

ADS-B and Functions for Flight Inspection

Frank Musmann, *Aerodata AG*

BIOGRAPHY

Frank Musmann

Dipl.-Ing. Aeronautical Engineering, Technical University of Braunschweig

Main subject: Flight Guidance and Control

With Aerodata AG, since 2000

Responsibilities:

- Project management
- Flight inspection system design
- Development of AFIS cockpit flight guidance and autopilot interfaces
- Development of moving map applications for AFIS and cockpit displays
- Development of RNAV/RNP procedure inspection capabilities
- Development of GBAS inspection capabilities
- Certification of flight inspection systems and aircraft modifications
- Private pilot & flight instructor, aerobatic, >2300 flight hours

ABSTRACT

Automatic Dependent Surveillance Broadcast (ADS-B) provides functions for surveillance of aircraft and ground vehicles with high accuracy. The capability for ADS-B output will become mandatory for many aircraft very soon. A network of ADS-B ground stations is currently under installation. The requirements for flight inspection of ADS-B are not yet settled.

This paper introduces the most significant ADS-B performance parameter in the DF17 1090MHz extended squitter messages. Theoretically, ADS-B seems to be ideal for surveillance, but on the other hand a lot of problems can be observed in reality when analyzing ADS-B data transmitted by various aircraft. These typical problems during the use of ADS-B for air traffic surveillance are explained in detail. Based on these case studies desirable functions for the flight inspection of ADS-B ground stations are derived.

INTRODUCTION

Automatic Dependent Surveillance Broadcast (ADS-B) is a technique of broadcasting aircraft (or ground vehicle) parameter via a data link to other users of this data. ADS-B equipped aircraft transmit their identification, position, altitude, velocity and many other data for the purpose of surveillance. The position of the aircraft is determined by on-board equipment, like a GPS/GNSS receiver. ADS-B ground stations receive the broadcast data and provide it to a data network for display to air traffic controllers for surveillance. Surveillance means identifying aircraft or vehicle with their three dimensional position, in other words: “who is where and when”. For identification, a unique 24 bit ICAO address (Mode S address) is broadcast with each data message.

The on board equipment for transmission of ADS-B data messages is the Mode S Secondary Surveillance Radar (SSR) transponder. In contradiction to transponder replies to SSR interrogation, ADS-B data is transmitted “automatically” without interrogation from any ground station. For ADS-B out transmissions, the transponder is connected to various data sources:

Aircraft Equipment for ADS-B out via 1090ES:

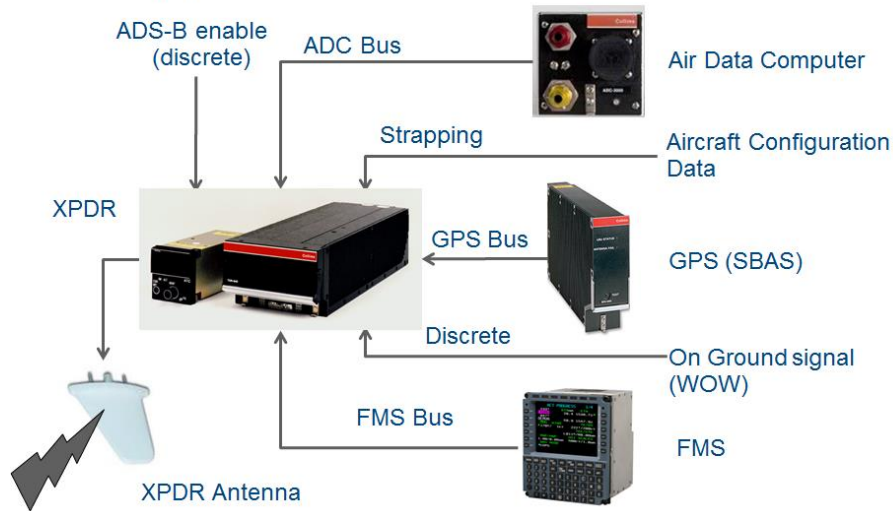


Figure 1 ADS-B block diagram

The Air Data Computer (ADC) provides air data parameter to the transponder, such as:

- Pressure Altitude
- Indicated Airspeed
- True Airspeed
- Vertical Speed
- Baro-Correction

Via hard coded strapping the transponder is configured for:

- 24 bit ICAO address
- Emitter Category (e.g.: Light or heavy aircraft, balloon or surface vehicle)
- Aircraft Length
- Aircraft Width
- GPS antenna longitudinal offset (GPS antenna offset from nose)
- On board data link capability
- On board ACARS capability
- System Design Assurance (SDA) level

The GPS/SBAS receiver provides Position, Velocity and Time (PVT) including quality factors for transponder:

- Latitude
- Longitude
- Velocity
- UTC Time
- Track angle
- Geoid height
- Integrity Limits
- Figure of Merit

A Weight On Wheels (WOW) strut switch provides information for Air/Ground detection.

The Flight Management System (FMS) is connected to the transponder to provide:

- Selected Heading
- Selected Altitude
- Roll angle
- Track angle rate
- True heading
- Radio altitude

An ADS-B enable/disable switch might be installed optionally, which allows inhibiting the transmission of ADS-B data. Disabling ADS-B might be desirable, if transmission of incorrect ADS-B data is detected for removing the false data from the surveillance display.

