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1 author:

Busyairah Syd Ali
RMIT University

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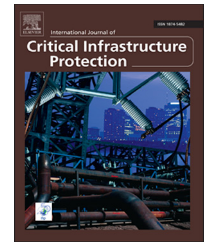

System specifications for developing an Automatic Dependent Surveillance-Broadcast (ADS-B) monitoring system

Busyairah Syd Ali

Department of Software Engineering, Faculty of Computer Science and Information Technology, University of Malaya, Kuala Lumpur 50603, Malaysia

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ABSTRACT

Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance system placed in aircraft that periodically transmits state vector estimates and other information to air traffic control centers and other nearby aircraft (and may also receive traffic and weather information from various entities). The state vector estimates are derived from navigation avionics and are transmitted via a common communications channel, which means that ADS-B is highly dependent on aircraft navigation and communication systems. ADS-B also requires ground stations to receive information from aircraft. As a result of this complex architecture, the ADS-B system is prone to various failure modes.

A systematic and comprehensive performance monitoring system is required to ensure the safe use of ADS-B data for air traffic control operations. It is vital that such monitoring systems are in place before a global ADS-B implementation date is mandated by the International Civil Aviation Organization. A number of air navigation service providers and regulators have developed ADS-B performance monitoring methods without a standardized guideline for system specifications. These include Airservices Australia, the U.S. Federal Aviation Administration, EUROCONTROL, the Civil Aviation Authority of Singapore and the Civil Aviation Department of Hong Kong.

This paper presents a holistic set of system specifications for ADS-B monitoring systems. In particular, the paper analyzes the ADS-B infrastructure, conducts a systematic review of existing ADS-B monitoring systems, classifies the system characteristics to identify gaps, and derives a set of specifications for developing ADS-B monitoring systems. The paper also assesses the compliance of existing ADS-B monitoring systems against the proposed specifications using a mapping exercise. The system specifications serve as a foundation or minimum requirements for air navigation service providers and original equipment manufacturers to develop systematic and comprehensive ADS-B monitoring systems.

E-mail address: busyairah@um.edu.my

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1. Introduction

Automatic Dependent Surveillance-Broadcast (ADS-B) [1,14] is an automated surveillance system placed in aircraft that uses satellite navigation technology to periodically transmit important information to and receive information from air traffic control centers and other nearby aircraft. It provides several benefits to air traffic control and pilots, including enhanced aircraft situational awareness, the transmission and receipt of flight information, and the receipt of weather information. ADS-B has two services: (i) ADS-B Out, which broadcasts information about aircraft (e.g., aircraft identification and real-time position, altitude and velocity); and (ii) ADS-B In, which receives traffic and weather information.

The implementation of ADS-B Out is actively taking place in many regions of the world. This includes voluntary efforts by air navigation service providers, airline operators, regulators and manufacturers, ahead of a globally mandated implementation date that will be imposed by the International Civil Aviation Organization (ICAO).

In order to ensure that the implementations of mixed-mode (radar and ADS-B) and sole operations of ADS-B in non-radar airspace are operationally safe, numerous safety assessment methods have been put in place by air navigation service providers and researchers [3,4,8,9,13,14,20,21]. According to ICAO, ADS-B shall only be used for the provision of air traffic services when an assessment proves that ADS-B performance in a particular airspace exceeds the required performance level [15]. Therefore, it is compulsory to conduct a safety assessment before an ADS-B system becomes operational. However, this is a one-off process and is inadequate because system performance may degrade over time for a variety of reasons. Hence, periodic safety monitoring of the ADS-B system is essential; this includes the monitoring of ADS-B ground stations, avionics and performance levels.

This paper discusses ADS-B operations and conducts a detailed analysis of the ADS-B infrastructure and implementation requirements. It also reviews the efforts undertaken by a number of air navigation service providers, including Airservices Australia, the U.S. Federal Aviation Administration, EUROCONTROL, the Civil Aviation Authority of Singapore and the Civil Aviation Department of Hong Kong, in developing and implementing ADS-B monitoring systems. Based on an analysis and systematic review, a set of specifications for developing ADS-B monitoring systems is presented. The system specifications adopt a holistic view of the ADS-B system, including ground stations, avionics and performance. The compliance of the reviewed ADS-B monitoring systems against the derived specifications is also assessed via a mapping exercise.

