Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)

ADS-B: The Case for London Terminal Manoeuvring Area (LTMA)

Busyairah Syd Ali, Arnab Majumdar, Washington Y. Ochieng and Wolfgang Schuster
Centre for Transport Studies
Imperial College London
London, United Kingdom
b.syd-ali09@imperial.ac.uk

Abstract*—EUROCONTROL in collaboration with various Air Navigation Service Providers (ANSPs) in Europe and in the United Kingdom established the CASCADE program to coordinate the implementation of Automatic Dependent Surveillance Broadcast (ADS-B) applications. In this program, the CRISTAL initiative provides data from validation trials in each country, to test the ADS-B technology in real scenarios where the operational needs exist. The ADS-B system is expected to play a key role to facilitate some of the safety-critical functions envisioned under the future operational concepts, including self-separation and Air Traffic Control based separation with reduced separation minima. ADS-B is a very complex system, highly dependent on the navigation and communication systems. A rigorous, clear and comprehensive assessment method is required to ensure that it is safe to operate in any particular context. This paper proposes a comprehensive framework to evaluate ADS-B data (from the NATS CRISTAL project) to determine its capability to meet the accuracy, integrity, latency, availability and update rate requirements to support the relevant safety-critical applications. In the proposed framework, the Global Positioning System (GPS) data from the aircraft navigation system are used as the reference data to validate ADS-B data accuracy as recorded by ground stations. The framework begins by decoding both sets of data (ADS-B and GPS) into the ASCII format. Both sets are then correlated based on the time and horizontal position, the most challenging task in the data evaluation process. The performance evaluation is carried out in terms of accuracy, integrity, latency, availability and update rate. The results show that 66.7% of the aircraft meet the requirement to support 3NM separation with horizontal position error less than 150 meters while the update rate analysis shows an inconsistent value for majority of the aircraft assessed. The key challenges in this analysis and errors identified in each dataset are also discussed in this paper.

Keywords- ADS-B; LTMA; GPS; accuracy

I. INTRODUCTION

Automatic dependent surveillance broadcast (ADS-B) is a surveillance technology based on the aircraft, which broadcast aircraft identification, state and position information periodically to other ADS-B equipped aircraft within a specified range and to ground stations for ATC use [1]. ADS-B relies on on-board navigation systems to obtain aircraft position information. [1]ADS-B is a key enabler of the Single European Sky (SES) ATM Research (SESAR) and the USA Next Generation Air Transportation System (NextGEN) programs. Therefore, it is crucial to ensure that ADS-B is safe. Even though ADS-B has been deployed on a large scale in Australia, the safety justification is based on the assessment that ADS-B is as good as the radar system [2]. Therefore, the capability of the system to support enhanced safety application is still to be determined. Furthermore ADS-B implementation in Australia is in non-radar airspace. From an operational perspective, the requirements for surveillance in non-radar airspace and dense airspace are different.

Figure 1 depicts the components that influence ADS-B system performance. These include the:

- positioning system on-board;
- ADS-B avionics on-board;
- data link;
- ADS-B ground station; and
- ADS-B data and quality indicators

In this paper, a comprehensive framework is proposed to evaluate ADS-B performance. Throughout the framework implementation and analysis processes, various problems were encountered due to dissimilar data characteristics and errors in the contributing components.

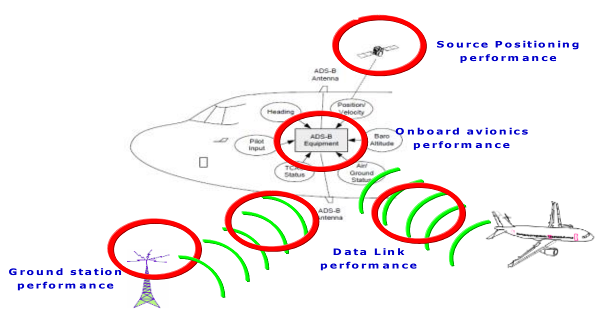


Figure 1. Components influencing ADS-B system performance

The scope of the study presented in this paper is based on a trial ADS-B system in the London Terminal Manoeuvring Area (LTMA) by NATS UK under the CRISTAL Project [3][3]. All twenty-six commercial aircraft

Malaysian-Imperial Doctoral Programme
The Lloyd's Register Educational Trust

included in this study use the Global Positioning System (GPS) as the onboard navigation system which feeds the aircraft position and velocity data to the ADS-B avionics. Mode- S 1090 MHz Extended Squitter (1090ES) is used as the data link to the ground stations.

The ADS-B infrastructure under the CRISTAL project include the ADS-B system network for surveillance coverage in the LTMA. It involved the installation of ADS-B ground receiver sensors and also equipage of an ADS-B emitter onboard each aircraft involved in the project. Six receiver sensors are installed at the existing NATS radio transmitter communication sites at Ventnor, Winstone, Chedburgh, Warlingham, Greenford and Reigate. The central processors, central monitoring servers and remote control and monitoring systems are located within the Test and Development equipment room at NATS CTC [3]. Figure 2 and 3 illustrates the ground receiver sensor installation sites and its coverage respectively.