The data provided to the transponder is internally stored in Binary Data Store (BDS) registers. 256 internal BDS registers are defined, each containing 56 bit of ADS-B data payload. The internal registers are cleared by the transponder if the

corresponding data content is not updated within a fixed period by the data sources. For ADS-B out the following BDS registers are commonly used:

- BDS 05h Airborne Position
- BDS 06h Surface Position
- BDS 08h A/C Id & Category
- BDS 09h Airborne Velocity
- BDS 62h Target State and Status Message
- BDS 65h Aircraft Operational Status

These messages are transmitted in different transmission rates, depending on Air / Ground status and when on ground if the aircraft is moving or not:

- On Ground not moving (low rate ~ every 5 s)
- On Ground moving (high rate ~ every 0,5 s)
- Airborne (high rate ~ every 0,5 s)

The determination of the AIR/GND status is based on the Weight On Wheels strut switch and velocity and radio altimeter information. Normally the AIR/GND status is determined by WOW switch, but in case ground speed or indicated airspeed exceed 100kts the transponder transits into AIR mode regardless of the WOW switch. This should ensure proper data transmission in case of a blocked WOW switch. For transition to AIR mode some transponders also evaluate the radio altitude information. When Radio Altitude exceeds 50ft the transponder enters AIR mode.

Depending on AIR/GND status not only the ADS-B data transmission rate is increases, also the content of the messages changes. Other message types are transmitted when the aircraft is in AIR on GND. Correct function of AIR/GND status determination is essential for correct ADS-B data transmission!

ADS-B Messages

Position information is transmitted using an algorithm for data reduction. Within the airborne or surface position message, latitude and longitude are transmitted by just 17 bit. For precise position data 17 bit are not sufficient. For position report with the required accuracy, 34 bit are required. For that purpose an algorithm for Compact Position Report (CPR) is applied. This CPR algorithm composes different ODD and EVEN messages, which are transmitted alternating. High order bits are not transmitted in every message, resulting in accurate position resolution but with ambiguities. The position of an aircraft can only be determined unambiguously is the rough position of the aircraft is already known, or by receive of a pair of ODD and EVEN messages. The complexity of the algorithm and these ambiguities have significant potential for resulting in wrong position indication.

ADS-B Specifications

Allowable Failure Rate:

According to the ADS-B specification [1] the integrity of the ADS-B out system is classified to cause “major” failure conditions for most parameters in case of false data. Therefore, the allowable failure probability must be “remote” (less than 10^{-5} per operating hour). Only a few parameter are classified to cause only “minor” failure conditions, resulting in an allowable failure probability of “probable” (less than 10^{-3} per operating hour).

For most ADS-B parameters, only 1 failure per 100.000 flight hours is allowed. This requirement seems quite hard to achieve in reality. The experiences with ADS-B in the following will underline these concerns.

Latency:

The ADS-B specification [1] requires, that aircraft must transmit its geometric position no later than 2.0 seconds from the time of measurement of the position to the time of transmission. Within the 2.0 total latency allocation, a maximum of 0.6 may be uncompensated latency. The aircraft must compensate for any latency above 0.6 seconds up to the maximum 2.0 seconds by extrapolating the geometric position to the time of message transmission.

The transponder performs extrapolation of the position information provided by GPS/SBAS! Many things can go wrong during this “future position estimation”.

Performance Parameters:

In parallel to the aircraft position and velocity data broadcast by ADS-B also numerous performance parameters are transmitted. These parameters indicate the integrity and the accuracy of the position and velocity data. Air traffic surveillance displays will only accept ADS-B data with sufficient accuracy and integrity. The parameters are also used for the position fusion algorithms when data of different surveillance system, like SSR or Multi Lateration (MLAT) are used for indication of one aircraft position symbol on the air traffic controllers display.

The most important performance parameters are:

- Navigation Integrity Category (NIC): 95% Integrity Containment Radius of horizontal position based on Horizontal Protection Limit (HPL)
- Navigation Accuracy Category for Position (NACp): 95% Probability that the estimated position will be within a threshold. Estimated Position Uncertainty (EPU) based on Horizontal Figure of Merit (HFOM)
- Navigation Accuracy Category for Velocity (NACv): 95% velocity accuracy threshold based on figure of Merit for horizontal velocity (Horizontal Velocity FOM)

The transponder internally performs mapping of e.g. the HFOM into a NACp value in accordance with the ADS-B Minimum Operational Performance Standard (MOPS) [2] :

Coding		95% Horizontal Accuracy Bounds (EPU)	Comment
(Binary)	(Decimal)		
0000	0	EPU ≥ 18.52 km (≥ 10 NM)	Unknown accuracy
0001	1	EPU < 18.52 km (10 NM)	RNP-10 accuracy
0010	2	EPU < 7.408 km (4 NM)	RNP-4 accuracy
0011	3	EPU < 3.704 km (2 NM)	RNP-2 accuracy
0100	4	EPU < 1852 m (1 NM)	RNP-1 accuracy
0101	5	EPU < 926 m (0.5 NM)	RNP-0.5 accuracy
0110	6	EPU < 555.6 m (0.3 NM)	RNP-0.3 accuracy
0111	7	EPU < 185.2 m (0.1 NM)	RNP-0.1 accuracy
1000	8	EPU < 92.6 m (0.05 NM)	e.g., GPS (with SA on)
1001	9	EPU < 30 m	e.g., GPS (SA off)
1010	10	EPU < 10 m	e.g., WAAS
1011	11	EPU < 3 m	e.g., LAAS
1100	12	Reserved	
1101	13	Reserved	
1110	14	Reserved	
1111	15	Reserved	

Figure 2 NACp Coding [2]

The corresponding tables are programmed to the transponder software.