2. ADS-B operation

ADS-B is a service implemented on an aircraft (or surface vehicle operating within its movement area) that periodically broadcasts its position and other information without knowing the recipients and without expecting acknowledgements as the system only supports one-way broadcasts. The system is automatic in the sense that it does not require external intervention to transmit the information. It is characterized as dependent due to its reliance on aircraft navigation avionics to obtain the required surveillance information. ADS-B is a cooperative system because it requires common equipage for aircraft and surface vehicles to exchange information. It provides aircraft state information such as horizontal position, altitude, vector, velocity and trajectory intent information. The latter is critical for trajectory prediction, which is the basis of the trajectory-based operations concept of the Single European Sky ATM Research (SESAR) [19] and Next Generation Air Transportation (NextGen) [12] systems.

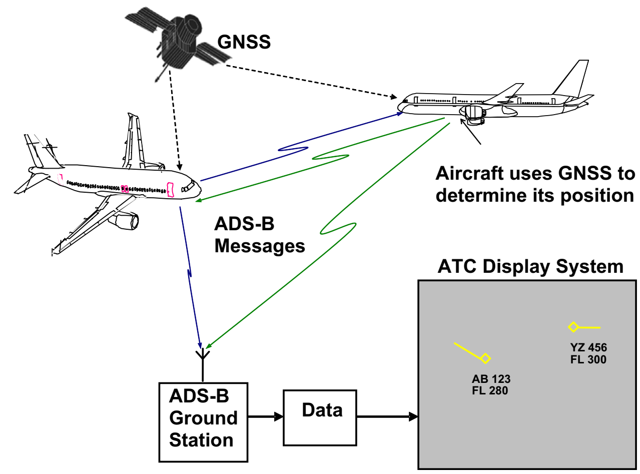

Fig. 1 – Automatic Dependent Surveillance-Broadcast (ADS-B) system [17].

Fig. 1 presents a schematic diagram of the ADS-B system. ADS-B has two subsystems: (i) ADS-B Out; and (ii) ADS-B In. ICAO [1] defines ADS-B Out as the broadcast of ADS-B transmissions from an aircraft, without the installation of receiving equipment to process and display ADS-B data on cockpit displays. The complementary subsystem, ADS-B In, provides air-to-air situational awareness to pilots. ADS-B Out has the ability to operate independently to provide air-ground surveillance services to support air traffic control (ATC). However, the implementation of ADS-B In requires a fully operational ADS-B Out as a prerequisite, the certification of cockpit displays, the consideration of pilot human factors and other activities that have a longer deployment schedule.

An aircraft equipped with ADS-B uses an on-board navigation system to obtain the aircraft position from the Global Navigation Satellite System (GNSS). ADS-B periodically broadcasts aircraft position, velocity and trajectory intent data to other ADS-B equipped aircraft and ADS-B ground stations within its range via a data link service. The ground stations transmit the received ADS-B reports to a surveillance data processing system for use by air traffic control.

3. ADS-B infrastructure

The ADS-B infrastructure includes ground and airborne infrastructures. Figs. 2 and 3 illustrate the avionics for ADS-B Out and ADS-B In, respectively. Note that GNSS denotes the

Global Satellite Navigation System, FMS denotes a flight management system, CDTI denotes the controller display of traffic information and ASAS denotes an airborne separation assurance system.

Tables 1 and 2 list the ground and airborne infrastructure components and their functionalities. The aircraft equipage requirements for ADS-B differ according to the implementation of ADS-B Out and ADS-B In.

To enable an ADS-B equipped aircraft to operate in non-radar airspace in Europe, the ADS-B equipment on the aircraft must be certified to the Acceptable Means of Compliance (AMC) 20-24 Standard [7] (Airworthiness and Operational Approval of Enhanced Air Traffic Services in Non-Radar Areas using ADS-B Surveillance). The European Union (EU) Regulation 1207/2011 applies to aircraft that operate in European radar airspace [18]. However, this regulation is not adopted globally.