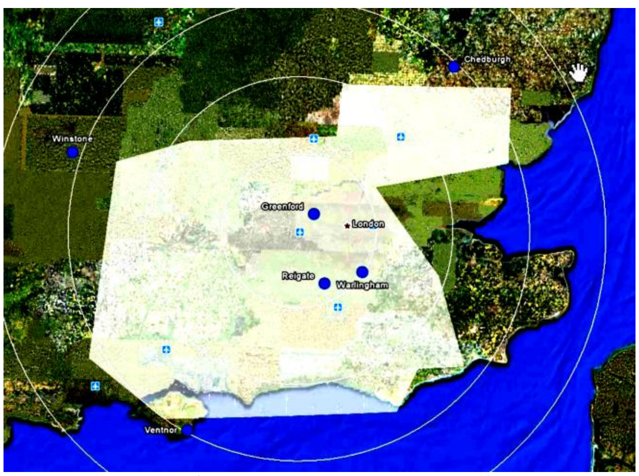


Figure 2. Coverage of ADS-B ground receiver sensors for the LTMA [3]

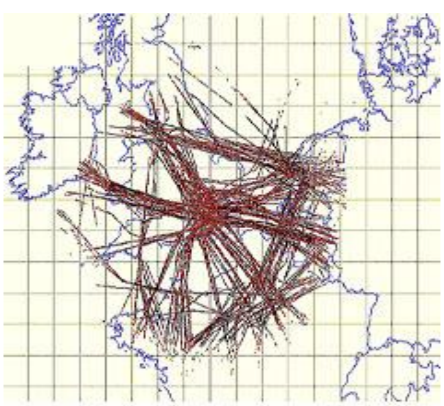


Figure 3. ADS-B Coverage [3]

The airspace is divided into 5 sectors (Figure 4). The sectors are designed to manage traffic arriving and departing from London Heathrow, Gatwick, Luton, Stansted, City as well as Birmingham, East Midlands and smaller airfields in the region. All the sectors are low-level, from the base of controlled airspace to FL195–215.

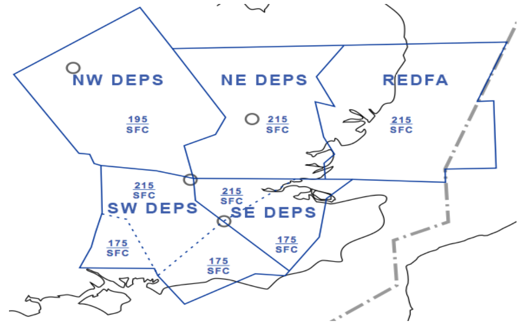


Figure 4. London Terminal Airspace Structure [4]

II. DATA CHARACTERISTICS

Two types of data are used in the study:

- ADS-B data recorded from the ADS-B ground stations (ASTERIX CAT021)
- Navigation data from the aircraft navigation system (GPS)

The ADS-B data are obtained from ADS-B ground stations (NATS) while GPS positioning data from aircraft, is obtained from British Airways, recorded on 10 January 2011 between 00:00:00 – 23:48:29. Figure 5 shows a descriptive statistical analysis to identify the percentage of fields present in the ASTERIX Category 021 message.

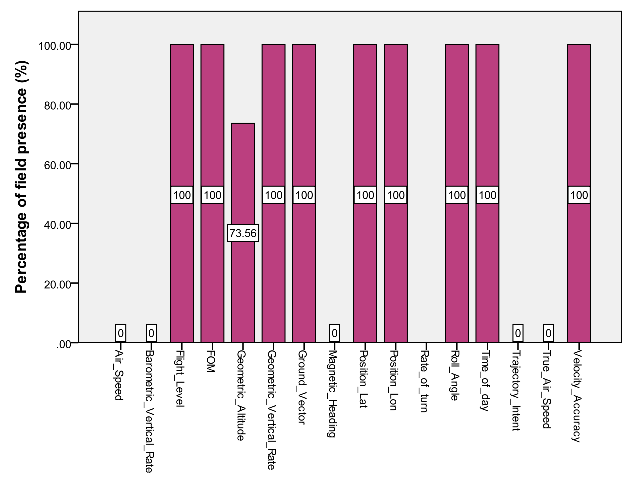


Figure 5. Analysis of fields present in ADS-B report (ASTERIX Category 021)

The time of detection, target position, aircraft address, flight level, Figure of Merit (FOM) and ground vector (speed and track angle) are always present in the ASTERIX messages, which are sufficient for the scope of this study. Other parameters, such as the air speed or trajectory intent, are noticeably lacking. The data fields present in the ADS-B message depend on the ADS-B avionics make model. The data used in this study complies with the requirements in RTCA DO-260 [5]. However, the latest standard available is RTCA DO-260B [6]. Table I presents the data field descriptions in the ADS-B message. A detailed description of each data field is provided in EUROCONTROL Standard

Document for Surveillance Data Exchange – ASTERIX Cat 021 ADS-B Messages [7].

TABLE I. ADS-B DATA FIELD DESCRIPTION

Data	Description
System Area Code (SAC)	An area identifier code, unique to a specific area, usually a whole country, displayed in decimal however usually displayed in hexadecimal, the UK is allocated 34 and 35 (Hex).
System Identification Code (SIC)	A unique identifier code allocated to each Radar / Surveillance System, the Cristal ADS-B system is counted as one consolidated surveillance source and hence is allocated one SIC code.
Target Report Descriptor (TRD)	Each of these items reports on the type and quality of the data received from the aircraft, for example, ARC refers to the altitude reporting capability of the aircraft, when aircraft report their altitude in the 1090 MHz Extended Squitter, it is quantised into either 100ft or 25 ft bands.
Time of Day (TOD)	Time of day in seconds after midnight.
Latitude (LAT) Longitude (LONG)	Latitude and Longitude in WGS-84 format displayed in decimal degrees.
ADD	The aircrafts unique ICAO 24 bit address in Hexadecimal, most registered aircraft in the world and all registered aircraft in the UK has a unique address that is hard coded into the Mode-S transponder.
GALT	Geometric Altitude in feet from a plane tangent to the earth's ellipsoid.
Flight Level (FL)	The flight level of the aircraft, which is the altitude of the aircraft expressed at a standard pressure setting of 1013 Mb and rounded to the nearest 100ft. This is used by en-route aircraft flying IFR to ensure all aircraft fly at the same relative altitudes and thus retain vertical separation. This is as opposed to flying on local QNH pressure settings generally used during VFR flight.
GV-GS	Ground Vector – Ground Speed
GV-TA	Ground Vector – Track Angle, direction the aircraft is heading
Target Identification (TID)	This is the callsign or registration of the aircraft.