Surveillance systems require minimum performance e.g.: NACp > 7 (EPU ≤ 0.1 NM) for surveillance use.

Other important parameters are:

- Source Integrity Level (SIL): Probability that the reported horizontal position exceeding the radius of containment as defined by NIC without alerting. Static value derived from the kind of position source and its integrity. The SIL does not consider avionic faults.
- System Design Assurance (SDA): Probability of an avionics fault causing the reported horizontal position to exceed the radius of containment as defined by NIC, without alerting. Static value dependent on installation (based on System Safety Assessment)

Table 2-72: “SIL” Subfield Encoding

SIL Coding		Probability of Exceeding the NIC Containment Radius (R_c)
(Binary)	(Decimal)	
00	0	Unknown or $> 1 \times 10^{-3}$ per flight hour or per sample
01	1	$\leq 1 \times 10^{-3}$ per flight hour or per sample
10	2	$\leq 1 \times 10^{-5}$ per flight hour or per sample
11	3	$\leq 1 \times 10^{-7}$ per flight hour or per sample

Figure 3 SIL Coding [2]

Typical values:

- SIL = 3 ($\leq 10^{-7}$ per flight hour) when using GPS.
- SDA = 2 ($\leq 10^{-5}$ per flight hour) when GPS receiver is directly connected to the transponder

ADS-B Experience

ADS-B provides a huge number of parameters for surveillance use. ADS-B is a complex system that contains high potential for transmitting incorrect ADS-B data.

Incorrect Installations:

Typical problems are related to false or intermittent strapping configuration resulting in false SIL, SDA, Emitter Category or Mode S-Address. Other problems might result from incompatibility between the transponder and the connected GPS/FMS equipment. The individual combination of the transponder and the GPS/FMS equipment must be tested and approved regarding compliance with ADS-B requirements. Whenever one of the ADS-B data sources or the transponder itself is modified (e.g. FMS software upgrade or GPS receiver upgrade) all ADS-B functions must be tested again to ensure proper operation. Aircraft maintenance organizations might not be aware of such impacts to ADS-B when performing FMS upgrades. In order to be able to check ADS-B for proper function, detailed knowledge of the content in ADS-B messages is required.

Incorrect input to transponder:

ADS-B surveillance becomes unavailable in case of GNSS problems like interference, jamming or spoofing.

Incorrect transponder behavior:

The ADS-B MOPS [2] require implementation of numerous software algorithms in the transponder. Avionic manufacturers seem to struggle with these requirements. Transponder problems are often related to:

- incorrect AIR / GND determination
- Incorrect position extrapolation

Numerous Service Bulletins (SB) and Airworthiness Directives (AD) have been issued for transponders. All avionic manufacturers are effected.

GNSS receiver related problems:

Many GNSS receivers do not output velocity accuracy output (Horizontal Velocity FOM). In such installation, a typical value for HFOM velocity is strapped during installation, resulting in possible problems during position extrapolation. HPL calculations when based on RAIM are only accurate to about 0.1 NM however many GNSS receiver can output a much smaller HPL resulting in a too optimistic integrity.

Systematic Problems of certain aircraft types:

Many problems have been identified in certain types of aircraft. Also state-of-the-art aircraft are effected. The Boeing B787 for example has been blacklisted in Canada and Australia. Examples of B787 issues are illustrated in the following:

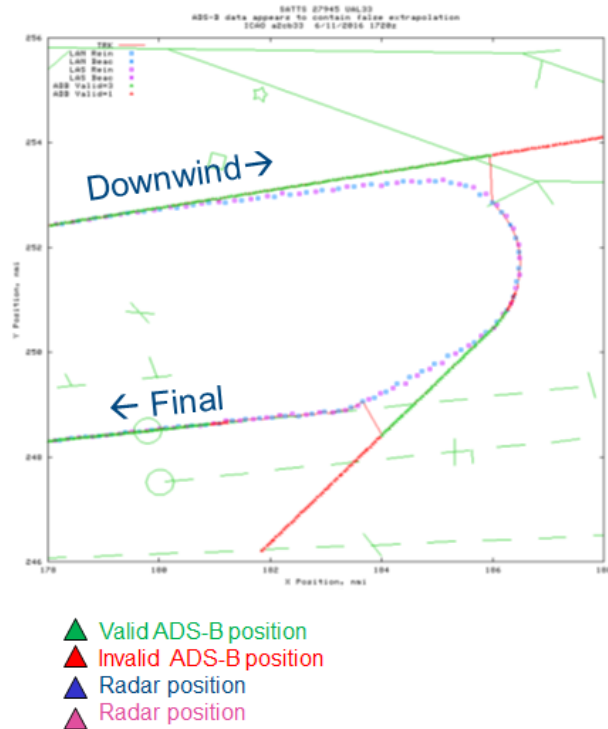


Figure 4 Typical B787 issue ([3])

The aircraft was on a traffic pattern downwind position. During the base turn the ADS-B position was a straight ahead extrapolation, while the position determined by SSR indicated the correct flight path. As similar wrong extrapolation occurred during turn to final. Although the ADS-B position was obviously wrong, the ADS-B quality parameters were labeled “good”. The problem was not detected until the ADS-B position differed by 0,57 NM from the SSR position. The following figure shows other typical B787 issues with obviously wrong ADS-B data:

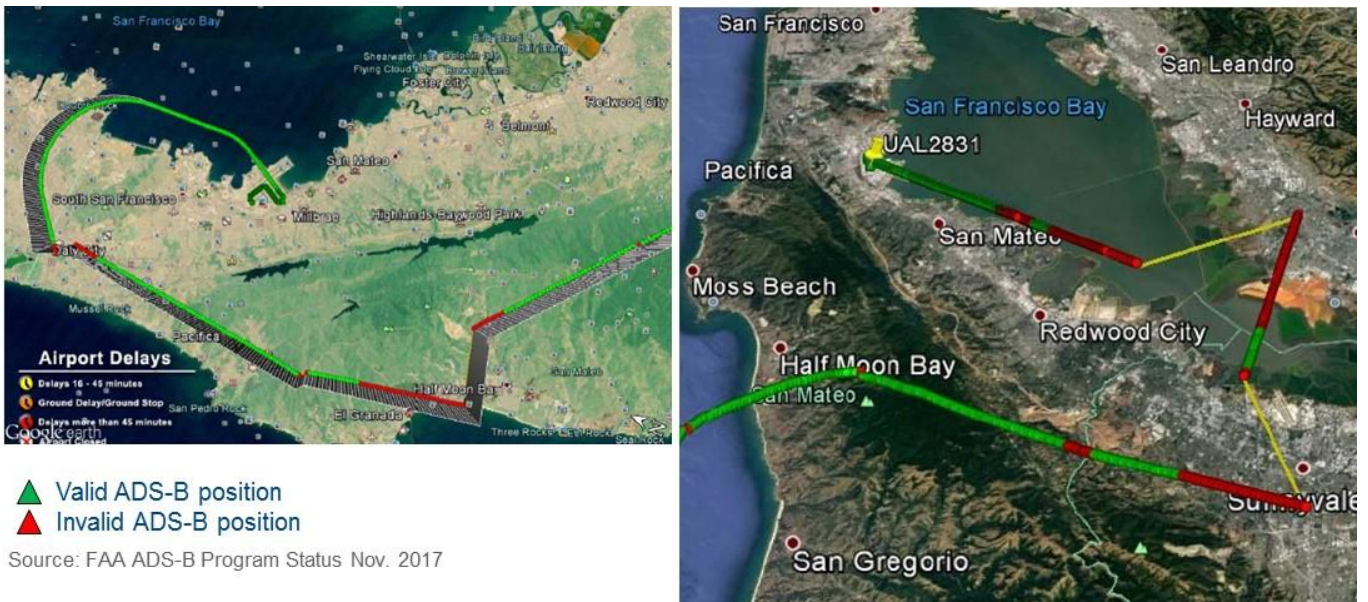


Figure 5 B787 issues ([3])

In the ADS-B Implementation and Operations Guide [4] , ICAO has established a database with known ADS-B issues. In this database various cases with ADS-B position jumps and erroneous position data can be found:

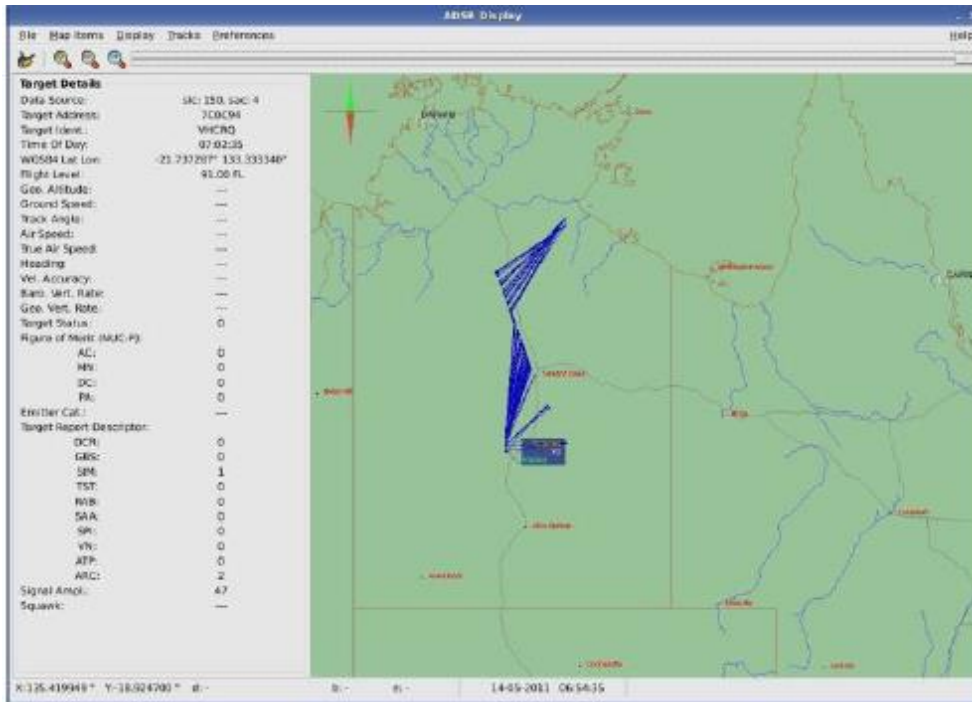


Figure 6 Erroneous Position Data [4]