According to the Surveillance Performance and Interoperability Implementation Rule (SPI-IR) [10], aircraft with airworthiness certificates issued on or after January 8, 2015 are to be equipped with secondary surveillance radar transponders with the capabilities specified in Annex IV of the SPI-IR (forward-fit). For aircraft certified before this date, an exemption allows retrofitting by December 7, 2017.

The requirements stipulated in Annex IV of the SPI-IR enable the full implementation of ADS-B Out by aircraft operators. However, at this time, regulations do not require air navigation service providers to implement ADS-B in ground infrastructures. It is expected that regulations will follow in the near future due to the need to implement ADS-B globally.

Note that ADS-B is highly dependent on navigation and communications systems. At present the Global Positioning System (GPS) is widely used and supported as the navigation source for ADS-B. Three types of data links are used: (i) Mode S-Extended Squitter (1090ES); (ii) Universal Access Transceiver (UAT); and (iii) VDL-Mode 4. Mode S-Extended Squitter (1090ES) are the most widely deployed data link.

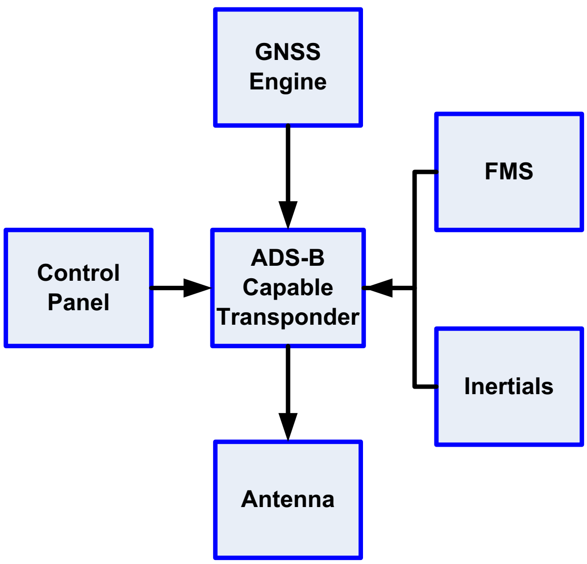

Fig. 2 – ADS-B Out avionics.

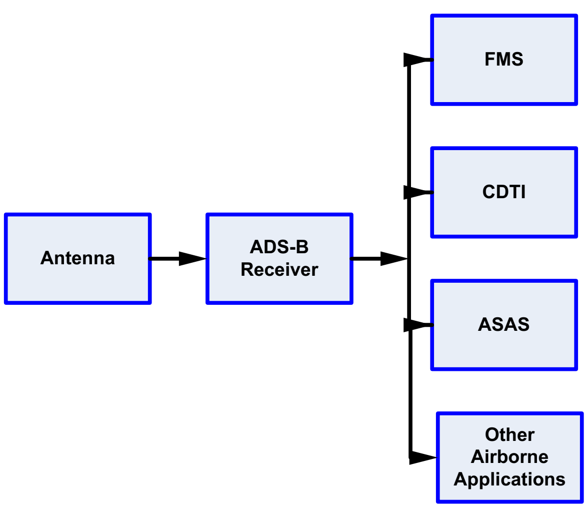

Fig. 3 – ADS-B In avionics.

4. ADS-B implementation

A fully operational ADS-B system (ADS-B Out and ADS-B In) requires all aircraft to be equipped with certified ADS-B avionics, certified ADS-B ground stations with complete airspace coverage, globally agreed operational procedures and a mandate. These in turn depend on airline operators to equip aircraft, air navigation service providers to provide the ground infrastructure and regulators to specify operational procedures and grant mandates to the various stakeholders. The willingness of equipment manufacturers to develop the functionalities that support ADS-B is also crucial. Before the ADS-B system can be fully operational, collaborative engagements between air navigation service providers and airline operators should be made compulsory. This is vital to achieve the required system performance and safety goals that would support the intended surveillance applications.

Despite the anticipated benefits of ADS-B, its adoption rate is tied to a cost–benefit analysis made by each operator. The greater the benefits over the costs, the greater the likelihood

Table 1 – ADS-B ground infrastructure components.

