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Evaluation of the Capability of Automatic Dependent Surveillance Broadcast to Meet the Requirements of Future Airborne Surveillance Applications

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Automatic Dependent Surveillance Broadcast (ADS-B) Out supports various ground applications including Air Traffic Control (ATC) surveillance in radar airspace, non-radar airspace and on the airport surface. In addition, the capability of aircraft to receive ADS-B Out messages from other aircraft within their coverage (ADS-B In) enables enhanced airborne surveillance applications. The requirements of the application vary depending on its safety-criticality. More stringent applications will require higher levels of performance. It is therefore critical that the ADS-B system performance is measured against the most stringent application it is designed for. This paper reviews the various enhanced airborne surveillance applications and the required ADS-B information to support them. It identifies the ADS-B based applications required for Air Traffic Management (ATM) modernisation under the SESAR/NextGen programs. It discusses existing ADS-B Out versions and their capabilities. A mapping exercise is undertaken to assess the credibility of the ADS-B system performance to support the functionalities and requirements of the various enhanced airborne surveillance applications and establish those that require further research and development, highlighting some of the key challenges.

KEYWORDS

1. ADS-B. 2. Airborne surveillance. 3. ATSAW. 4. Performance requirements.

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1. INTRODUCTION. The evolution of navigation and surveillance technologies is a key element of the modernisation of Air Traffic Management (ATM), to enable better planning and thereby increase capacity and efficiency without jeopardizing safety and the environment. The Single-European-Sky ATM Research (SESAR, 2012) and Next Generation Air Transportation System (Federal Aviation

Administration (FAA), 2010; 2012) initiatives recognise that at the core of more efficient navigation is the need to integrate aircraft operations as a seamless continuum and to involve all relevant stakeholders, including airspace users, air navigation service providers, airport operators and the military in the decision making process. This requires the capability to provide shared Air Traffic Situational AWareness (ATSAW) with high accuracy and integrity aircraft state information. This capability is envisioned through the Automatic Dependent Surveillance-Broadcast (ADS-B) system. High-performance surveillance systems have the potential to increase both airspace efficiency (and thereby capacity) and safety, by improving the capability to perform the necessary synchronisation and separation activities in advance, making it possible to use an optimised strategic approach to the integration of traffic instead of the current inefficient tactical process. Therefore, performance and reliability of the ADS-B system will be a major factor in future ATM performance. Optimal integration of air traffic will be achieved on the basis of various Concept of Operations (ConOps) elements (i.e. applications) that each require surveillance information with specific levels of performance.

To date, no studies are available in the public domain, investigating real time ADS-B quantitative performance and information available in the ADS-B messages transmitted to other aircraft or Air Traffic Control (ATC) on the ground to support the future enhanced aircraft surveillance applications. However, flight tests have been performed for some of the applications. The CRISTAL-ITP Project (EUROCONTROL, 2009) concluded that the quality of the ADS-B Out information from the reference aircraft in terms of update interval, accuracy and integrity as received was sufficient to support an In Trail Procedure (ITP) flight trial. The data recorded from the trial also showed that the received ADS-B Out information was compliant with ATSAW-ITP Safety Performance Requirements (Radio Technical Commision for Aeronautics (RTCA), 2008).

Furthermore, ATSAW has been operational in Europe since February 2012 under the ATSAW Pioneer project CASCADE in cooperation with airlines, Air Navigation Service Providers (ANSPs) and avionics manufacturers to provide an airborne traffic situation to the flight crew. The objective of the ATSAW project is to assist airlines in equipping aircraft with certified ATSAW equipment and use it in their operations. The ATSAW equipage is voluntary and no mandate is envisaged in Europe. The project is conducting two operational applications; ATSAW during flight operations (ATSAW AIRB) and the ATSAW ITP over the North Sea (Shanwick FIR and Reykjavik FIR). Six airlines equipped 28 aircraft with the ATSAW equipment, including British Airways, Delta, Lufthansa, Swiss International Airlines, US Airways and Virgin Atlantic. The ATSAW Pioneer project marked the first operational use of surveillance in the cockpit in Europe and paves the way for the deployment of other “ADS-B In” applications (Rekkas, 2013). In the United States, NASA has been developing and testing the Traffic Aware Strategic Aircrew Requests (TASAR) concept for aircraft operations featuring a NASA-developed cockpit automation tool, the Traffic Aware Planner (TAP)(Wing, 2015).

This paper identifies the ground and airborne applications required to support the SESAR/NextGen ATM modernisation. It identifies the required ADS-B information and system performance to support the airborne applications. The paper assesses the real time ADS-B performance of 29 aircraft certified to the DO-260 standard (RTCA, 2003), based on opportunity traffic, and discusses the performance results. The paper maps the required performance and information to the actual ADS-B system