Position reference data (obtained from the GPS) from British Airways contains less data fields than the ADS-B message:

- Time
- Latitude –WGS84
- Longitude-WGS84
- Altitude (Flight Level based on standard pressure setting of 1013 Mb)
- Radio Height
- Computed Air Speed
- Ground Speed

III. DATA EVALUATION FRAMEWORK

The framework of ADS-B data evaluation is shown in Figure 6. In this framework, the GPS data obtained from the aircraft is used to derive the TRUE position against which ADS-B horizontal position data are compared. The GPS derived position from the aircraft satisfies the requirement for the navigation system [8].In the first part of the process, ADS-B data collected from ground stations is decoded from ASTERIX 021 to ASCII format. It was found that the two data sets are generally asynchronous. Prior to correlation, it is important to check the timestamp accuracy of both data sets. A correlation algorithm was developed and applied to correlate the data sets. The algorithm uses timestamp and horizontal position differences as well as the 24 bit aircraft address. The correlated data set is then stored in a database and the GPS position is then extrapolated to derive a reference position (the TRUE). Next, various statistical analyses are conducted to clean up the data set. Not every ADS-B message can be used for the performance assessment. Less accurate and corrupt data are identified and discarded. Finally, performance analysis to measure data accuracy, integrity, availability, latency and update rate is conducted.

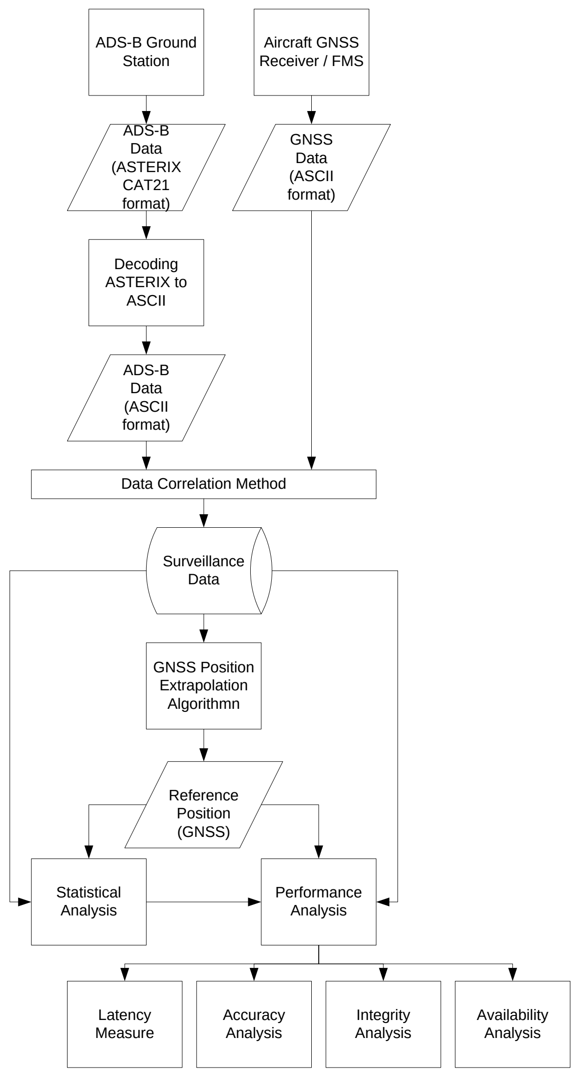


Figure 6. ADS-B Data Evaluation Framework

A. *Data Correlation*

Correlation of ADS-B data recorded from the ground stations and the corresponding GPS data from aircraft is made difficult due to vast differences in the data characteristics:

- Mismatch of update rates between data
- Inconsistent update rate of ADS-B data
- Lack of ADS-B data due to lack of coverage of the ADS-B ground station especially for lower altitude operations;
- Differences in the decimal precision of the horizontal position data from each source; and
- Time differences due to the delay in the ADS-B 'time' data with respect to GPS data, a key source of error.

Due to the discrepancies identified in the nature of the data sets, neither 'time' nor the 'horizontal position' data could be used to correlate the data sets directly. A systematic data synchronization method is thus a crucial prerequisite to any analysis.

The synchronization method initially identifies GPS data sets corresponding to a given ADS-B time-stamp on the basis of relative timing for the identified GPS subset. Geometrical differences with respect to the ADS-B position data (latitude and longitude) are assessed and the final GPS candidate is chosen on the basis of minimal difference. This process is repeated for each ADS-B data point. The flow chart in Figure 7 illustrates the flow of the processes in the method. All aircraft involved in this study are based on the ADS-B avionics certified under RTCA D0-260 [5] which performs extrapolation (by 200 ms) on the horizontal position received from the onboard GPS receiver due to the anticipated delay in the Flight Management System (FMS).

Based on this information, the method starts by identifying the first time stamp in the ADS-B data set as 'T1'. It then identifies the data set with a time-stamp 'T' from the GPS data set which are less than the 'T1'. For the identified subset, the difference between the ADS-B (latitude and longitude) at 'T1' and all the GPS (latitude and longitude) at 'T' when (T<T1) are measured. Based on the measurement, the GPS (latitude and longitude) with the minimal difference is kept and the rest from the subset are discarded from the GPS data set. The process is repeated for T2 of the ADS-B data set until the last 'Tn'.