Components	Function
ADS-B Receiver and Antenna	Receives ADS-B messages broadcasted from aircraft
GPS Clock	Timestamps all the received ADS-B messages
Communications Link	Transmits messages from a ground station to the air traffic control surveillance data processing unit
ADS-B Situational Display	Displays aircraft position and state vector in a similar manner to radar

Table 2 – ADS-B airborne infrastructure components.

Component	Function
Navigation Source (e.g., Global Satellite Navigation System)	Derives and transmits aircraft position and state vector information to ADS-B avionics
ADS-B Avionics	Encodes and broadcasts ADS-B messages
Antenna for ADS-B Transponder and Global Satellite Navigation System	Supports ADS-B Out; a single antenna at the bottom of an aircraft is required
	Supports ADS-B In; antenna diversity is required – two antennas, one at the top and the other at the bottom of an aircraft, are required
Antenna Duplexer	Enables the sharing of a single antenna between the transponder and ADS-B units
Barometric Altimeter	Provides the barometric altitude of an aircraft
Altitude Encoding Altimeter	Synchronizes altitude information transmitted in an ADS-B message with the altitude transmitted by the transponder
Control Panel	Enables a pilot to key in or select aircraft identification, surveillance performance and interoperability (SPI) and emergency pulse
Flight Management System	Manages the flight plan and connects to other avionics

of early adoption of ADS-B. Unfortunately, political interference has impacted the adoption and implementation of ADS-B. For these reasons, as well as the complexity of the task, the involvement of numerous parties and the costs, the ADS-B implementation is being carried out in phases. Indeed, the ADS-B implementation in recent years has been driven by voluntary efforts and, in some cases, by a regional mandate (e.g., in Australia). Unless there is a global mandate, it will not be possible to provide complete ADS-B services. Until this occurs, air traffic control will have to operate in a mixed-mode operational environment (i.e., radar and ADS-B) with the ADS-B In functionality disabled.

5. ADS-B system monitoring

ADS-B system monitoring seeks to ensure system reliability and safety. Efforts are currently underway at Airservices Australia, U.S. Federal Aviation Administration, EUROCONTROL, Civil Aviation Authority of Singapore and Civil Aviation Department of Hong Kong. This section provides details about these monitoring efforts.

5.1. *Airservices Australia*

Airservices Australia monitors ADS-B performance at a number of levels. At the first level, site monitoring is conducted to check the receiver sensitivity and antenna cable in real time. This is performed by injecting an ADS-B signal into the antenna and checking if the signal is received at the correct signal strength and if the message is received reliably by the air traffic control system [2]. At the second level, a significant number of ground station parameters [2] are monitored remotely. If the parameter performance exceeds the predefined thresholds, then alerts are generated. At the third level, all failures, service outages and repair/return to service times for each ADS-B site are recorded. The fourth and final level captures and reports the avionics performance of each airframe. The report contains the following information:

- 24-bit code;
- Associated flight ID;
- Minimum and maximum figure of merit;
- Number of position jumps;
- Number of zero integrity reports;
- Registered operator and aircraft type (for Australian aircraft);
- ADS-B data version.

The reports are recorded in the Airservices System Issue Database (ASID). Anomalies that are identified are passed to the relevant airlines, operators and manufacturers for further analysis and mitigation.

5.2. *U.S. Federal Aviation Administration*

The U.S. Federal Aviation Administration (FAA) has developed the active Surveillance and Broadcast (SBS) monitoring system to ensure that ground equipment at each ADS-B site delivers the required services [16]. However, the Federal Aviation Administration has not developed automated procedures for analyzing the large amount of performance data recorded by the Surveillance and Broadcast monitor nor has it assigned adequate human resources to carry out the analysis [16]. In addition, the Federal Aviation Administration has not ensured that the network used by the Surveillance and Broadcast monitor works as intended and is a reliable tool that can help avoid and resolve outages [16]. A recent update by the Federal Aviation Administration [11] indicates that the Surveillance and Broadcast monitor may include avionics compliance monitoring in the future.