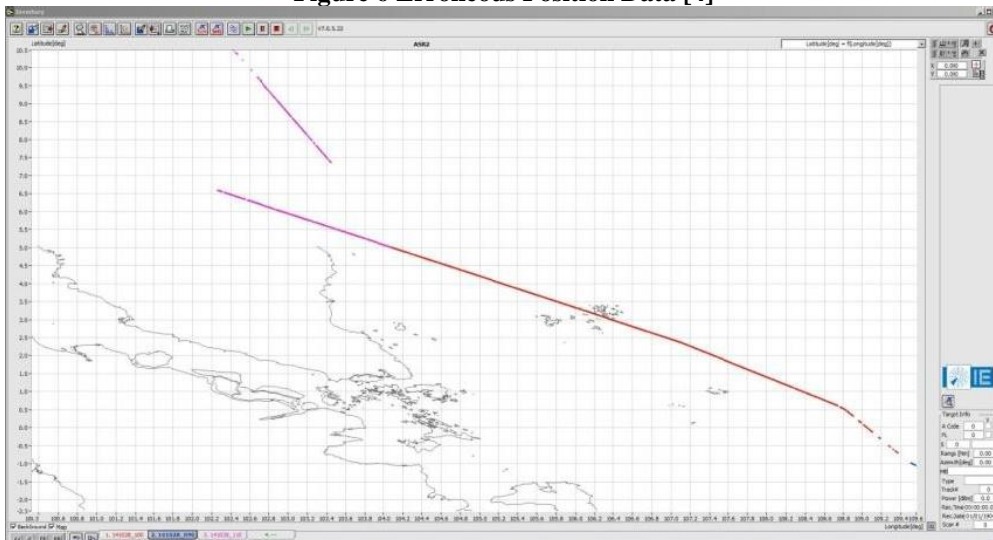


Figure 7 Position Jumps [4]

In order to avoid incorrect ADS-B data, aircraft are tested by avionic maintenance personnel after installation of ADS-B. Such tests must also be repeated after any change to the data sources used for ADS-B. Test equipment is available that can display all BDS data transmitted by the ADS-B transponder. Due to the huge number of parameters and transponder internal table-mapping (e.g. NIC value based on HPL) it is extremely difficult for maintenance personnel to decide whether the displayed data is complete and correct or not.

Example BDS 05h Airborne Position

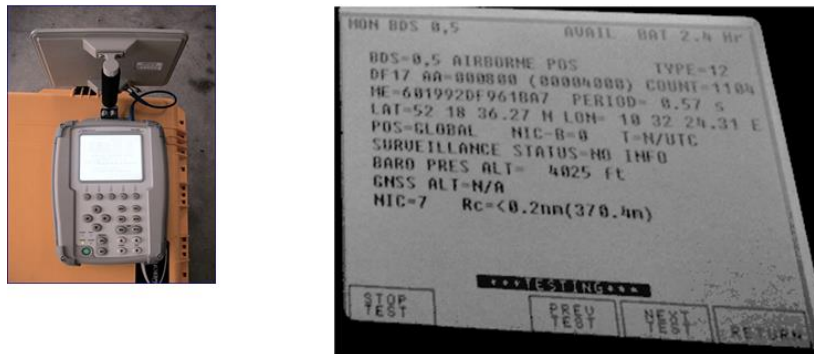


Figure 8 ADS-B Test Equipment

For example: the Airborne Position message (BDS 0,5h) indicates GNSS Altitude “N/A (not available)”. On the first glance, one might think that this data is missing on the transponders input from the GNSS receiver. Only with detailed knowledge about ADS-B message content an avionic installer is able to understand that this is normal. Airborne Position Messages with Type Code 9-18 contain only Barometric Altitude (and no GNSS Altitude), while Airborne Position Messages with Type Code 20-22 contain GNSS altitude (and no Barometric Altitude). Preferable Barometric Altitude is reported by ADS-B when Barometric Altitude and GNSS Altitude is available to the transponder. Therefore, GNSS Altitude “N/A” on message type code 12 is normal.

Surveillance Sensor Fusion

A surveillance system for air traffic management might be based on data from different systems e.g.: Secondary Surveillance Radar (SSR), Multi Lateration (MLAT), Primary Surveillance Radar (PSR) and ADS-B. The air traffic controller needs only one symbol for the aircraft position indication on the screen. Therefore, the position data provided by the different systems is fed to an algorithm (e.g. Kalman filter) that calculates the most likely position of the aircraft. The different systems are weighed according to their position quality. It can be expected that strange results might be the output is the position data of the different systems differs:

PSR Position



ADS-B Position,
with NACp indicating high accuracy

Where to place the traffic symbol on ATC screen?

Figure 9 Sensor Fusion with Uncorrelated Position Data

Since the ADS-B targets claim to know their own accuracy, integrity and design assurance level, the ADS-B position report might “win” in the sensor fusion process if performance parameter indicate good quality. It becomes obvious that NAC, SIL and SDA are essential for the sensor fusion. As the experiences with ADS-B demonstrate, many aircraft today are reporting wrong values.

For save operation correct sensor fusion, even under abnormal conditions (abnormal ADS-B values not correlating with other surveillance systems) is essential and should be subject of ADS-B flight inspection.

Flight Inspection Requirements

Flight inspection requirements for ADS-B are not settled today. Based on the above-described experiences with ADS-B and the possible problems during sensor fusion in the ATM system the following flight inspection requirements have been compiled:

- The flight inspection equipment shall be able to record all input data (ADC, GPS and FMS) to the transponder. In comparison to ADS-B data recording on ground it serves for detection of coverage gaps where ADS-B data transmitted by aircraft cannot be received on ground.