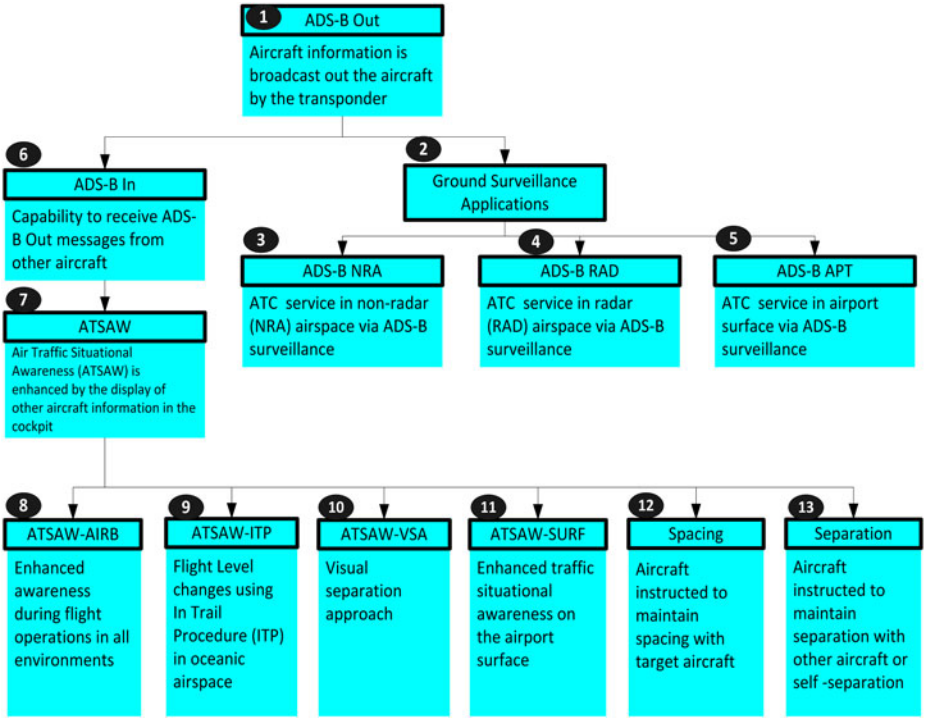

Figure 1. ADS-B system evolution.

performance and the information available in the ADS-B messages from the aircraft used in this study. The paper concludes with a discussion on the capability of the ADS-B system analysed in this paper to support the foreseen applications and specifies which of these applications can realistically be met with the ADS-B system.

2. ADS-B FOR THE FUTURE ATM SYSTEM MODERNISATION.

At the core of the future SESAR and NextGen ATM are advanced automation systems based on ADS-B. These must progressively fulfil a number of functions, as exemplified in Figure 1. This may not be an exhaustive and/or validated list of functions. These functions may evolve in the future.

The first step requires the aircraft to be equipped with ADS-B Out. The second step involves the implementation of ground surveillance applications for ATC including in Non Radar Airspace (NRA) (step 3), in Radar (RAD) airspace (step 4) and on the Airport surface (APT) (step 5). The implementation is conducted in sequence, based on the criticality of the limitations of the current radar system to support ATC to provide surveillance services to the aircraft. ADS-NRA has been fully implemented and is operational in various regions such as Australia while ADS-B RAD and ADS-B APT are still currently under trial. These applications are meant to provide radar-like services where the radar is unavailable, or to supplement the reduced radar services in a particular operational environment or airspace. Future applications envision providing enhanced surveillance services (e.g. reduced separation to aircraft) by exploiting the higher performance of ADS-B. However, these are still to be implemented due to a lack of confidence in the system performance and aircraft equipage.

The sixth step is the implementation of ADS-B In, which requires ADS-B In equipment to enable aircraft to receive ADS-B Out messages from other aircraft within their specified range. ADS-B In is a means to enable various airborne surveillance applications including providing ATSAW via display of other aircraft information to the flight crew. At present, pilots build traffic situational awareness by integrating information from two main sources: visual observation and radio communication with ATC. The radio communication includes traffic information provided to flight crew by a controller, transmission from a controller to other aircraft, and responses from other aircraft, and air-to-air radio communication outside controlled airspace. Additionally, to enhance situational awareness, pilots of suitably equipped aircraft may use their Traffic Collision Avoidance System (TCAS) traffic display to supplement the available traffic information. Even though the TCAS display is meant to support visual acquisition when the TCAS generates a Traffic Advisory (TA), in some cases it has confused the pilot's perception of the traffic situation (CASCADE Operational Focus Group, 2009). This causes unsynchronised situational awareness between pilots and ATC which may lead to undesirable incidents. According to EUROCONTROL (CASCADE Operational Focus Group, 2009), this particular situation has been one of the drivers of the development of airborne surveillance applications. ATSAW has led to the development of various surveillance applications: enhanced traffic situational awareness in all environments (ATSAW-AIRB), flight level changes using In-Trail Procedure (ITP) in oceanic airspace (ATSAW-ITP), visual separation approach (ATSAW-VSA) and enhanced traffic situational awareness on the airport surface (ATSAW-SURF). The successful implementation of the ground and airborne surveillance applications is underpinned by ADS-B Out performance that is sufficient for each of these applications. The next section describes the airborne applications, the operational environment and their requirements. This is followed, in the last section, by the performance of real time ADS-B being mapped to the requirements of these applications.

3. AIRBORNE SURVEILLANCE APPLICATIONS USING ADS-B.

This section reviews and discusses the various airborne surveillance applications envisioned with the ADS-B system, highlighted in Figure 1.

3.1. *Air Traffic Situational Awareness During Flight Operations (ATSAW-AIRB).*

ATSAW-AIRB is defined as the enhancement of a flight crew's knowledge of the surrounding traffic situation in all environments. It is meant to improve flight safety and operations by assisting flight crews in building their traffic situational awareness through the provision of an appropriate on board traffic display (CASCADE Operational Focus Group, 2009). This is achieved by retrieving ADS-B information transmitted by other aircraft transponders via Mode S 1090 MHz. The information is then fed to the Cockpit Display of Traffic Information (CDTI) tool to provide instantaneous and up-to-date traffic information (including aircraft identification, position, direction, ground speed, vertical tendency, relative altitude and wake vortex category). The use of ATSAW-AIRB does not require any changes to the ATS infrastructure, systems or ATC procedures (CASCADE Operational Focus Group, 2009). The ATSAW-AIRB application requires all aircraft within the airspace to be capable of transmitting ADS-B Out messages and the "owner aircraft" to be equipped with a traffic display (e.g. CDTI or merged TCAS/ADS-B traffic display). Standardisation for the implementation of the application is developed jointly by EUROCAE and the RTCA (EUROCAE and RTCA, 2010). EUROCONTROL has developed a Preliminary Safety Case for ATSAW-AIRB. To date more than 3000 ATSAW-AIRB equipped flights have been performed in Europe (Rekkas, 2013). However, the relevant safety case is not publicly available.