5.3. *EUROCONTROL*

In Europe, the European Organization for the Safety of Air Navigation (EUROCONTROL) is evaluating the ADS-B performance of 13,000 aircraft that currently participate in the monitoring project. Twenty billion reports have been analyzed up to 2013 to assess ADS-B data accuracy against multiradar data accuracy for all the participating aircraft. Aircraft compliance with the European Aviation Safety Agency (EASA) AMC 20-24 Standard is also monitored. Anomalies identified in the participating aircraft are resolved in cooperation with airlines, operators and avionics manufacturers [18].

Table 3 – Proposed ADS-B monitoring system specifications.

ADS-B ground station monitoring
1. Site Monitoring
• Receiver sensitivity
• Antenna cables
• GPS health
• Coverage checks
• Probability of detection
2. Remote Control and Monitoring
• CPU process operation
• Temperature
• Asterix output load
• Time synchronization
• GPS status
• Power status
• Site monitor status
3. Logistic Support Monitoring
• Records of all failures, service outages and repair/return to service times
ADS-B Equipage Monitoring
• Updates and maintenance of ADS-B equipped airframe details in a database
ADS-B Avionics Monitoring
• Consistency tracking
• Valid flight IDs
• Presence of NAC/NIC/NUC values
• Presence of geometric altitude values
• Presence and correctness of velocity vectors
• Correctness of 24-bit codes
• Avionics configurations and connections
ADS-B Performance Monitoring
• Validity of NIC/NUC values
• Accuracy of ADS-B horizontal positions (based on reference sensors)
• Deviations between geometric heights and barometric heights
• Comparison of ADS-B reports from two or more stations
• Spread of ADS-B position data
• Message interval rates
ATC Display Monitoring
• Split tracks: ADS-B reported positions might be off
• Coupling failures: Incorrect aircraft IDs

5.4. *Civil Aviation Authority of Singapore*

The Civil Aviation Authority of Singapore (CAAS) has implemented a Surveillance Monitoring System (SMS) to assess the performance of its operational surveillance sensors [5]. The Surveillance Monitoring System is primarily used to monitor radar performance. However, the Civil Aviation Authority of Singapore has extended the system to monitor ADS-B ground stations and ADS-B avionics of aircraft operating within its flight information region. The Surveillance Monitoring System assesses the performance of ADS-B ground stations by performing coverage analysis and measuring the probability of detection at each ground station based on opportunity traffic. Problems at ground stations are identified by the performance assessment. For example, poor probability of detection could be due to a faulty antenna or a poor location.

The Surveillance Monitoring System also monitors ADS-B avionics performance by measuring the accuracy of the ADS-B horizontal position and validating the accuracy performance indicator included in ADS-B navigational uncertainty category (NUC) messages. Navigational uncertainty category message values are validated by checking the deviation between the ADS-B-reported position and the corresponding radar-reported position. In addition, the probability of detection of each aircraft flying in the flight information region is computed. The system also identifies split track and coupling failures in the Air Traffic Control Automation System.

The Civil Aviation Authority of Singapore is currently implementing the following features in its Surveillance Monitoring System:

- Measurements of the gaps between geometric heights and the respective barometric heights to prevent misleading mode C heights from being used.
- Comparison of ADS-B reports from two separate stations in order to detect ADS-B data corruption at a particular station and spoofed (fake) targets.
- Monitoring the spread of ADS-B position data, where a large spread may imply poor position integrity.

5.5. *Civil Aviation Department of Hong Kong*

The Civil Aviation Department of Hong Kong (CAD HK) has implemented performance monitoring and analysis of ADS-B equipped aircraft flying within the Hong Kong flight information region. At the beginning of each month, the system gathers all the recorded information on ADS-B, radar target data and flight plans in the Hong Kong flight information region in an offline mode. The system compares each ADS-B flight with its radar and flight plan to analyze compliance with the following criteria [6]:

- Deviation between ADS-B reported position and independent referenced radar position is greater than 1 nm for no more than 5% of the total number of ADS-B updates.
- Navigation uncertainty category messages accompanying ADS-B reported positions are less than four in number for no more than 5% of the total number of ADS-B updates.
- Flight identification entered via a cockpit interface and transmitted in ADS-B data does not match with aircraft call sign in the air traffic services flight plan for no more than 5% of the total number of ADS-B updates.