- The recording shall be time synchronized with GPS and or UTC in order to allow time synchronization and for checking the overall system latency.
- The ADS-B ground system and the integration to the ATM system shall be checked and evaluated under normal conditions (good correlation between SSR, PSR and ADS-B)
- The flight inspection equipment shall be able to simulate abnormal ADS-B data. The abnormal ADS-B data shall be used to check the behavior of the ATM system under abnormal conditions, where ADS-B data differs from other systems.
- The following parameters shall be modifiable:
 - o Latitude
 - o Longitude
 - o Altitude
 - o NIC (HPL)
 - o NACp (HFOM)
 - o NACv (Horizontal Velocity FOM)
 - o SDA
 - o Emitter Category

AFIS Implementation

Base on the derived requirements for ADS-B flight inspection, an ADS-B capable transponder (Rockwell Collins TDR94, -501) is integrated to the AFIS. In contradiction to standard aircraft installation, the AFIS Realtime computer System (RTS) serves as data source for the transponder:

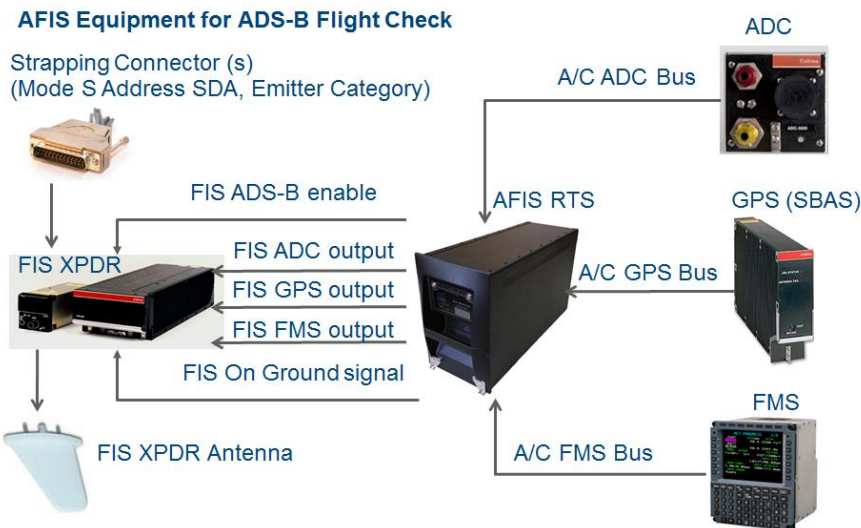


Figure 10 ADS-B in AFIS Block Diagram

The RTS receives ADC, GPS and FMS data from the aircrafts avionic and directly forwards this data to the transponder. The WOW input signal can be individually controlled from the RTS independent from the real WOW strut switch in the aircraft. This allows transmitting ADS-B AIR and GND messages as well as simulating problems with WOW strut switch. Aircraft strapping is realized by a connector. The Mode S address is configured to the connector as well as the aircraft specific ADS-B configuration like: SDA, Emitter Category, GPS Antenna longitudinal offset, aircraft width and length. By installing connector with different strapping, one can simulate other types of aircraft or surface vehicles. The AFIS software allows to “user modify” important ADS-B input parameters. A position offset can be applied to the true position as input to the transponder for simulating ADS-B data non-correlated with SSR/PSR:

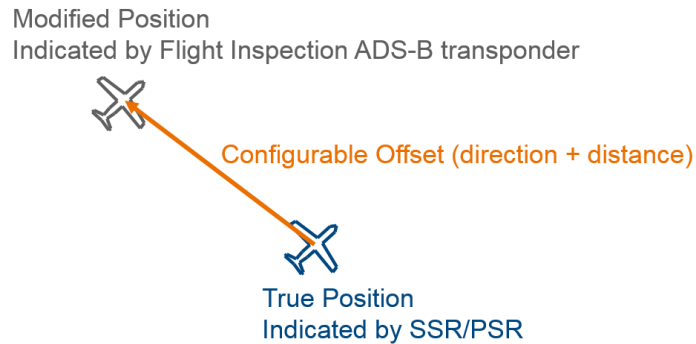


Figure 11 Configurable Position Offset

The GNSS and Barometric altitude input to the transponder can be “user modified” for simulating an aircraft that triggers the Minimum Safe Altitude Warning (MSAW) without actually flying in such conditions:

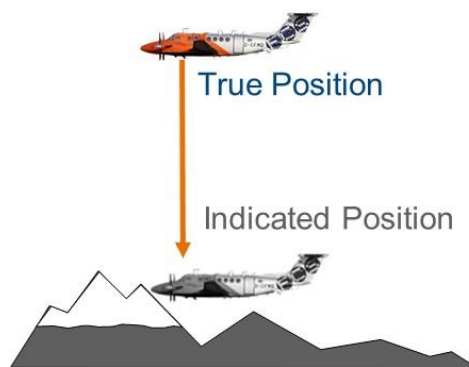


Figure 12 Configurable

The relevant ADS-B performance parameters can be “user modified” for simulating poor- or extremely good navigation quality.

The total the following parameters can be user modified via the AFIS software:

- Position (with configurable Position Offset to create offset to SSR/PSR)
- Baro. Pressure Altitude
- GNSS Altitude
- HIL (for modified NIC)
- HFOM (for modified NACp)
- HFOM Velocity (for modified NACv)
- VFOM

The ADS-B output can be enabled or disabled from the AFIS. With this feature, it is possible to simulate loss of ADS-B out without losing SSR replies. The transponder still replies to SSR interrogations but does not transmit ADS-B data.