3.2. *Air Traffic Situational Awareness In-Trail Procedure in Oceanic Airspace (ATSAW-ITP).* Currently, aircraft operating in procedural airspace (oceanic or remote) are constrained to fly at the same flight level, and thus do not necessarily fly at an optimum flight level. ATSAW-ITP using ADS-B is meant to enable altitude changes. The ITP is achieved with the combination of ATSAW and Controller-Pilot Data Link Communication (CPDLC). The ATSAW display allows the pilot to detect a climb/descend opportunity. The clearance exchange for the altitude change is then requested via CPDLC. The shared situational awareness between pilot and the ATC enabled by ADS-B will provide confidence to ATC to grant the clearance requested. This will also lead to reduced separation between aircraft in these airspaces. The current standard longitudinal separation requirement is 80 NM (International Civil Aviation Organization (ICAO), 2007), while with ATSAW-ITP, a reduced longitudinal separation of 15 NM (Vidal, 2012) is expected to be achieved.

3.3. *Air Traffic Situational Awareness Visual Separation in Approach (ATSAW-VSA).* Visual separation is meant to separate aircraft (Instrument Flight Rules (IFR) and Visual Flight Rules (VFR)) by means of pilots seeing and avoiding other aircraft or by means of a tower controller directly observing and separating aircraft visually. ATSAW-VSA is meant to assist this type of operation for pilots. The objective of this application is to safely execute approach procedures using "own separation" from the preceding aircraft more efficiently and more regularly (CASCADE Operational Focus Group, 2008). It aids the pilot in acquiring and maintaining visual contact with the preceding aircraft. More importantly it supports safe operations in marginal meteorological conditions. ATSAW-VSA improves efficiency by increasing runway capacity, and also improves safety by providing enhanced situational awareness and enhanced identification of the target aircraft (Vidal, 2010). The ATSAW-VSA paves the way for future spacing applications. To enable the ATSAW-VSA, the aircraft has to be equipped with ADS-B In equipment, appropriate flight deck tools, and a traffic display tool (e.g. CDTI). Most importantly the application is only feasible with full mandate of ADS-Out, ensuring all surrounding aircraft are equipped with ADS-B Out capability. Partial equipage of surrounding aircraft is not sufficient for use of the ATSAW-VSA application.

3.4. *Air Traffic Situational Awareness on the Airport Surface (ATSAW-SURF).* ATSAW-SURF is intended to improve situational awareness of surrounding aircraft and ground vehicles operating in the vicinity of the aerodrome. This is achieved by providing the pilot with a display of the surrounding traffic position and identity, together with the "own aircraft" position overlaid on a map of the aerodrome. The enhanced situational awareness provided by the ATSAW-SURF application will improve the safety of aerodrome surface operations, in particular at taxiway and runway intersections, and for aircraft landing and take-off. A secondary outcome is to enhance taxi efficiency through improved traffic situational awareness

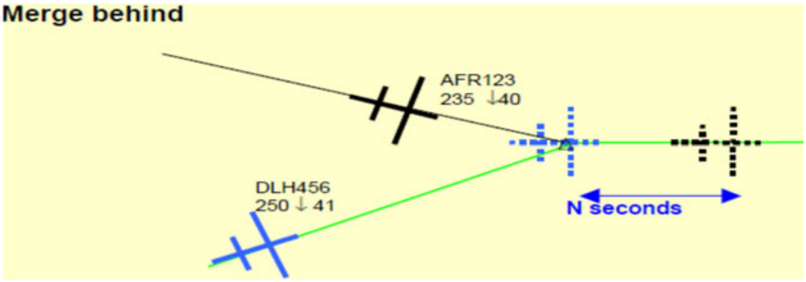

Figure 2. Manoeuvres supported by the Interval Management application.

during operations such as conditional taxi clearances, especially during low visibility conditions, night operations and at airports unfamiliar to flight crews. The application is also expected to decrease pilot and controller workload by reducing requests for repeat information with respect to surrounding traffic (ICAO, 2012a). To enable the ATSAW-SURF application, the aircraft has to be equipped with ADS-B In equipment, a traffic display tool and must have access to the airport map database.

3.5. *Spacing / Interval Management (IM).* The step following the introduction of ATSAW applications is the introduction of spacing applications (Vidal, 2012). This is also known as Interval Management (IM). According to the ICAO, IM provides improved means for managing traffic flows and aircraft spacing. This includes both the use of ground and airborne tools as follows (ICAO, 2012a):

- Ground tools that assist the controller in evaluating the traffic scenario and determining appropriate clearances to merge and space aircraft efficiently and safely, and allow the controller to issue an IM clearance; and
- Airborne tools that allow the pilot to conform to the IM clearance. These airborne capabilities are referred to as the Flight-deck-based Interval Management (FIM) capabilities. The requirements for the FIM are provided in Safety Performance and Interoperability Requirements for Flight Deck Interval Management (EUROCAE, 2011).

Under IM, the equipped aircraft is instructed to merge behind and maintain a given time spacing from another aircraft. Three types of manoeuvres are supported by the IM application:

- Remain in trail;
- Merge in trail; and
- Radar vector then merge in trail.

This is illustrated in Figure 2. Compared with current operations, the controller is relieved of the provision of speed and turn clearance to manage traffic by assigning an interval to the pilot. However, during IM operations, the controller still retains responsibility for separation.

IM is currently one of the core capabilities of NextGen and avionic standards to support the application have recently been published. To date, numerous flight tests have been conducted in the National Airspace System (NAS). Furthermore, Advanced IM capabilities are under research and development to provide enhanced operations and performance. Barmore et al. (2016) provides more information on the IM development and deployment plan in the NAS.

