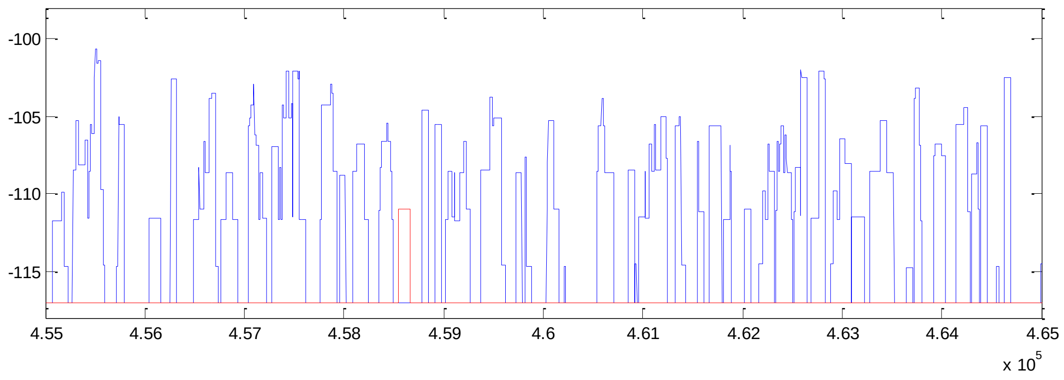
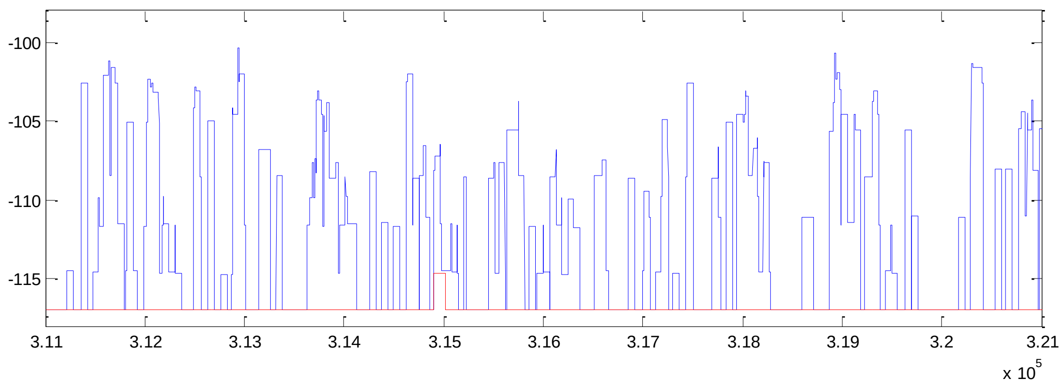


FIGURE A6-11

Typical automatic dependent surveillance-broadcast message drowned in interference from the other emissions in the spot beam of the satellite. Red line corresponds to an ADS-B pulse. Blue line corresponds to the satellite receiver noise level. The X axis represents time (in µs) and the Y axis represents the receiver noise sensitivity and interferences level (in dBW)



A6-4.2 Interpretations of the hypothesis and discussion

The minimum and maximum powers potentially received by the satellite (Table A6-4) in its spot beam are established to facilitate understanding of the results of the dynamic statistical simulations carried out. Table A6-4 points out the fact that the minimum power received from an aircraft with a 125 W transponder at the edge of the coverage area (between 12.5° and 16.5° in relation to the satellite nadir) does not exceed the receiver sensitivity level. These messages are thus never received for this specific position. Figure A6-9 shows that the area in which this situation is most probable is a ring approximately 58 km in width at the periphery of the spot beam.

It should be noted that a configuration increasing sensitivity by 10 or 20 dB and reducing the antenna gain by the same amounts would yield similar results.

In a spot beam, the distance between an aircraft and the satellite has no significant impact on the difference in power received by the satellite between several emissions from several aircraft. The difference in path loss is extremely small since the variation in its contribution between the beam axis and its edge, on the one hand, and the satellite, on the other, does not change by more than 2 dB. In a spot beam, the propagation loss of emissions to the satellite is almost identical for all aircraft. Transponder power and receiver gain are the only determining factors.