6. ADS-B monitoring system specifications

The ADS-B monitoring system specifications presented in this section take into account a holistic view of the ADS-B system, including ground stations, avionics and performance. The specifications were derived by a systematic review of monitoring systems currently in place, an analysis of the ADS-B infrastructure, the ADS-B performance requirements specified by ICAO and operational principles.

Table 3 presents the proposed system specifications. The specifications cover five main areas: (i) ground stations; (ii) equipage; (iii) avionics; (iv) performance levels; and (v) air traffic control displays. The ground station area has three sub-areas: (i) site monitoring; (ii) remote control and monitoring; and

Table 4 – Compliance analysis.

System Specifications	Airservices Australia	U.S. Federal Aviation Authority	EUROCONTROL	Civil Aviation Authority of Singapore	Civil Aviation Department of Hong Kong
ADS-B Ground Station Monitoring					
1. Site Monitoring					
• Receiver sensitivity	✓	✓			
• Antenna cables	✓	✓			
• GPS health	✓	✓			
• Coverage checks				✓	
• Probability of detection				✓	
2. Remote Control and Monitoring					
• CPU process operation	✓	✓			
• Temperature	✓	✓			
• Asterix output load	✓	✓			
• Time synchronization	✓	✓			
• GPS status	✓	✓			
• Power status	✓	✓			
• Site monitor status					
3. Logistic Support Monitoring					
• Records of all failures, service outages and repair/return to service times	✓	✓			
ADS-B Equipage Monitoring					
• Updates and maintenance of ADS-B equipped airframe details in a database	✓		✓		
ADS-B Avionics Monitoring					
• Consistency tracking	✓				
• Valid flight IDs	✓				✓
• Presence of NAC/NIC/NUC values	✓				
• Presence of geometric altitude values	✓				
• Presence and correctness of velocity vectors	✓				
• Correctness of 24-bit codes	✓				
• Avionics configurations and connections					✓
ADS-B Performance Monitoring					
• Validity of NIC/NUC values				✓	✓
• Accuracy of ADS-B horizontal positions (based on reference sensors)			✓	✓	✓
• Deviations between geometric heights and barometric heights				✓	
• Comparison of ADS-B reports from two or more stations				✓	
• Spread of the ADS-B position data				✓	
• Message interval rates					
ATC Display					
• Split tracks: ADS-B reported positions might be off				✓	
• Coupling failures: Incorrect aircraft IDs				✓	

(iii) logistic support monitoring. Table 3 also presents the functional elements in each area.

7. Compliance analysis

Table 4 presents a compliance analysis of the regulator and air navigation service provider monitoring systems described in Section 5 against the system specifications listed in Section 6.

8. Conclusions

The ADS-B monitoring system specifications presented in this paper cover every part of the ADS-B system, including ground stations, avionics and performance levels. In other words, the specifications adopt a holistic view of the ADS-B system to ensure safety. The specifications can be used as the basis of future ICAO guidelines for developing and implementing ADS-B monitoring systems. The specifications could also serve as foundational or minimum requirements for air navigation service providers and original equipment manufacturers as they develop ADS-B monitoring systems.

The compliance mapping demonstrates that the approach adopted by Airservices Australia is the most compliant with the set of indicators. The U.S. Federal Aviation Administration, Civil Aviation Authority of Singapore and Civil Aviation Department of Hong Kong have to improve their current monitoring approaches to ensure ADS-B safety in air traffic control operations. However, a compliance mapping does not indicate the importance of items and parameters. The importance levels depend on the safety impact that the items and parameters have on operations. Clearly, the implementation of ADS-B performance monitoring is crucial because it directly impacts the integrity of surveillance data and, hence, safety. Additionally, more efforts should be directed at monitoring aircraft equipage levels in the corresponding airspaces in order to achieve the planned operational mandate.

It is also important to note that the methods for developing and implementing ADS-B monitoring functions depend on the capabilities and resources of air navigation service providers. ADS-B monitoring may be performed in an automated manner, a manual manner or a combination of both – but adequate and periodic monitoring must be performed to ensure the safety of the air transportation infrastructure.

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