3.6. *Separation.* The separation application refers to Airborne SEParation (ASEP) and Airborne Self-SEParation (SSEP). According to ICAO (2012a), delegation of separation responsibility to flight crew is foreseen in the future. The pilot will be responsible for ensuring separation from designated aircraft as communicated in the future clearance, thereby relieving the controller from the responsibility for separation between these aircraft. Typical ASEP capabilities include (ICAO, 2012b):

- interval management with delegation of separation: the flight crew maintains a time-based separation behind designated aircraft;
- lateral crossing and passing: the flight crew adjusts the lateral flight path to ensure that horizontal separation with designated aircraft is larger than the applicable airborne separation minimum;
- vertical crossing: the flight crew adjusts the vertical flight path to ensure that vertical separation with designated aircraft is larger than the applicable airborne separation minimum;
- paired approaches in which the flight crew maintains separation on final approach to parallel runways; and
- in oceanic airspace, improved procedures of ITP using new airborne separation minima: ASEP-ITF In-trail follow; ASEP-ITP In-trail procedure; and ASEP-ITM In-trail merge.

During SSEP, the pilot ensures separation of their aircraft from all surrounding traffic. Hence the controller has no responsibility for separation. Typical airborne self-separation applications include (ICAO, 2012b):

- airborne self-separation in ATC-controlled airspace;
- airborne self-separation in segregated en-route airspace;
- airborne self-separation in mixed-equipage en-route airspace; and
- airborne self-separation – free flight on an oceanic track.

An early implementation of the ASEP and SSEP applications is anticipated in oceanic and low density airspace. Advanced Safe Separation Technologies and Algorithms (ASSTAR) initiated the work on ASEP and SSEP applications in Europe which has been supported by two dedicated SESAR projects (EUROCONTROL, 2016), i.e., 04·07·04.b ASAS-ASEP Oceanic Applications and 04·07·06 En Route Trajectory and Separation Management – ASAS Separation (Cooperative Separation).

Airborne separation minima have yet to be defined for the ASEP and SSEP applications. These are expected to be very stringent, leading to the requirement of very high performance navigation and surveillance functions on board. In addition, due to the impact of these applications on the controller and pilot responsibilities, provisions for these applications are expected to require modification of the ICAO annexes i.e. PAN ATM (ICAO, 2007) and PAN OPS (ICAO, 2006).

All of the airborne surveillance applications discussed above rely on the capability of ADS-B Out to provide the required information elements with a specific level of performance. Section 5 provides the required ADS-B information elements and the corresponding minimum ADS-B system performance requirements to support these applications.

4. ADS-B PERFORMANCE ASSESSMENT. This section describes briefly the data, performance assessment parameters and the results of the assessment.

4.1. *Data.* Two types of data; ADS-B data recorded from the ADS-B ground stations (ASTERIX CAT021) and corresponding navigation data from aircraft navigation system (used as reference) were collected for 29 aircraft based on opportunity traffic in the London Terminal Manoeuvring Area (LTMA), obtained from National Air Traffic Service (NATS) UK and British Airways respectively, to assess ADS-B system performance (accuracy, integrity, update interval and latency).

Accuracy is evaluated by measuring ADS-B Horizontal Position Error (HPE). This is performed by comparing the received position from an ADS-B ground station with a reference position (derived from corresponding raw Global Positioning System (GPS) data collected from the aircraft navigation system). Integrity is assessed based on the position integrity quality indicator called Navigational Uncertainty Category (NUC) value, included in the ADS-B messages. The NUC value encodes the integrity bound, on the basis of Horizontal Protection Limit (HPL) provided by the on board GPS receiver, as a numerical value from 0 to 9. The higher the value, the higher the position integrity. Update interval is measured as the rate (seconds) at which periodic ADS-B messages are received at the ground stations. Latency is the amount of the time taken to broadcast a position relative to the time of applicability of the position measured.

Detailed information on the performance assessment process is provided by the authors in Ali et al. (2013). Among the data collected, only data from 12 aircraft were suitable for the performance analyses. The following problems were identified in the remaining aircraft:

- GPS clock errors recorded on board the aircraft. This error could be due to the settings in the receiver;
- GPS position fluctuations recorded on board the aircraft. This refers to jumps in position of about 0·1° every 100–200 seconds in latitude and, in the longitude, every 50 seconds. This is still under investigation with British Airways;
- Lack of a consistent GPS position format output by the aircraft. For example, at time t1, only the latitude information is given and at time t2, only the longitude information is provided. This may be the result of the configuration in the Flight Management System (FMS);
- Uncorrelated time intervals between GPS data (at aircraft level) and ADS-B data (at ground level). This may be due to clock errors in either the aircraft or the ground station;
- Missing altitude information.

Further investigations on the anomalies identified have been published by the authors in Ali et al. (2015).

4.2. *Results.* Performance of the 12 aircraft in terms of accuracy, integrity, update interval and latency are provided in Table 1. Based on the results, aircraft 40087B, 406250 and 400952 exhibit unacceptable position errors of 14,287, 11,093, and 11,026 metres respectively. Further investigation is in progress on the performance

Table 1. ADS-B system performance.

Aircraft Identification	Type	Accuracy (HPE) metres	Integrity (NUC)	Update Interval (seconds)	Latency (seconds)
40608 F	A318	476	7	1·7	1·7
405A48	A320	66	7	4·3	0·6
400A26	A320	553	7	1·4	1·9
400877	A319	109	7	2·5	0·6
400878	A319	113	7	3·6	0·5
40087B	A319	14287	7	2·5	1·7
4008F2	A319	49	6,7	1·1	0·6
400935	A319	145	7	2·4	0·7
406250	A320	11093	7	3	15·7
4008B4	A319	26	6,7	1·3	0·6
4009C7	A320	169	7	1	0·7
400942	A319	11026	7	1	0·7

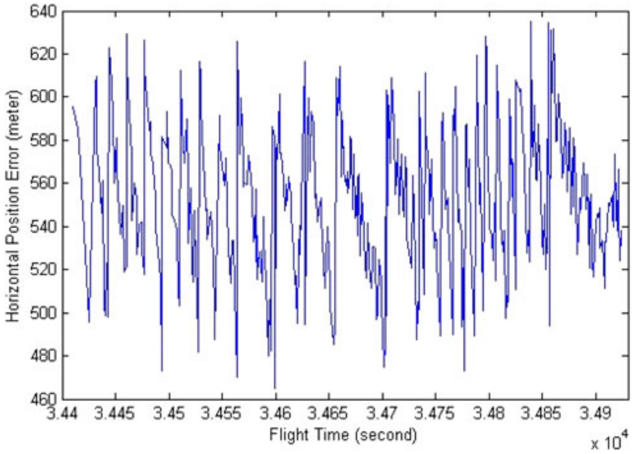

Figure 3. Horizontal Position Error (HPE) distribution for aircraft 400A26.

of these particular aircraft, which are not considered in the subsequent analysis in this paper.