TABLE A6-4

Input data and framework values for the simulations

Input data	Values for simulations
Aircraft altitude (km)	5-15
Aircraft speed (m/s)	0.19 to 0.25
Satellite altitude (km)	780
Satellite speed (m/s)	7.45
Number of air routes	59000
Number of non-ICAO aircraft	1-10
Observation window (s)	10
Minimum satellite-aircraft distance	765
Maximum satellite-aircraft distance	815
Maximum ADS-B power received* (dBW)	−100.5
Minimum ADS-B power received* (dBW)	−119.4

* Values calculated on the basis of the minimum and maximum distances, transmitting powers and receiving gain in the satellite's area of visibility.

On the basis of the foregoing and considering:

1) that the 58 km ring is identical for two adjacent spot beams (spot beams overlap);

2) the satellite speed;

3) the ratio below the satellite speed and the aircraft speed (aircraft fixed in relation to the satellite in the terrestrial reference area).

It may be considered that coverage of this area by the satellite is difficult for aircraft equipped with a low-power transponder for a period of approximately eight seconds (minimum time during which the aircraft remains in the 58 km ring). This lack of effective coverage occurs at least every 46 seconds (the maximum time during which the aircraft is in the 346 km radius disc of the spot beam (see Fig. A6-9). This thus implies that, with the assumptions used in the current study, an aircraft making ADS-B emissions with a 125 W transponder (i.e. more than 16% of the world's fleet, see Table A6-1) would not be detected by the satellite system for around 16% of the time, without taking account of any interference.

The simulation results provide a matrix (see Table A6-5) with:

– in columns every second during 10 s;

– in rows, for each aircraft the final percentages of "located aircraft" calculated.

The percentage of "located aircraft" is based on the number of detected ADS B message per aircraft during a 10 s period (at least one detected ADS-B message during a period of 10 s) divided by the total number of aircraft emitting ADS-B during the entire period (in the given example below in Table A6-5, this percentage is equal to 94.4%).

Table A6-5 enables the extraction of the percentage of "no detected position". In fact, as mentioned in the previous paragraph, some positions, close to the edge of the spot beam would not be over the sensitivity of the satellite receiver taking into account an ADS-B emission with a 125 W transponder. In the given example, 180 positions are defined (one position every second by 18 aircraft transmitting ADS-B) and 10 of them (see third line of "Aircraft with ADS-B") are in visibility but not detected (value equal to −1). In this situation 5.6% of the positions are not detected.

Due to the previous consideration (aircraft in visibility but not detected), a really low percentage of detected ADS-B emissions could appear in the case of a very low number of aircraft. In fact, if 3 aircraft with ADS-B are in the spot beam, but one is at the edge of the beam with a transponder of 125 W, only 2 will be detected and the percentage of “located aircraft” will be equal to 66.6%.

TABLE A6-5

Example of simulation results in the case of 21 aircraft in line of sight of one satellite during a 10-second period

			Desired message received each second (Time in seconds)										**Total number of desired messages**	**Total number of “detected aircraft” during 10s**
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
Total Aircraft visible during 10s	Aircraft without ADS-B	1	0	0	0	0	0	0	0	0	0	0	Messages only used to define interference in the satellite receiver *	
		2	0	0	0	0	0	0	0	0	0	0		
		3	-2	0	0	0	0	0	0	0	0	0		
		4	-2	-2	-2	-2	-2	-2	-2	-2	0	0		
		5	0	0	0	0	0	0	0	0	0	0		
	Aircraft with ADS-B	1	1	1	1	1	1	1	1	2	0	1	10	1
		2	1	1	0	1	1	1	1	1	0	1	8	1
		3	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0
		4	1	1	1	1	1	1	1	1	1	1	10	1
		5	1	1	1	1	1	1	1	1	1	1	10	1
		6	-2	-2	-2	-2	-2	0	1	1	1	1	4	1
		7	0	1	1	0	1	2	0	1	1	1	8	1
		8	1	1	1	1	1	1	1	1	1	0	9	1
		9	1	1	0	1	1	1	1	1	1	1	9	1
		10	1	1	1	1	1	1	1	1	1	1	10	1
		11	1	1	1	1	1	1	1	1	1	1	10	1
		12	-2	1	1	0	1	1	1	1	1	1	8	1
		13	1	1	1	1	1	1	1	1	1	1	10	1
		14	-2	-2	-2	-2	-2	2	1	1	0	1	3	1
		15	1	1	1	1	1	1	1	1	1	1	10	1
		16	1	1	1	1	1	1	1	1	1	1	10	1
		17	-2	-2	-2	-2	1	1	1	0	2	0	5	1
		18	1	1	1	1	1	1	1	1	1	1	10	1

Legend of values:
1: One desired ADS-B message was decoded
0 : No desired ADS-B message was decoded
−1 : The aircraft is in the spot beam, but its emission is under the noise level of the satellite receiver
−2 : The aircraft is not in the satellite spot beam for the satellite location
* All emissions, apart from ADS-B messages in the case of “Aircraft with ADS-B” are also considered to be interference.