AFIS Software

All transponder input is displayed and recorded by the AFIS. The following figure shows the ADC data input to the transponder, as well as the switch for enabling/disabling ADS-B output and the AIR/GND switch:

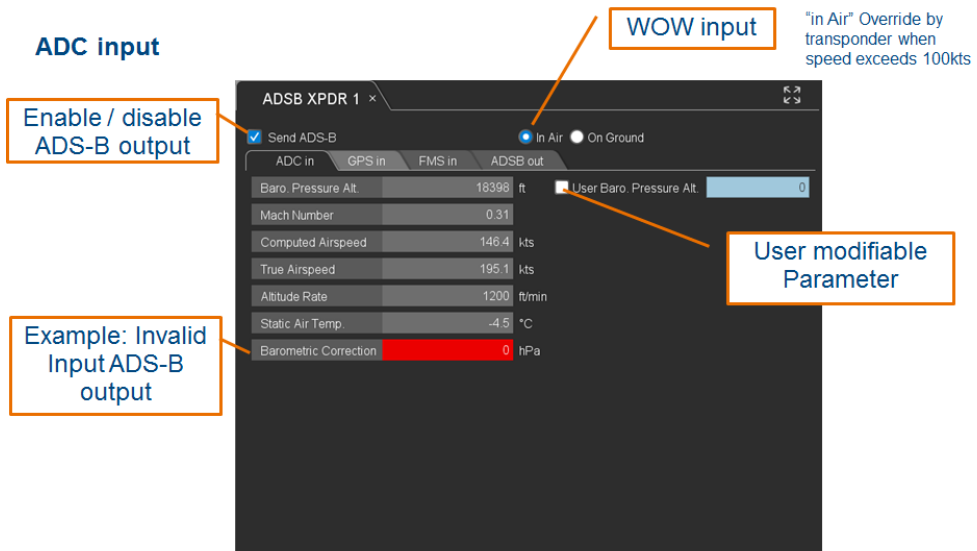


Figure 13 ADC Input Data

The following figure shows the GPS input window with configurable Position Offset and “user modifiable” performance parameters:

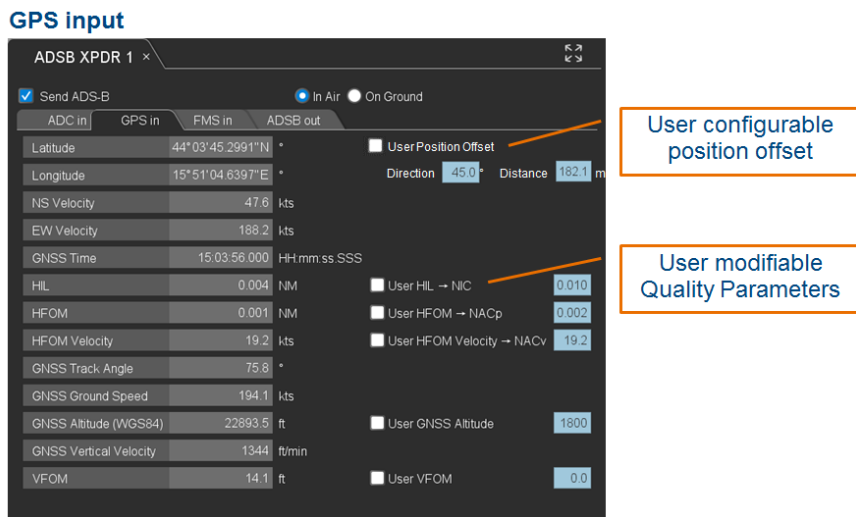


Figure 14 GPS Input Data

The next figure shows the FMS input data with an example of invalid input data (highlighted in red):

FMS input

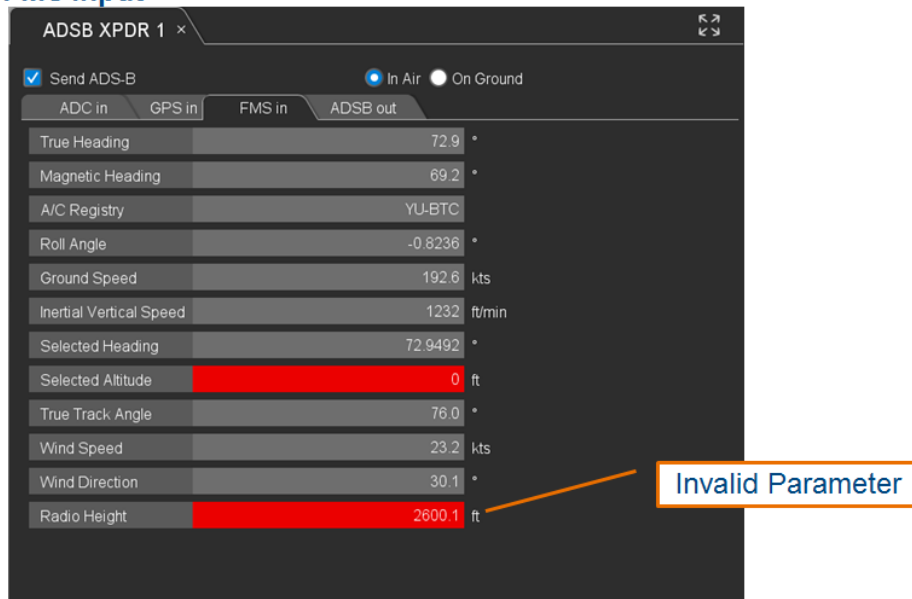


Figure 15 FMS Input Data

The ADS-B output data window directly shows the resulting ADS-B performance parameter, that result from the input. The AFIS software performs the data mapping according to [2]