Among the remaining aircraft, Aircraft 400A26 shows the worst accuracy performance with 553 metres Horizontal Position Error (HPE), consistent integrity value at NUC = 7, mean update interval of 1·4 seconds and mean latency of 1·9 seconds. The latency performance is outside the general performance requirement for ADS-B which is ≤1·5 seconds. Figure 3 shows the HPE distribution throughout the flight duration with minimum HPE at 460 metres and maximum HPE at 620 metres. Further analysis in Figure 4 indicates that 87% of the update intervals as measured at the ground station are ≤2 seconds. However, the scatterplot analysis shows that there is no deterministic pattern on the message update rate for aircraft 400A26. Figure 5 shows the latency distribution for the aircraft which is between 0·1 to 3 seconds.

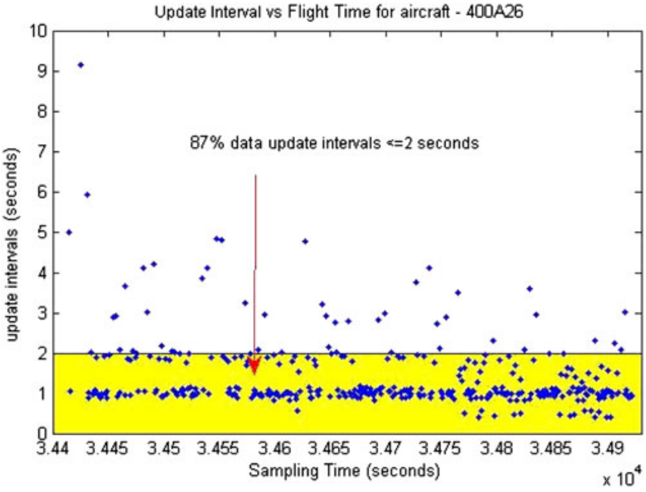

Figure 4. ADS-B message update interval vs. flight time for aircraft 400A26.

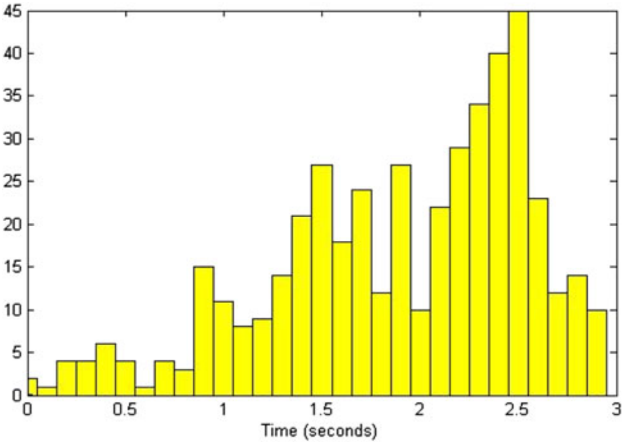

Figure 5. ADS-B message latency distribution for aircraft 400A26.

Aircraft 4008B4 shows the best performance with an accuracy of 26 metres HPE, positioning integrity of NUC = 6 or 7 in each epoch, mean update interval of 1·3 seconds and mean latency of 0·6 seconds. Figure 6 shows the HPE distribution with a minimum error of 3 metres and maximum error of 85 metres during the flight time. Analysis in Figure 7 shows that 96% of the update intervals as measured at the ground station are ≤2 seconds throughout the flight with a deterministic pattern. Figure 8 shows the latency distribution between 0·1 and 1·1 seconds with a few outliers between 1·2 and 1·9 seconds.

It was found that there is no deterministic pattern in the ADS-B message update interval for analysis conducted with data collected for less than 30 minutes. ADS-B

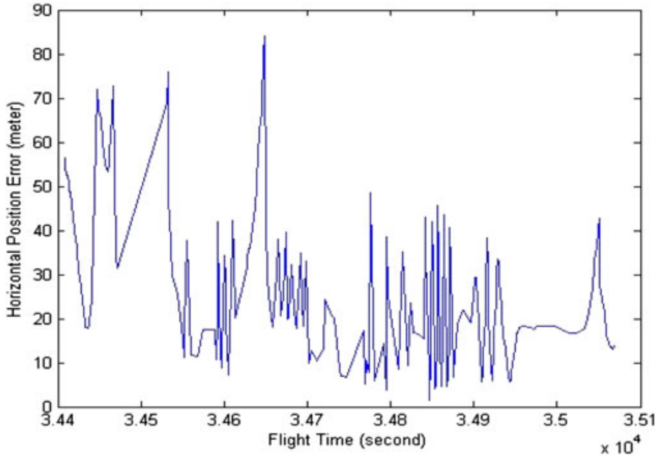

Figure 6. Horizontal Position Error (HPE) distribution for aircraft 4008B4.