A6-4.3 Results of dynamic-statistical studies

Figure A6-1 clearly shows that there are currently no air routes crossing a large part of the oceans (in particular the southern Pacific and the Indian Ocean). For these areas, there is no ambiguity on the satellite’s capability to receive ADS-B messages from aircraft with the appropriate transmission power. However, the results of the studies presented in the form of a cumulative distribution function will make the distinction between reception capabilities over sea or land areas.

FIGURE A6-12

Locations of spot beams simulated over the northern part of Region 1. Green beam: fewer than 50 aircraft in the area. Yellow beam: between 50 and 100 aircraft. Orange beam: between 100 and 400 aircraft. Red beam: more than 400 aircraft

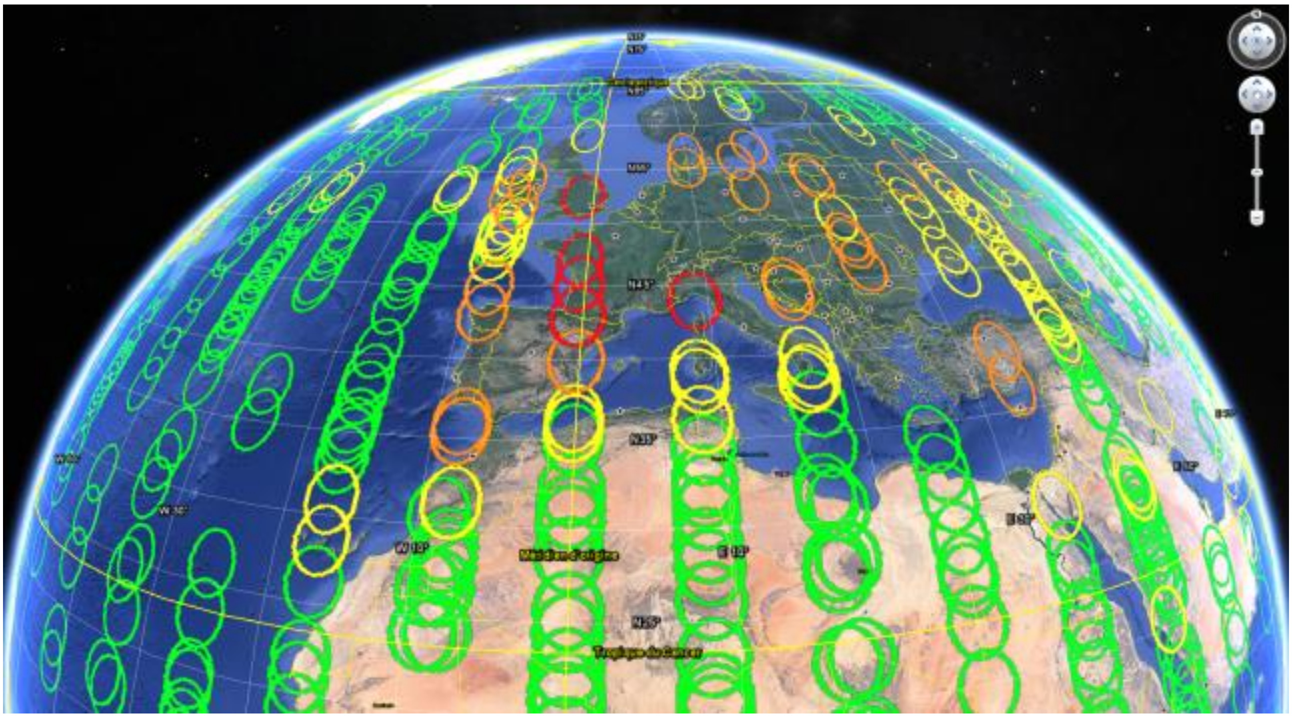


FIGURE A6-13

Locations of spot beams simulated over the northern part of Region 2. Green beam: fewer than 50 aircraft in the area. Yellow beam: between 50 and 100 aircraft. Orange beam: between 100 and 400 aircraft. Red beam: more than 400 aircraft