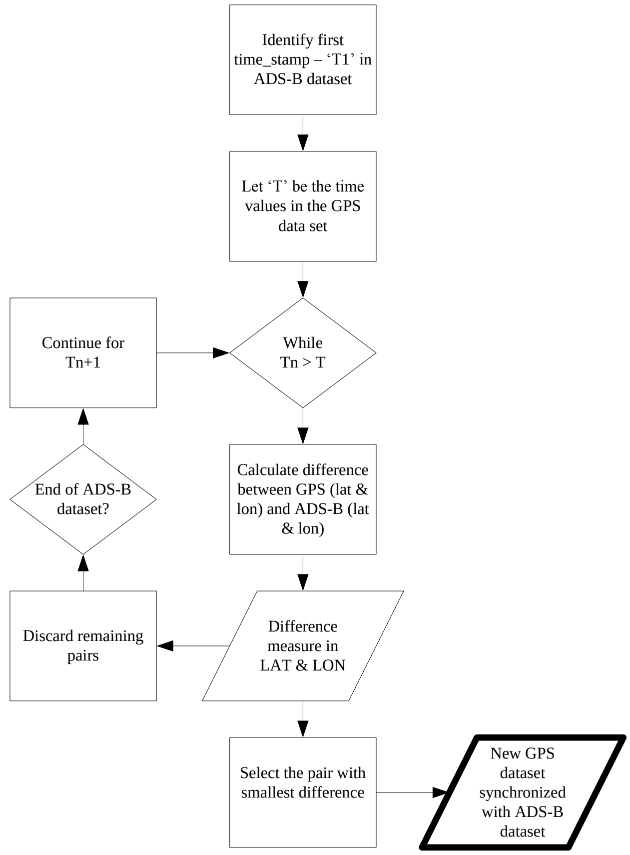


Figure 7. Flow chart for data correlation algorithm

B. Reference Horizontal Position Derivation Using Extrapolation Method

In this study, reference method is used to assess the performance of ADS-B horizontal position (latitude, longitude) recorded from ADS-B ground stations. GPS horizontal positions recorded from the aircraft FMS, are extrapolated to the exact time the ADS-B data is received at the ADS-B ground station. The extrapolated GPS horizontal position is used as the 'Reference' (TRUE).

The TRUE (φ_2, λ_2) is derived as:

$$\varphi_2 = \varphi_1 + d \cos \theta$$
$$\lambda_2 = \lambda_1 + d \sin \theta$$

where
φ_1 *is GPS latitude,*
λ *is GPS longitude,*
θ *is the bearing,*
d is the distance travelled.

The distance parameter 'd' is calculated using aircraft speed and latency in the data transmission from the aircraft to the ground station. 'θ' bearing is the heading of the aircraft. Further analyses to assess the data performance are conducted based on this TRUE.

IV. RESULTS OF EVALUATION

The aircraft assessed cover a number of different types of GPS Receivers, ADS-B Emitters and FMSs, thereby enabling the assessment of the impact of variable avionics systems on ADS-B performance. All the aircraft use Mode S 1090 MHz Extended Squitter (1090ES) as the data link technology to transmit ADS-B data from the aircraft to the ground stations. Among the 26 aircraft data collected for this study, only 9 aircraft were found to be suitable for performance analysis. The remaining aircraft were analysed for various problems that made them unfeasible for performance analysis. The following problems were identified to various extents in the data sets:

- Duplicate ADS-B messages, as recorded at ground level;
- GPS Clock errors as recorded on board the aircraft;
- GPS position fluctuations recorded on board the aircraft;
- Lack of consistent GPS position format output by the aircraft;
- Uncorrelated time intervals between GPS data (at aircraft level) and ADS-B data (at ground level).

Detailed descriptions on the problems are tabulated in Table II for each aircraft analysed.

TABLE II. PROBLEMS IN THE DATA SET FOR EACH AIRCRAFT TO CONDUCT PERFORMANCE ANALYSIS

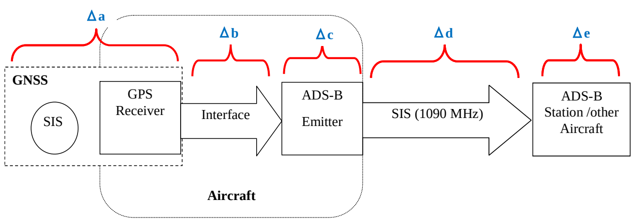
Aircraft ID	**Aircraft Make-model**	**Flight Level Data Availability**	**GPS Receiver**	**ADS-B Emitter**	**Findings**	**Feasibility for Performance Analysis**
40608F	A318	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set. GPS Clock error- no data on the 59th second in the time set. It appears as 00. Ground_Speed values contain '0'.	Feasible
405A48	A320	YES	Thales TLS755 MMR	Honeywell TRA-67A	Ground_Speed values contain '0'.	Feasible
400A26	A320	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set. Ground_Speed values contain '0'.	Feasible
40093D	A319	NO	Thales TLS755 MMR	Honeywell TRA-67A	GPS Clock error- time 'minute' does not add after the '59th' second. Groundspeed values contains '-'.	Not Feasible due to insufficient data
400877	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	GPS Clock error- time 'minute' does not add after the '59th' second.	Feasible
400878	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set.	Feasible
40087B	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set. GPS Clock error- time 'minute' does not add after the '59th' second.	Feasible
4008B4	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	GPS Clock error – time list does not include second '00'. Duplicate time values. Ground_Speed values contains '-'.	Feasible
4008F2	A319	NO	Thales TLS755 MMR	Honeywell TRA-67A	Duplicate ADS-B messages in the data set.	Feasible
400935	A319	YES	Thales TLS755 MMR	Honeywell TRA-67A	No peculiarities.	Feasible
All 6	B747-400		Rockwell Collins GLU920 MMR	ACSS XS-950	GPS horizontal position given every 4 seconds.	Not Feasible due to unreliable GPS data to generate TRUE
All 4	B767-300		Honeywell Mercury Card equipped EGPWC MkV	ACSS XS-950	GPS latitude and longitude values are given individually at different time update-every 2 seconds. Data is assumed to be corrupted.	Not Feasible due to unreliable GPS data to generate TRUE
4005C1	B777-200	NO	Honeywell GNSSU	Honeywell TRA-67A	GPS Data and ADS-B Data time interval does not correlate	Not Feasible due to uncorrelated timing information
4005BC	B777-200	YES	Honeywell GNSSU	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE
4005BE	B777-200	YES	Honeywell GNSSU	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE
400610	B777-200	YES	Honeywell GNSSU	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS

Aircraft ID	Aircraft Make-model	Flight Level Data Availability	GPS Receiver	ADS-B Emitter	Findings	Feasibility for Performance Analysis
						data to generate TRUE
4006C2	B777-200	YES	Rockwell Collins GLU920 MMR	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE
4007F7	B777-200	YES	Rockwell Collins GLU920 MMR	Honeywell TRA-67A	GPS latitude and longitude position jumping.	Not Feasible due to unreliable GPS data to generate TRUE

A. ADS-B Latency

ADS-B latency is the time delay between aircraft position determination by the on-board navigation system and position reception by the ground station. Figure 8 shows the ADS-B latency model. Various potential sources for the latency are identified, including:

- ADS-B ground station antenna delay
- GPS antenna on the ground station (for clock)
- Delay in the FMS (due to flight duration)
- Interfacing between FMS to transponder (ADS-B emitter)
- Interfacing between GPS receiver to transponder (ADS-B emitter)
- Time error at the ground station
- Data link delay (signal in space)



$$\textbf{Latency Model} = \Delta a + \Delta b + \Delta c + \Delta d + \Delta e$$

Figure 8. ADS-B Latency Model

The Δb varies due to ADS-B avionics configuration based on either D0-260/D0-260A or D0-260B. The configuration based on D0-260/D0-260A requires connection from the GPS receiver to the FMS, in which case the positioning information will be transmitted to the ADS-B emitter from the FMS while for the configuration based on D0-260B, the position information from the GPS receiver will be directly transmitted to the ADS-B emitter, bypassing the FMS. The first configuration will increase Δb not only due to the additional transmission stage, but the size of the FMS database will also contribute to the delay by increasing the data transmission processing time relative to the database size. The size of the FMS database is influenced by the flight duration as more information is gathered throughout the flight. The second type of configuration will improve Δb dramatically.

Latency for nine aircraft are analysed and tabulated in Table III. Based on the analysis, aircraft 400A26 shows the highest mean latency 1.9050 seconds with a standard deviation of 0.6485 seconds while aircraft 400878 shows the lowest latency 0.5597 seconds with a standard deviation of 0.2627 seconds. Aircraft 40087B shows the highest and aircraft 400877 lowest variation in the latency for each ADS-B message transmitted to the ground stations. Since the aircraft type and avionics make-model are the same for all the aircraft in this list, no particular conclusion is made to justify the variation in the latency performance.

TABLE III. LATENCY ANALYSIS RESULTS

Aircraft ID	GPS Receiver	ADS-B Emitter	Mean Latency (second)	Std. Dev (second)
40608F	Thales TLS755 MMR	Honeywell TRA-67A	1.7227	0.4851
405A48	Thales TLS755 MMR	Honeywell TRA-67A	0.6289	0.2430
400A26	Thales TLS755 MMR	Honeywell TRA-67A	1.9050	0.6485
400877	Thales TLS755 MMR	Honeywell TRA-67A	0.6927	0.1615
400878	Thales TLS755 MMR	Honeywell TRA-67A	0.5597	0.2627
40087B	Thales TLS755 MMR	Honeywell TRA-67A	1.7414	0.7008
4008B4	Thales TLS755 MMR	Honeywell TRA-67A	0.5895	0.2760
4008F2	Thales TLS755 MMR	Honeywell TRA-67A	0.6235	0.2584
400935	Thales TLS755 MMR	Honeywell TRA-67A	0.7094	0.2158

The latency performance impacts the performance of Air Traffic Control (ATC). Assuming for example, that an aircraft travels at 400 knots, the highest mean latency as identified in the analysis of 1.9050 seconds translates into an error in the 3D geometrical distance of 392 meters. This is may be a problem for ATC to provide 3NM separation based on the requirements in ED-142 [9]. Figure 9 to 12 show the latency distribution for aircraft 400A26 and 400878 respectively.