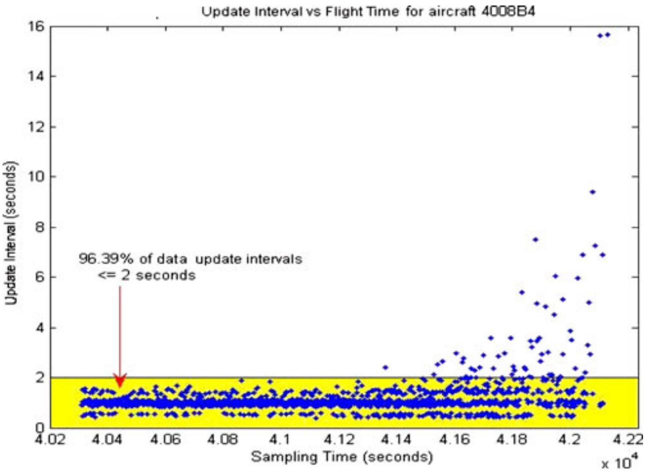

Figure 7. ADS-B message update interval vs. flight time for aircraft 4008B4.

data for aircraft 400A26 in Figure 4 is less than 10 minutes while ADS-B data for aircraft 4008B4 in Figure 7 is more than 30 minutes. A clear pattern can be seen in Figure 7. Further analysis by the authors of 30 aircraft over a time-frame larger than 30 minutes indicated a similar pattern. Future work will identify the cause for the increase in the update interval beginning at a certain point onwards. Overall, 67% of the aircraft included in this study display an accuracy of <150 metres, 100% provide consistent positioning integrity of NUC = 6 or 7, 56% indicate update intervals ≤2 seconds and 78% show latencies ≤1·5 seconds. The results of the best and worst performing aircraft will be used in the next section to analyse the capability of ADS-B to support the various enhanced surveillance applications discussed in the earlier sections.

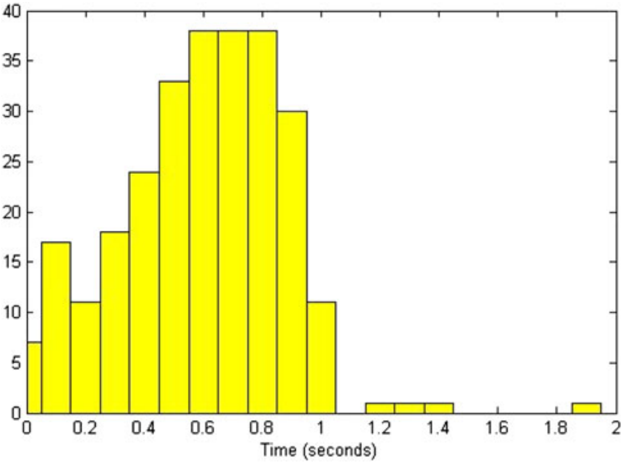

Figure 8. ADS-B message latency distribution for aircraft 4008B4.

5. ADS-B OUT CAPABILITIES VERSUS THE AIRBORNE SURVEILLANCE APPLICATIONS REQUIREMENTS. There are currently three different versions of ADS-B Out and hence ADS-B avionics with different levels of performance: DO-260, DO-260A and DO-260B. The differences between the three versions are summarised below:

a) Version 0 (DO-260) provides a basic ADS-B capability, with position integrity provided by the NUC parameter. This was the initial version of ADS-B and there are a variety of Version 0 installations; typically only those ADS-B version 0 installations complying with EASA AMC 20–24 are approved for use in ATC separation applications;
b) Version 1 (DO-260A) provides, among others, separate accuracy and integrity parameters which replace the NUC – Navigational Accuracy Category (NAC) and Navigation Integrity Code (NIC) and Surveillance Integrity Level (SIL); also, a new message provides Target State and Status data; and
c) Version 2 (DO-260B) provides, among others, a renaming and new definition for SIL; includes several new fields, such as the System Design Assurance (SDA) and Geometric Vertical Accuracy; removes vertical information from the NIC, NAC, and SIL parameters; provides improved support of surface operations through changes to the NIC encoding; supports non-diversity antenna options for smaller (general aviation) aircraft in addition to various other fixes/improvements.

The differences between the three versions lie in the amount of information (particularly the quality indicators for the aircraft state information) transmitted in the ADS-B messages. However, the performance of the aircraft state information is the same. The additional information in the last version increases the user's confidence level on the aircraft state information broadcast by the ADS-B system. To date, most of the aircraft are equipped with DO-260 avionics on a voluntary basis. The aircraft analysed in this study are certified to DO-260 standards and compliant with European Air Safety

Agency Acceptable Means of Compliance (EASA AMC) 20–24. This section analyses the performance of ADS-B Out and its capability to support the ADS-B ground and airborne surveillance applications. Table 2 presents the results of the mapping exercise between the specific information in the ADS-B message required for each of the applications and the availability of this information in real time.

Based on the mapping exercise, the required Identification Information and State Vector Information are available in the real time ADS-B message to support all the applications in Table 2. The only Mode Status Information available in the ADS-B message, required to support the ATSAW-AIRB/VSA/ITP, Spacing and ATS Surveillance, is the Emergency/Priority Status Information. Apart from the Velocity Accuracy (NAC_V), none of the State Vector Quality Indicator information required by these applications is available in the ADS-B message. However, the NUC information in the ADS-B message is a substitute for the NIC and NAC_P information, indicating the quality of the transmitted aircraft position information. The Air-Reference Vector information required for the ASEP application is not available in the ADS-B message. Intent Data required for the ASEP and SSEP are also not available in the ADS-B message.

Based on the assessment in this study, the ADS-B performance between aircraft is variable. Therefore it is currently not possible to derive a representative ADS-B performance. Hence, in order to validate the ADS-B performance to support the airborne surveillance applications in this paper, the best and worst aircraft performances from the sample are mapped to the minimum required ADS-B performance to support these applications. The applications include ATSAW-AIRB, ATSAW-VSA, ATSAW-SURF, Oceanic-ITP, as well as Interval-Management/Spacing and Airborne Separation delegation (ASEP) for en-route/terminal phases of operation. Self-Separation (SSEP) is not included as the requirements for this application are not yet established. In fact, most of the applications envisioned to use the information provided by ADS-B are not fully established. The requirements for each of the airborne applications included in the mapping exercise in this section are obtained from Safety Performance and Interoperability Requirements for ATSAW during flight operations (ATSAW-AIRB) (DO-319), Visual Separation in Approach (ATSAW-VSA) (DO-314), on the Airport Surface (ATSAW-SURF) (DO-322), and In-Trail Procedure in oceanic airspace (ATSAW-ITP) (DO-312); and Minimum Aviation System Performance Standards (MASPS) for Aircraft Surveillance Applications (ASA) (DO-289). The required ADS-B position accuracy is represented by the NAC_P value. This value is translated as a 95% Horizontal Accuracy Bound or measured as a Horizontal Position Error (HPE). The required ADS-B integrity is indicated as the NIC value, representing an integrity containment radius around an aircraft's reported position. The required ADS-B velocity accuracy is presented as NAC_V. On board navigation sources such as GNSS provide a direct measure of velocity to the ADS-B system. The navigation data source 95% accuracy for the Horizontal ($HFOM_V$) and Vertical Figures Of Merit Vertical ($VFOM_V$) components are summarised in Table 3.