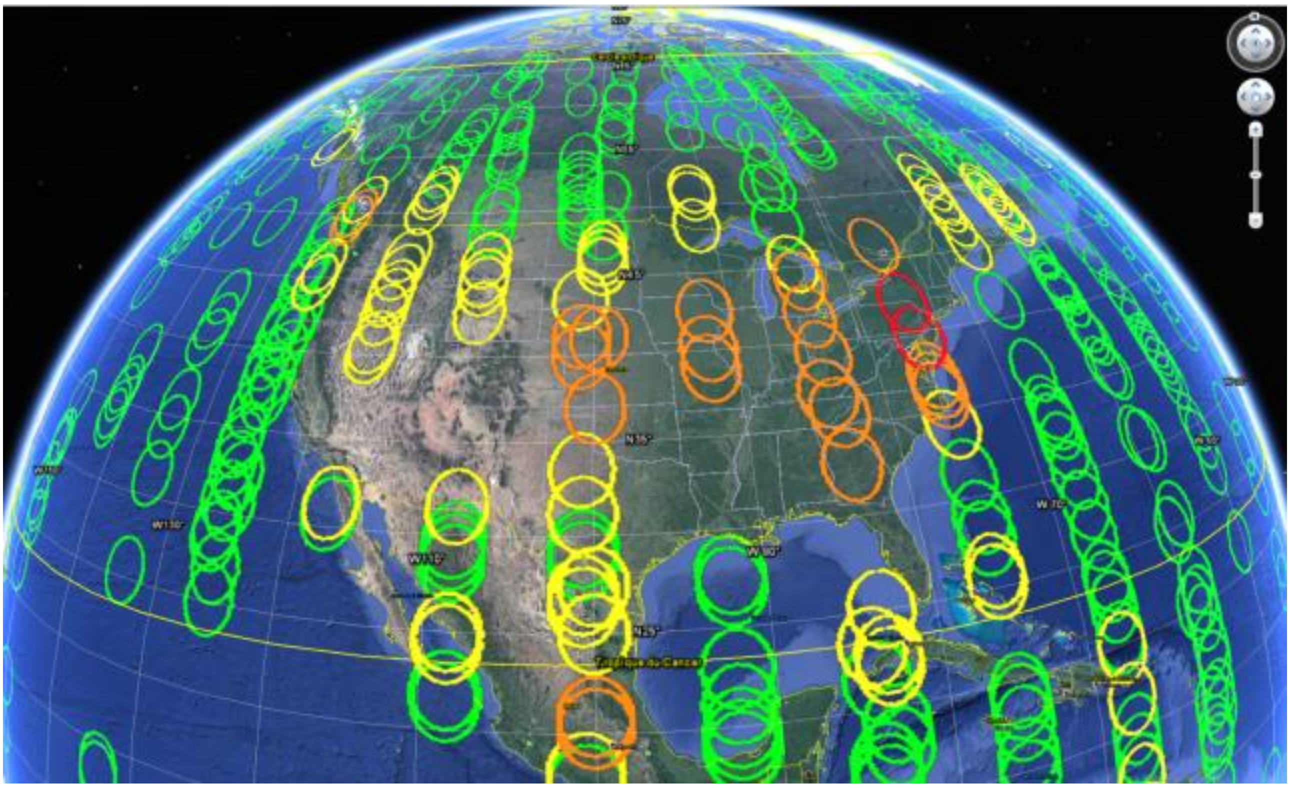


FIGURE A6-14

Locations of spot beams simulated over the northern part of Region 3. Green beam: fewer than 50 aircraft in the area. Yellow beam: between 50 and 100 aircraft. Orange beam: between 100 and 400 aircraft. Red beam: more than 400 aircraft