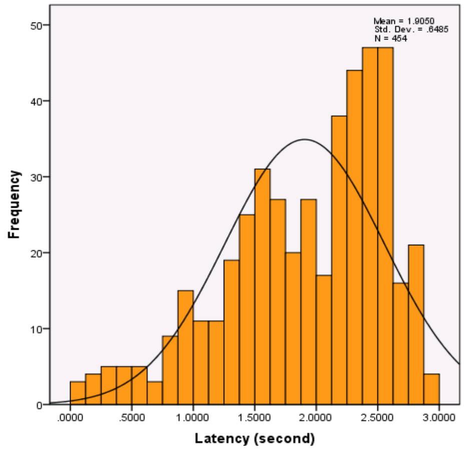


Figure 9. Latency distribution for aircraft 400A26

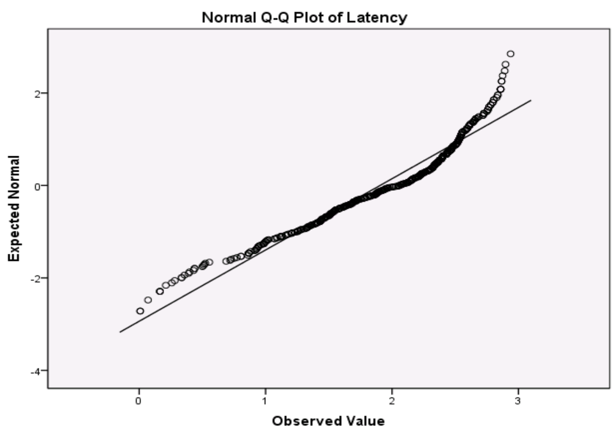


Figure 10. Deviation from normal distribution for aircraft 400A26

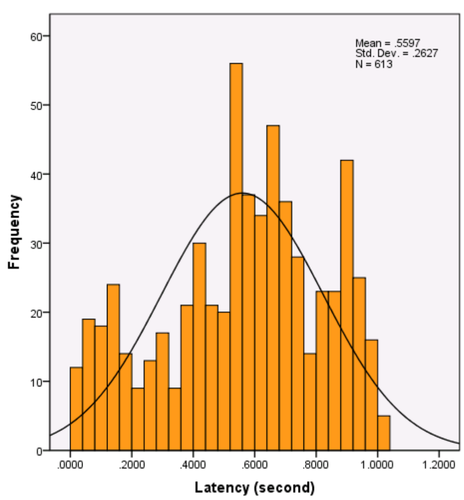


Figure 11. Latency distribution for aircraft 400878

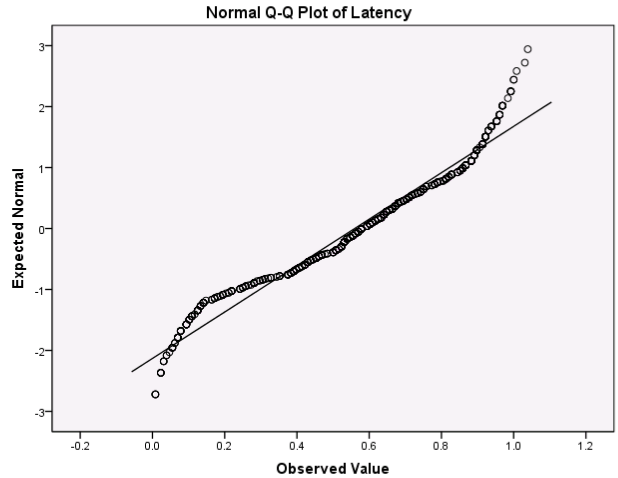


Figure 12. Deviation from normal distribution for aircraft 400878

B. ADS-B Horizontal Position Accuracy

In this paper, evaluation of ADS-B horizontal position accuracy is conducted by comparing the received position from ADS-B ground station and TRUE position derived based on the method explained in Section III-B. Table IV tabulates the Root Mean Square (RMS) horizontal position error measured for each suitable aircraft.

TABLE IV. RMS HORIZONTAL POSITION ERROR

Aircraft ID	GPS Receiver	ADS-B Emitter	RMS Position Error (meter)	Mean Update Rate (second)
40608F	Thales TLS755 MMR	Honeywell TRA-67A	476.2826	9.6
405A48	Thales TLS755 MMR	Honeywell TRA-67A	66.2622	1.1
400A26	Thales TLS755 MMR	Honeywell TRA-67A	552.8482	1.4
400877	Thales TLS755 MMR	Honeywell TRA-67A	109.4822	2.5
400878	Thales TLS755 MMR	Honeywell TRA-67A	113.1374	1.4
40087B	Thales TLS755 MMR	Honeywell TRA-67A	14287	1.0
4008B4	Thales TLS755 MMR	Honeywell TRA-67A	30.8691	2.3
4008F2	Thales TLS755 MMR	Honeywell TRA-67A	48.8772	1.3
400935	Thales TLS755 MMR	Honeywell TRA-67A	145.4744	1.1

Based on the results, aircraft 40087B shows an unacceptable position error of 14287 meters. Further investigation is in progress with British Airways on the performance of this particular aircraft. Six of the aircraft are commensurate with the requirement of 3NM separation i.e <150 meters RMS error [9] . Figure 13 to 16 shows the worst and least position error over time and the position error distribution for aircraft 40087B and 4008B4 respectively.

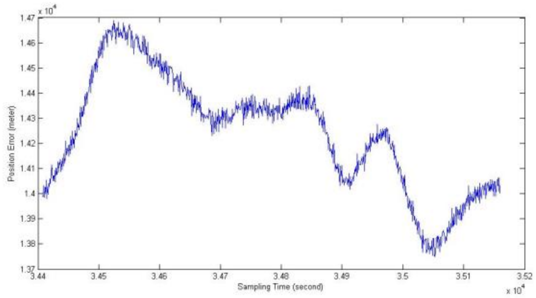


Figure 13. Position error over time for aircraft 40087B

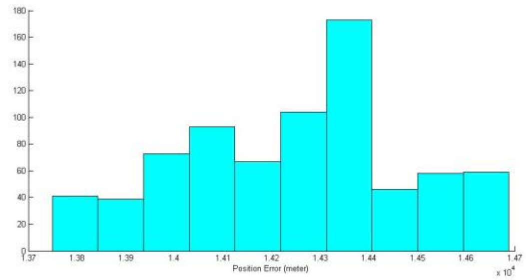


Figure 14. Position error distribution for aircraft 40087B

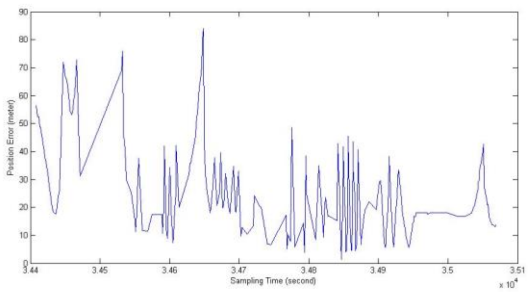


Figure 15. Position error over time for aircraft 4008B4.

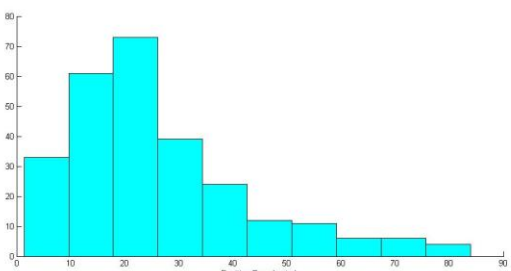


Figure 16. Position error distribution for aircraft 4008B4.

C. ADS-B Update Rate

Update rate is the rate at which the aircraft's position is updated to users. These are envisioned to be between 0.5 and 2 seconds to support enhanced separation minima. However, based on the analysis conducted in this paper, the update rate values for most of the aircraft are inconsistent. Table IV shows the mean update rate for each aircraft assessed. Possible reasons for the inconsistency maybe due to the Mode-S signal jamming, delay in the aircraft FMS as an intermediary between the GPS receiver and the ADS-B emitter or the phases of flight; whereby there are less detection by the ground station when the aircraft is taxiing on the airport surface.