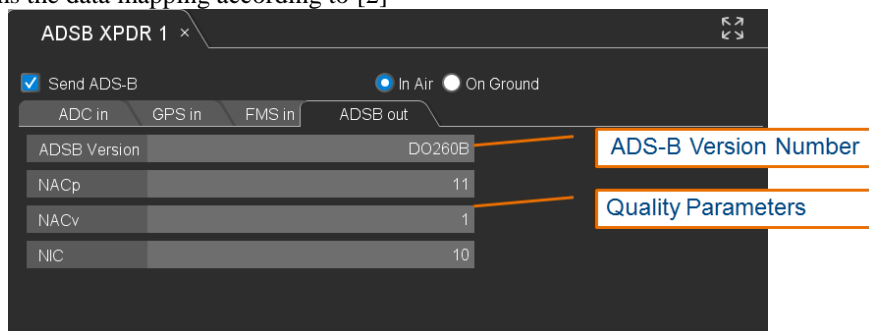


Figure 16 ADS-B Output Data (Performance Data)

All transponder input data can be exported to an ASCII text file for post flight evaluation in comparison to ADS-B or ATM ground recordings. The GPS UTC time serves for time synchronization of the recordings. The parameter set, the output rate and the unit can be individually configured as required:

ADS-B ASCII output configuration

ASCII export configuration		
General		Channel Selection
Parameter	Number format	Unit
GPSTime_UTC	decimal	HH:mm:ss.SSS
GPSTime_UTC	decimal	s.SSS
XPDRFmsSelectedAltitude	decimal	ft
XPDRAdcBaroAltitude	decimal	ft
XPDRAdcMachNumber	decimal	
XPDRAdcComputedAirSpeed	decimal	kts
XPDRAdcTrueAirspeed	decimal	kts
XPDRAdcAltitudeRate	decimal	ft/min
XPDRAdcStaticAirTemperature	decimal	K
XPDRAdcBarometricCorrection	decimal	hPa
XPDRGpsLatitude	decimal	°
XPDRGpsLongitude	decimal	°
XPDRGpsNsVelocity	decimal	kts
XPDRGpsEwVelocity	decimal	kts
XPDRGpsGnssTime	decimal	s
XPDRGpsHil	decimal	NM
XPDRGpsHfom	decimal	NM
XPDRGpsHfomVelocity	decimal	kts
XPDRGpsGnssTrackAngle	decimal	°
XPDRGpsGnssGroundSpeed	decimal	kts

ASCII File output for Post Flight Analysis in comparison to ATM Ground Recording

```

-----+-----
: 24 : 26
: XPDRGpsLatitude : XPDRGpsLongitude
: [°] : [°]
-----+-----
O 44.04019782438991 O 15.727188556069448
O 44.040241409587864 O 15.727360217446401
O 44.040241409587864 O 15.727428160811542
O 44.040241409587864 O 15.727428160811542
O 44.04028533341625 O 15.727667426923288
O 44.04032934123097 O 15.727907619548205
O 44.04032934123097 O 15.727907619548205
O 44.04037334903842 O 15.728146801677214
O 44.04037334903842 O 15.728146801677214
O 44.04041685026186 O 15.728386154463806
O 44.04041685026186 O 15.728386154463806
O 44.0404607740893 O 15.728557815840759
O 44.0404607740893 O 15.728625423260382
O 44.0404607740893 O 15.728625423260382
O 44.04050469792128 O 15.728864353433892
O 44.04054862174962 O 15.729103454264987
O 44.04054862174962 O 15.729103454264987
O 44.04059206955126 O 15.729342216473015
O 44.04059206955126 O 15.729342216473015
O 44.040631307796 O 15.72958123331773
O 44.040631307796 O 15.72958123331773
O 44.040679970625206 O 15.729820166176067
O 44.040679970625206 O 15.729820166176067
O 44.040679970625206 O 15.729820166176067

```

Figure 17: ASCII File Output

SUMMARY

A large number of parameters are transmitted by an ADS-B out capable aircraft. Due to the complexity of the ADS-B MOPS [2] many functions are implemented in software inside the transponder. The ADS-B system is a complex system. Checking ADS-B aircraft installations for proper function is not a simple task. Even when using special ADS-B test sets a lot of knowledge about DS-B message content is required. Due to the complexity there is a big potential for transmission erroneous data. Many ADS- Problems are already known from experience. Problems during Sensor Fusion of ADS-B and other surveillance systems are very likely. Therefore the reaction of the ATM surveillance system to wrong ADS-B input should be subject of flight inspection. An AFIS with ADS-B capability for simulation of abnormal ADS-B data in combination with SSR, MLAT and PSR data can be used for testing ATM systems during ADS-B commissioning to ensure proper sensor fusion under such conditions.

REFERENCES

- [1] EASA, Certification Specifications and Acceptable Means of Compliance for Airborne Communications, Navigation and Surveillance, CS-ACNS, initial issue, December 2013
- [2] RTCA DO-260B, Minimum Operational Performance Standards for 1090ES ADS-B and TIS-B. December 2, 2009 © 2009, RTCA, Inc
- [3] FAA, ADS-B Program Status Nov. 2017, presented during ICAO NAM/CAR/SAM ADS-B Implementation Meeting & Workshop
- [4] ICAO, ADS-B Implementation and Operations Guidance Document, 10. Edition, June 2017