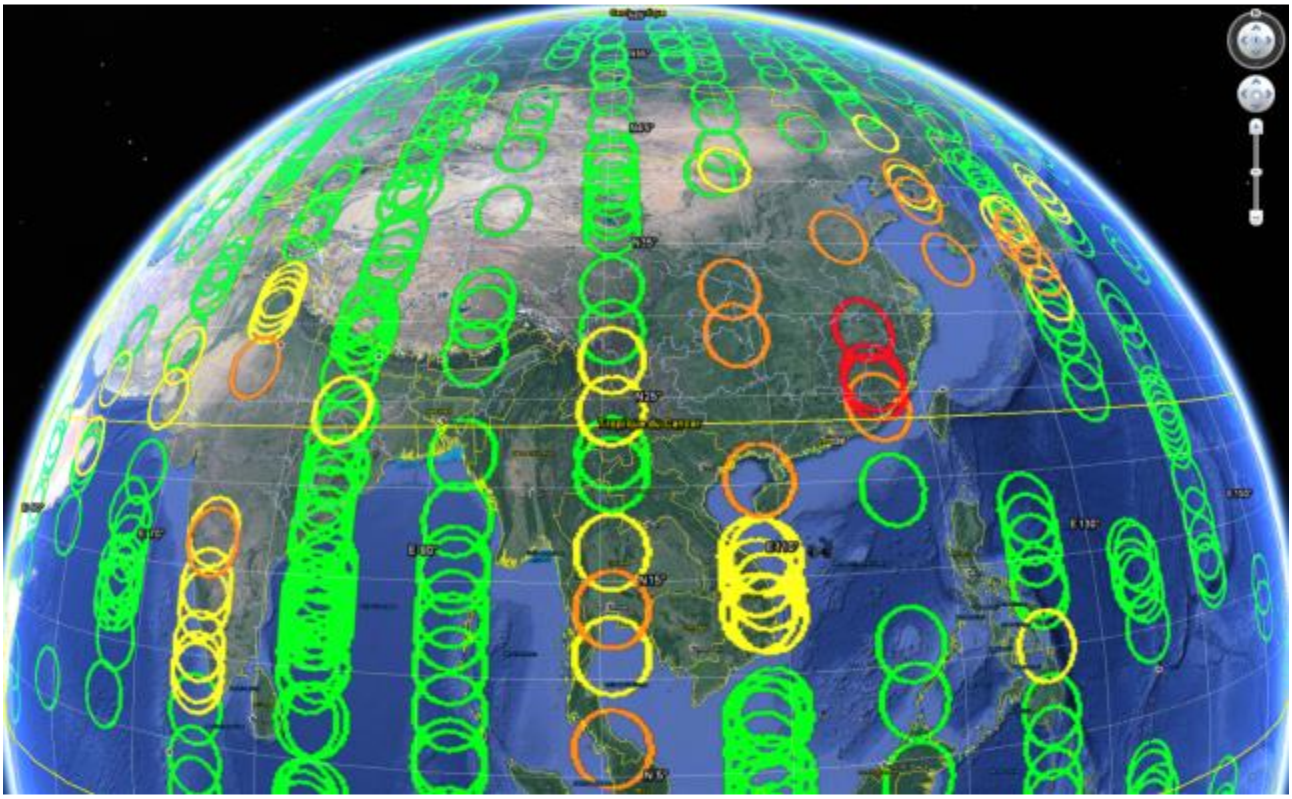


Figure A6-15 shows the evolution of the percentage of messages with location information decoded by the receiver as a function of the aircraft count in the spot beam. The degradation in percentage of "located aircraft" for low numbers of aircraft (until around 40), is linked to the spatial distribution of aircraft in the spot beam associated to the distribution of aircraft with a low power transmitter. As described in § 5.2, in this situation, it is possible to find some aircraft within the ring of 58 km presenting the lowest gain. The percentage is low not due to the collision between ADS-B message with location information, but only because some or all aircraft presenting a low power transmitter are in this ring and so are not detected. Between 40 and around 100 aircraft, the spatial distributions of aircraft are more homogenous and therefore their number is not sufficient to produce too many collisions (between 80% to 100% of aircraft could be located during 10s). From around 100 aircraft and above, the cause of the "located aircraft" degradation is the collision of ADS-B messages between aircraft. In order to avoid the issue relative to the spatial distribution (even if this situation occurs in reality), the cumulative distribution is based on a minimum number of aircraft equal to 30.