D. ADS-B Horizontal Position Integrity

As for the ADS-B horizontal position integrity assessment, the ADS-B data available for this study includes a position integrity quality indicator called Figure of Merit (FOM). FOM in ASTERIX Category 21 format represents the Navigational Uncertainty Category (NUC). The NUC basically encodes the integrity bound, Horizontal Protection Limit (HPL) provided by the GPS receiver (for avionics based on DO-260) as a numerical value, from 0 to 9, whereby higher the NUC value, higher the position integrity. In order to determine whether ADS-B data may be used to provide ATC separation service, position integrity indicator is required [10]. In this paper, the term FOM is used to represent the horizontal position integrity quality indicator.

Based on the data analysis in Table V, the mean position integrity of the sample is 5.43, i.e. above the threshold specified in Table VI.

FOM=0 cases maybe the result of the ADS-B ground station detecting unreasonable position jumps. Such position jumps can result from avionics faults, and sometimes, for unknown reason, at the edge of coverage [11]. When the ADS-B ground stations detect an unreasonable jump, the FOM value transmitted to ATC is zero (so that the position is not be used by the ATC system).

TABLE V. DESCRIPTIVE ANALYSIS OF FIGURE OF MERIT (FOM) FOR POSITION INTEGRITY

	N	Min	Max	Mean	Std. Dev
FOM	95676	0	8	5.43	2.620

E. ADS-B Availability

The Air Traffic Control System only considers ADS-B data "good" and displays ADS-B data to controllers when the FOM value is above a given threshold value. If the FOM does not reach this threshold, the ADS-B data is not displayed and the ADS-B service is disrupted to that aircraft.

The FAA-EUROCONTROL Requirements Focus Group (RFG) has developed guidance material for Non Radar Airspace (NRA) and the Radar Airspace (RAD) ADS-B applications. RFG documents include consideration of an acceptable NUC/FOM value for delivery of 5 Nm and 3 Nm separations as shown in Table VI.

TABLE VI. SEPARATION REQUIREMENT BASED ON 'NUC'AS QUALITY INDICATOR

RTCA standard for Non Radar Airspace (NRA) : DO303 [12]	RTCA standard for Radar Airspace (RAD) : DO318 [13]
5 NM en-route separation : NUC = 4 3 NM separation: NUC = 5	5 NM en-route separation: NUC = 4 3 NM separation: NUC = 5

Whilst it may be attractive to focus on avionics requirements where NUC=4 is the minimum (en-route 5NM), it is well accepted that NUC=5 is required for terminal area operations at 3NM [5].

The percentage of "good" reports (FOM > threshold) during the sample period effectively represents the availability of the GPS position data to the ADS-B transmitter during the sample period. Failures of the ADS-B transmitter, the ADS-B ground station receiver will affect the sample period, because no data will be collected during that time. Based on the data analysis in Figure 17 and correlation to the requirements in Table VI, the ADS-B data availability is 81.8% and the percentage of good ADS-B reports is 81.78% when the threshold value is set to 4.

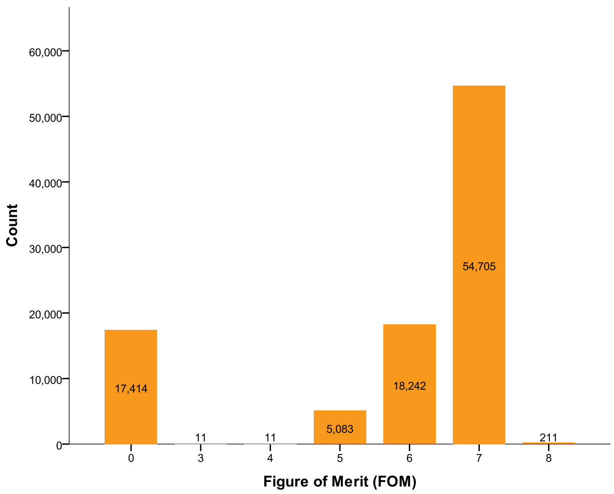


Figure 17. Availability of the ADS-B positional data

F. *Corresponding Integrity Quality Indicator Validation*

The ADS-B position accuracy is presented in section IV-B as the Horizontal Position Error (HPE). The integrity risk of the ADS-B position is the probability that the error larger than the Alert Limit (AL) is undetected. The AL based on the FOM/NUC for aircraft certified under DO-260 is given in Table VII.

TABLE VII. ALERT LIMIT BASED ON FOM/NUC

NUC in DO-260	**HPL in DO-260 (Alert Limit)**
0	≥ 20NM
1	< 20NM
2	< 10NM
3	< 2.0NM
4	< 1.0NM
5	< 0.5NM
6	< 0.2NM
7	< 0.1NM
8	< 25meters
9	< 7.5meters

Based on the information (AL) in Table VII, the integrity performance provided in the ADS-B reports in the form of FOM/NUC is validated. The integrity performance is assessed and categorized into three states:

- A Correct Detection event occurs when the FOM value presented to the controllers is less than the alert limit and the actual HPE is also less than the alert limit; (HPE<FOM< AL).
- A Missed Detection event occurs when the FOM value presented to the controllers is less than the alert limit while the actual HPE is greater than the alert limit; (FOM<AL<HPE).
- A False Alert event occurs when the FOM value presented to the controllers is less than the alert limit while the actual HPE is greater than the FOM but less than the alert limit; (FOM<HPE<AL).

Table VIII provides the results. Based on the results, it is found that 3 aircraft indicate missed detection and no false alert events are identified. Missed detection event is a crucial issue that needs to be addressed as it involves safety due to the reliance of the ATC on the integrity quality indicator to use the position information provided by the ADS-B system for aircraft separation.