Another ADS-B performance indicator required is the System Design Assurance (SDA). The SDA defines the failure conditions that the position transmission chain is designed to support, as defined in Table 4. The supported failure conditions will indicate the probability of a fault in the position transmission chain which would cause false or misleading position information to be transmitted.

Table 5 maps the performance of the best performing aircraft analysed in this study to the minimum required ADS-B performance for future applications. The best ADS-B

Table 2. Required Information Elements to Support ADS-B Applications vs. Available Information in the ADS-B Message (certified with DO-260).

	Required									
Information Element	ATSAW-AIRB	ATSAW-VSA	ATSAW-ITP	Spacing	Airborne Separation (ASEP)	Self – separation (SSEP)	ATSAW-SURF & ADS-B APT	ATS Surveillance	Available	Comments
							Identification			
Call Sign				✓	✓	✓	✓	✓	✓	
Address	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Category					✓	✓	✓	✓	✓	
Mode A Code								✓	✓	
							State Vector			
Horizontal Position	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Vertical Position	✓	✓	✓	✓	✓	✓		✓	✓	
Horizontal Velocity	✓	✓	✓	✓	✓	✓		✓	✓	
Vertical Velocity	✓	✓	✓	✓	✓	✓		✓	✓	
Surface Heading							✓		✓	
Ground Speed							✓		✓	
							Mode Status			
Emergency/ Priority Status	✓	✓	✓	✓				✓	✓	
Capability Codes				✓	✓	✓	✓	✓		No Capability Codes available in the ADS-B message
Operational Modes				✓	✓	✓	✓	✓		No Operational Modes available in the ADS-B message
							State Vector Quality Indicator			
NIC		✓	✓	✓	✓	✓	✓	✓		NIC value is presented as NUC representing horizontal position accuracy and integrity in the ADS-B message
NAC_P	✓	✓	✓	✓	✓	✓	✓	✓		No specific position accuracy available in the ADS-B message
NAC_V		✓	✓	✓	✓	✓	✓	✓	✓	
SIL		✓	✓	✓	✓	✓	✓	✓		No SIL information available in the ADS-B message
SDA	✓	✓	✓	✓	✓	✓	✓	✓		No SDA value available in the ADS-B message
Air-Reference Vector					✓					No Air-Reference Vector available in the ADS-B message
Intent Data					✓	✓				No intent information available in the ADS-B message

Table 3. Position Velocity Accuracy (NAC_V).

NAC_V	HFOMV Value $VFOM_V$ Value
0	$HFOMV \geq 10$ m/s or $VFOMV \geq 15{\cdot}2$ m/s or unknown
1	$HFOMV < 10$ m/s and $VFOMV < 15{\cdot}2$ m/s
2	$HFOMV < 3$ m/s and $VFOMV < 4{\cdot}6$ m/s
3	$HFOMV < 1$ m/s and $VFOMV < 1{\cdot}5$ m/s
4	$HFOMV < 0{\cdot}3$ m/s and $VFOMV < 0{\cdot}46$ m/s

Table 4. System Design Assurance (SDA).

SDA	Probability of Undetected Fault causing transmission of false or misleading information
0	$>1 \times 10^{-3}$ per flight hour or unknown
1	$\leq 1 \times 10^{-3}$ per flight hour
2	$\leq 1 \times 10^{-5}$ per flight hour
3	$\leq 1 \times 10^{-7}$ per flight hour

position accuracy of 26 metres, corresponding to $NAC_P = 9$, is better than the required accuracy performance for all airborne applications. The measured $NUC_P = 6{\cdot}4$ corresponds to a $HPL < 0{\cdot}2$ NM. Based on the specifications, ADS-B position integrity is not required for the ATSAW-AIRB and ATSAW-SURF. The required position integrity for ATSAW-VSA is $NIC = 6$ ($HPL < 0{\cdot}5$ NM), and Oceanic-ITP is $NIC = 5$ ($HPL < 1{\cdot}0$ NM). The Interval-Management en-route also requires a $NIC = 5$ and Interval-Management TMA a $NIC = 7$ ($HPL < 0{\cdot}2$ NM) and ASEP a $NIC = 9$ ($HPL < 25$ metres). Therefore the ADS-B system integrity is sufficient to support all of the applications except the ASEP and Interval Management TMA applications. The required SIL and SDA parameters are not available from the aircraft certified with DO-260 avionics. The required NAC_V value is missing from the ADS-B message collected for the particular aircraft. This reduces the credibility of the ADS-B system in the particular aircraft to support the envisioned applications. The measured update interval of 1·3 seconds is sufficient for all airborne applications. The latency performance of 0·6 seconds is better than the required latency for all of the airborne applications. The required latency for ATSAW-SURF is based on the on board latency of $<0{\cdot}5$ seconds, while the measured latency of 0·6 seconds is based on the total latency. However, the on board latency for the aircraft is assumed to be consistent with the established ADS-B RAD aircraft requirements of 0·2 seconds, and hence sufficient for the ATSAW-SURF.