FIGURE A6-15

Percentage of messages with location information decoded by the receiver as a function of the aircraft count in the spot beam

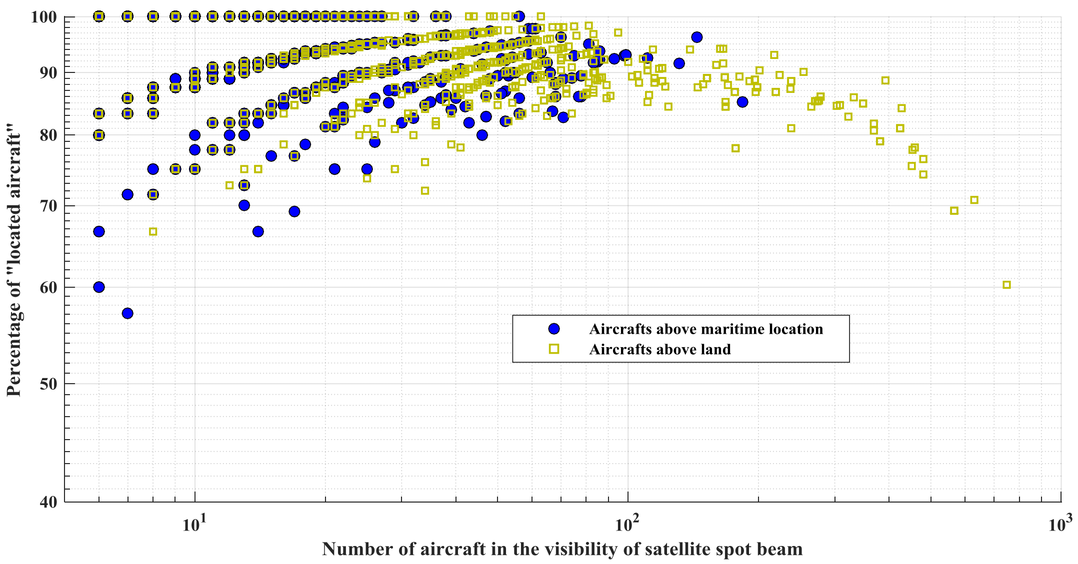


Figure A6-16 presents the cumulative distribution function of the number of ADS-B messages with location information decoded as a function of percentage of time (linked to the percentage of satellite position). This figure shows that:

– 32% of the time, all aircraft are located because at least one ADS-B messages with location information by aircraft is decoded by the satellite receiver during a 10s period;

– About 70% of aircraft can be located almost 100% of time. As a comparison with Fig. A6-12, for the satellite position with a coverage of 750 aircraft, the number of "located aircraft" is around 60% during a 10s period.

FIGURE A6-16

Overall cumulative distribution function of the number of automatic dependent surveillance-broadcast messages with location information decoded as a function of percentage of time. (Distribution built with all satellite positions)

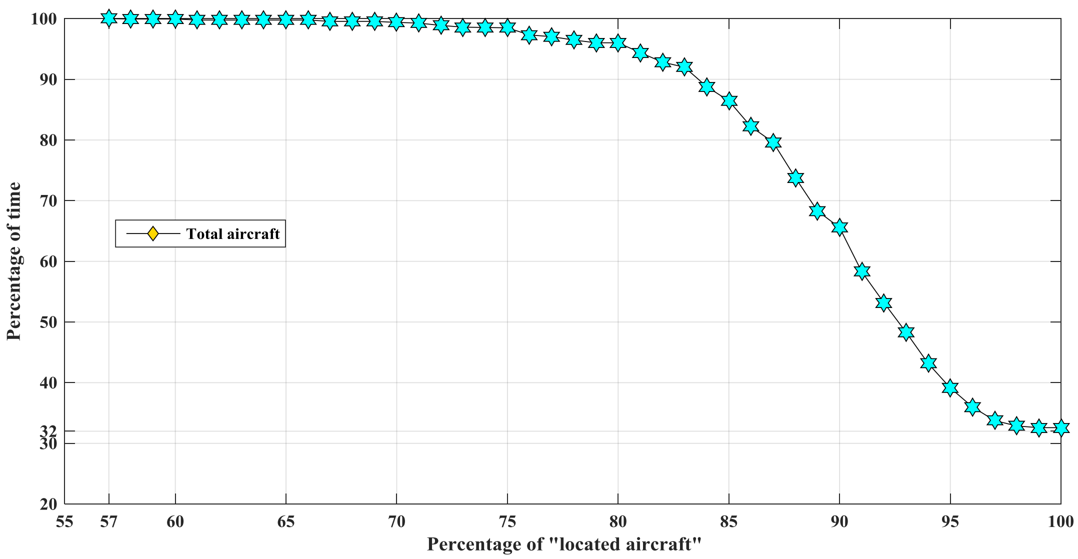


Figure A6-17 presents the cumulative distribution function of the number of ADS-B messages with location information decoded as a function of percentage of time, considering only the satellite position above land. This figure could be summarized as:

1) More than around 60 % of aircraft are located 100% of time during a 10s period;

2) 24% of the time, all aircraft are located because at least one ADS-B message with location information from the aircraft is decoded by the satellite receiver during a 10s period.