TABLE VIII. FOM VALIDATION

Aircraft ID	**HPE (meters)**	**FOM**	**AL (meters)**	**Δ=AL-HPE**	**Integrity Performance Category**
40608F	476.2826	7	<185.2	-291.0826	Missed Detection
405A48	66.2622	7	<185.2	118.9378	Correct Detection
400A26	552.8482	7	<185.2	-367.6482	Missed Detection
400877	109.4822	7	<185.2	75.7178	Correct Detection
400878	113.1374	7	<185.2	72.0626	Correct Detection
40087B	14287	7	<185.2	-14101.8	Missed Detection
4008B4	30.8691	6.4	<370.4	339.5309	Correct Detection
4008F2	48.8772	6.9	<185.2	136.3228	Correct Detection
400935	145.4744	7	<185.2	39.7256	Correct Detection

V. CONCLUSION

This paper has presented a comprehensive framework for ADS-B data performance evaluation using a comparison method (using extrapolated GPS horizontal position as the reference). The evaluation was made by analysing recorded data, observing tracks, measuring horizontal position error; accuracy, integrity, latency, availability and update rate. The paper also includes various errors identified in the datasets which limited the performance evaluation. Finally, it provides a method to validate the integrity quality indicator included in the ADS-B report. The aircraft used in this analysis are certified under DO-260 certification. However, the method proposed in this paper are applicable for the aircraft certified under DO-260B in the future.

VI. RECOMMENDATION

Unlike the radar system, ADS-B performance cannot be assessed as a whole whereby failure of ADS-B system on one aircraft does not affect the whole ATC surveillance. Each aircraft may show different performance due to the type of avionics or state of the communication link service. The main problem with the communication link is signal jamming. For example, Mode S 1090 MHz Extended Squitter (1090ES) is utilised not only by ADS-B, it is also used by Secondary Surveillance Radar (SSR) and Traffic Collision Avoidance System (TCAS). In the dense airspace this may affect ADS-B system reliability and availability, a problem that remains to be addressed. Common performance determinant for ADS-B is the Global Navigation Satellite System (GNSS) and ADS-B ground station, whereby failure of the GNSS or ground stations will affect the whole ATC surveillance. A redundant navigation source with a flag, for example Inertial Navigation System may be a good idea to resolve this issue. In order to identify performance of the ground station, it would help to include the ground station identification into the ADS-B message processed at the ground station for ATC system maintenance reference.

ACKNOWLEDGEMENTS

This research is funded by Lloyd Register and Educational Trust Fund (LRET) and Malaysian-Imperial Doctoral Programme (MIDP). It is being carried out in collaboration with NATS UK, British Airways and EUROCONTROL.

REFERENCE

1. RTCA, *Minimum Aviation System Performance Standards For Automatic Dependant Surveillance Broadcast (ADS-B).* 2002(DO-242A).
2. ICAO, *Assessment of ADS-B to Support Air Traffic Services and Guidelines for Implementation*. 2006.
3. Foster, C., *CRISTAL RAD HD*. 2011, NATS UK.
4. International Virtual Aviation Organisation. *London Terminal Control Centre*. 2012 [cited 2012 July]; Available from: http://ivao.co.uk/atc/ltcc/.
5. RTCA, *Minimum Operational Performance Standards For 1090 Mhz Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B)* in *DO-260*. 2003.
6. RTCA, *Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Services – Broadcast (TIS-B)*, in *DO-260B*. 2011.
7. EUROCONTROL, *EUROCONTROL Standard Document for Surveillance Data Exchange Part 12 : Cat 021 ADS-B Messages*. 2003, EUROCONTROL.
8. Department of Defense, U.S.o.A., *GPS Standard Positioning Service (SPS)* 2008.
9. EUROCAE, *Technical Specification for Wide Area Multilateration (WAM) Systems*, in *101/ ED-142*, EUROCAE, Editor. 2010.
10. ICAO, *ADS-B Implementation Issues*, in *Working Group Meeting*, Aeronautical Surveillance Panel, Editor. 2007: Brussels.
11. ICAO, *Further Analysis of ADS-B NUC Data.* 2009(SEA ADS-B WG4-IP 3 V2).
12. RTCA, *Safety, Performance and Interoperability Requirements Document for the ADS-B Non-Radar-Airspace (NRA) Application.* 2007(DO-303).
13. RTCA, *Safety, Performance and Interoperability Requirements Document for Enhanced Air Traffic Services in Radar-Controlled Areas Using ADS-B Surveillance (ADS-B-RAD).* 2009(DO-318).

Author Biography

Busyairah Syd Ali is a PhD student at Centre for Transport Studies within the Department of Civil and Environmental Engineering at Imperial College London. She is investigating the impacts of a new surveillance technology called Automatic Dependant Surveillance Broadcast (ADS-B) on Air Traffic Management operations. She worked as an Operation and Maintenance Engineer for Air Traffic Control Systems at Kuala Lumpur International Airport for five years.

Dr. Arnab Majumdar is The Lloyds Register Educational Trust (LRET) Lecturer in Transport Risk Management and the Director of the Transport Risk Management Centre (TRMC) at the Centre for Transport Studies, Imperial College London. He has spent over 20 years researching air transport.

Professor Washington Ochieng holds the Chair in Positioning and Navigation Systems in the Department of Civil and Environmental Engineering at Imperial College London. He is also the Director of the ICEGG and the Departmental Master of Science programmes. He is a Fellow and Member of Council of the Royal Institute of Navigation, and Member of the US Institute of Navigation.

Dr Wolfgang Schuster is the Director of the Air Traffic Management (ATM) and Intelligent Transport Systems (ITS) Groups. He is a Research Fellow (Assistant Professor) in Positioning and Navigation Systems and ATM. He is an Associate Fellow of the Royal Institute of Navigation, Senior Member of the American Institute for Aeronautics and Astronautics (AIAA) and Member of the Royal Aeronautical Society.