Table 6 maps the performance of the worst performing aircraft analysed to the minimum required ADS-B performance for the airborne applications. 553 metres ADS-B position accuracy corresponds to a $NAC_P = 6$, which is only sufficient to support ATSAW-AIRB, ATSAW-VSA, Oceanic-ITP and Interval-Management en-route. The ADS-B position integrity $NUC_P = 5$ corresponds to $HPL < 0{\cdot}5$ NM, which is equivalent to $NIC = 6$ and hence only sufficient to support the ATSAW-VSA, Oceanic-ITP and Interval-Management en route. ADS-B velocity accuracy $NAC_V = 0$ indicates that the system is unable to support the required velocity accuracy for any of the applications. The measured update rate = 1·4 seconds, sufficient for all airborne applications. The latency performance of 1·9 seconds is only sufficient to support ATSAW-ITP.

Table 5. Minimum Required ADS-B Performance for Airborne Surveillance Application vs Actual ADS-B Performances (best performing aircraft).

	Required ADS-B Performance						Measured ADS-B System Performance (Best performing aircraft)
	Situational Awareness Applications (ATSAW)				IM/Spacing (EnRoute/Terminal)	Airborne Separation (ASEP) (EnRoute/Terminal)	
Performance Metric	AIRB	VSA	SURF	ITP			
Accuracy (NAC_P)	5	6	7/9[1]	5	6/7	9	26 metres
Integrity (NIC)	N/A[2]	6	N/A	5	5/7	9	$NUC_P = 6{\cdot}4$
Velocity Accuracy (NAC_V)	1	1	2	1	1/2	3	Unknown
Source Integrity Level (SIL)	N/A	1	N/A	2	2	2	Not Available
System Design Assurance (SDA)	1	1	1/2[3]	2	$<1 \times 10^{-6}$/flight hour	TBD	Not Available
Update Rate (seconds)	3	N/A	≤2	≤5 to ≤24	*[4]	TBD	1·3
Latency (seconds)	<1·5	<1·6	<0·5 (on board)	≤4·575	*	TBD	0·6

[1] SURF surface targets require NACP > = 9
SURF airborne targets require NACP = 7 or 9 depending on parallel runway spacing

[2] N/A – Not Applicable

[3] Hazard level for ownship when airborne or on surface >80 knots = Major (SDA = 2)
Hazard level for ownship when airborne or on surface <80 knots = Minor (SDA = 1)

[4] Not available at time of writing

Table 6. Minimum Required ADS-B Performance for Airborne Surveillance Application vs Actual ADS-B Performances (worst performing aircraft).

	Required ADS-B Performance						Measured ADS-B Performance (Worst performing aircraft)
	Situational Awareness Applications (ATSAW)				IM/Spacing (EnRoute/Terminal)	Airborne Separation (ASEP) (EnRoute/Terminal)	
Performance Metric	AIRB	VSA	SURF	ITP			
Accuracy (NAC_P)	5	6	7/9	5	6/7	9	553 metres
Integrity (NIC)	N/A	6	N/A	5	5/7	9	$NUC_P = 5$
Velocity Accuracy (NAC_V)	1	1	2	1	1/2	3	0
Source Integrity Level (SIL)	N/A	1	N/A	2	2	2	Not Available
System Design Assurance (SDA)	1	1	1/2	2	$<1 \times 10^{-6}$/flight hour	TBD	Not Available
Update Rate (seconds)	3	N/A	≤2	≤5 to ≤24	*	TBD	1·4
Latency (seconds)	<1·5	<1·6	<0·5 (on board)	≤4·575	*	TBD	1·9

6. DISCUSSION. From the mapping exercise conducted to validate the credibility of the ADS-B Out messages analysed in this study to support the airborne surveillance applications, it is found that all of the applications require some of the Mode Status and State Vector Quality Indicator information, which are currently lacking in the ADS-B message. In addition, continuous ADS-B system monitoring is crucial to ensure safety. The analysis in this study indicates that some of the certified aircraft have missing data elements, corresponding to a performance inferior to their level of certification. Indications are that ADS-B accuracy from the best performing aircraft is sufficient for all foreseen applications while the worst performing aircraft only supports ATSAW-AIRB, ATSAW-VSA, Oceanic-ITP and Interval-Management en-route. ADS-B integrity from both aircraft is sufficient to support all applications except the most stringent application: ASEP. ADS-B velocity accuracy values from both aircraft are insufficient to support any application. The ADS-B update interval from the best performing aircraft at 1·3 seconds and worst performing aircraft at 1·4 seconds supports all applications. The best performing aircraft latency is sufficient for all applications while the worst performing aircraft latency is only sufficient for the ATSAW-ITP. In addition, the remaining required performance parameters SIL and SDA are unavailable from aircraft certified to DO-260 standards. Therefore, aircraft must be certified to DO-260B to support the applications with continuous monitoring to ensure the required system performance.

7. CONCLUSION. This paper has reviewed various enhanced aircraft surveillance applications envisioned for the future ATM Concept of Operations, which rely on the ADS-B system. The paper has identified the required ADS-B information elements and performance levels in terms of accuracy, integrity, update interval and latency to support each of these applications. It assessed ADS-B performance of 29 aircraft based on an approach developed in Ali et al. (2013), using real time ADS-B data and corresponding on board navigation data collected from NATS UK and British Airways respectively. Using the performance assessment results of the best and worst performing aircraft, a mapping exercise was carried out to evaluate the feasibility and credibility of the ADS-B system to support each of the aircraft surveillance applications. It was found that aircraft certified to DO-260 are unable to support these applications due to the unavailability of the SIL and SDA parameters in the message. However, it is important to note a number of limitations in this study: the best and the worst aircraft were withdrawn from a limited-in-size sample; the sample was not randomised; and the time frame for the data collection is limited at each aircraft flying over the LTMA. Therefore, the results should be interpreted as an initial attempt to substantiate the conclusions on the basis of limited empirical evidence and may not be inferred to a wider population of ADS-B equipped aircraft.

DISCLAIMER

Opinions expressed in this work reflect the authors' views only and British Airways and/or NATS UK shall not be considered liable for them or for any use that may be made of the information contained herein.

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