FIGURE A6-17

Cumulative distribution function of the number of automatic dependent surveillance-broadcast messages with location information decoded as a function of percentage of time. (Distribution built only with the satellite position above land)

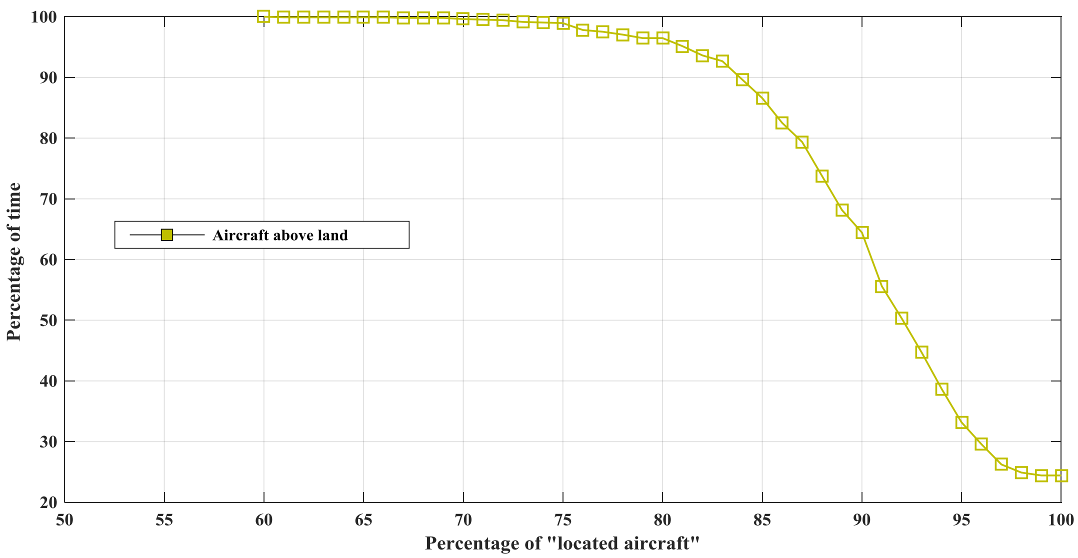


Figure A6-18 presents the cumulative distribution function of the number of ADS B message with location information decoded as a function of percentage of time, considering only the satellite position above sea/ocean. This figure could be summarized as:

1) More than around 57 % of aircraft are located 100% of time during a 10s period;

2) 43% of the time, all aircraft are located because at least one ADS-B message with location information from the aircraft is decoded by the satellite receiver during a 10s period.

FIGURE A6-18

Cumulative distribution function of the number of automatic dependent surveillance-broadcast messages with location information decoded as a function of percentage of time. (Distribution built only with the satellite position above sea/ocean)

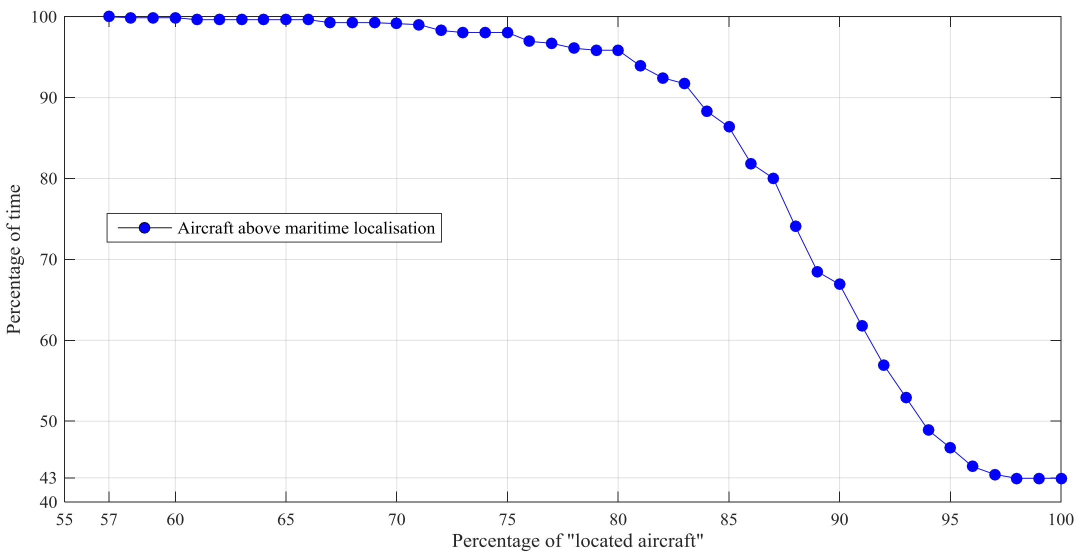


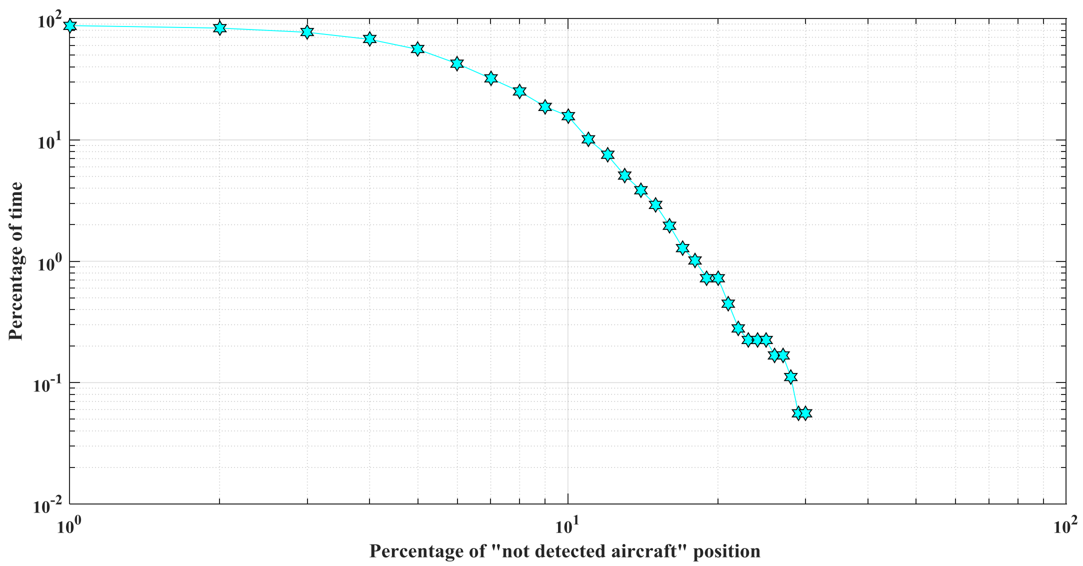
Figure A6-19 presents the cumulative distribution function of the number of aircraft positions that are in the line of sight in the spot beam but not detected by the receiver. This figure could be summarized as:

1) 90% of positions in the spot beam are always detected.

2) For a very low percentage of time, less than 0.1%, 30% of the positions in the spot beam are not detected. As mentioned before, this situation appears clearly during the simulation cases where only a few aircraft are present in the spot beam.

FIGURE A6-19

Cumulative distribution function of the percentage of not "detected position" in the satellite spot beam. Distribution built with all satellite



A6-5 Conclusion

On the basis of the study undertaken, and considering the assumptions, in particular the period of 10 seconds to locate an aircraft when at least one ADS-B message containing position information is received, it is possible to conclude that:

1. The reception probability of ADS-B messages in ocean areas or over isolated land masses is close to 100% more than 43% of the time, and always at least 57%.
2. Nevertheless, this reception is significantly affected over areas with particularly dense air traffic, notably over a large part of Europe, the eastern part of the United States and the whole of eastern Asia, where reception quality may fall to around 60% but in which the maximum of located aircraft never exceeds 90%

This contribution also highlights that the satellite receiver sensitivity is a key factor for determining accurately the system's capacity to decode ADS-B messages for aircraft equipped with low signal transmitter. As described in § A6-4.2, for the receiver used, 16% of the world's fleet could not be located accurately more than 16% of the time.