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Twelfth USA/Europe Air Traffic Management Research and Development Seminar (ATM2017)

Large-Scale ADS-B Data and Signal Quality Analysis

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Abstract

To investigate the contradicting findings of previous studies that investigated ADS-B quality, a study was performed to analyze the data and signal quality of ADS-B. For this study, a large dataset of raw ADS-B messages was analyzed, regarding the quality of the data and the signal, differentiating between internal and external sources of errors. The conclusions from this analysis show that ADS-B indeed is a promising technology, where aircraft are able to accurately report their navigational parameters, but that external factors (e.g., reception probability and malfunctioning on-board equipment) can cause issues with the usability of ADS-B as a primary means of surveillance.

***Keywords*—ADS-B, surveillance, latency, accuracy, update interval, integrity, availability**

I. Introduction

Automatic Dependent Surveillance - Broadcast (ADS-B) is a form of dependent surveillance that makes use of an aircraft's Mode-S transponder to periodically broadcast navigational information. ADS-B is seen as an enabler for improved surveillance, pilot situation awareness, and airborne spacing and separation applications, and will be mandated in both Europe and the United States by 2020. Even though the progress towards implementation is accelerating, there still are uncertainties regarding the quality of ADS-B [1]. Considering the intended role of ADS-B in future ATM systems, it is therefore vital that a sufficient level of surveillance quality with ADS-B can be guaranteed. For this paper, an ADS-B data- and signal quality study was therefore performed. This paper describes the method and results of an analysis of raw ADS-B messages that were received by a ground station installed for this purpose. Although several studies have already been performed to investigate ADS-B quality, their contradicting results leave the question whether ADS-B is suited for (primary) surveillance purposes unanswered. This research aims to analyze ADS-B data- and signal quality and to investigate the effects of internal and external factors on ADS-B performance, and by doing so to provide a contribution to the ADS-B evaluation on its path towards implementation.

This paper will provide a short ADS-B background in Section II, where the history, intended benefits, and message structure are explained. Section III describes the method of analysis, and illustrates how reference tracks are produced from track data, how evaluation parameters are calculated, and how the effects of internal and external factors on ADS-B performance are investigated. Section IV shows the results from the analysis, together with a discussion on the outcomes. This paper is concluded with the Conclusions and Recommendations sections.

II. ADS-B background

The predominant surveillance implementation worldwide makes use of ground-based radar installations. Although proven to be effective, it has several drawbacks. Its reliance on expensive equipment, and its limitation to line-of-sight operations foster the interest in dependent surveillance implementations such as ADS-B. In addition to cutting costs, ADS-B has the potential to enable surveillance over unpopulated areas like oceans, mountains, and deserts using satellite receivers and ADS rebroadcast. On-board, ADS-B can be used to increase pilot situation awareness, and it can be an enabler for airborne spacing and separation applications. [2] Next to operational applications, ADS-B can also be used for other applications which can result into economical or other operational benefits [3]. ADS-B can enhance flight following, also for public interests with flightradar24.com as example, and improve Search And Rescue (SAR) operations with the missing aircraft MH370 as a tragic example case, where improved flight following would have indicated the aircraft's whereabouts. Together with the predicted increase in traffic demand, ADS-B is therefore an important topic of investigation. [4], [5]

ADS-B is a form of co-operative dependent surveillance, where aircraft determine their own state (*dependent*), which they transmit to other users (*co-operative*). Radar surveillance, on the other hand, is a form of co-operative *independent* surveillance, where a ground station determines range and azimuth of aircraft with respect to the radar antenna. One of the advantages of ADS-B as opposed to radar is that its position determination (using GNSS) can be more accurate. As a result, separation minima can potentially be reduced, thereby increasing airspace capacity. ICAO endorsed the concept of ADS-B in 1991, and assumes ADS-B will play an important role in future ATM systems [6].

There have been several studies that aimed to assess the quality of ADS-B, with varying results. [1], [7]–[9] An investigation of ADS-B performance in the London Terminal Maneuvering Area (TMA) by Ali et al. showed inconsistent performance, but could not provide extensive performance statistics because of limited data. [1] Similarly, an investigation performed by Zhang, Liu, and Zhu also only analyzed three separate flights [9]. Rekkas and Rees and Barsheshat found similar results with respect to each other, stating that nearly 100% of all flights show an accuracy better or equal to radar. [7], [8]

III. Method

Based on previous studies, it can not be unequivocally concluded that ADS-B can serve as a primary means of surveillance. This study aims to address this question through

an analysis of a large set of ADS-B messages, received by a ground station situated in an area with high traffic density (Delft, near Schiphol airport). This section describes the method of data aquisition and analysis.

A. Data acquisition and preprocessing

The analysis presented in this paper made use of three data sources. The ADS-B data itself was acquired from a ground-based ADS-B antenna, situated on top of a high-rise building in Delft, with a near-unobstructed view of the surroundings. Two additional sources served as a reference: radar track data, provided by Maastricht Upper Area Control (MUAC), and on-board data from a Cessna c550, a laboratory aircraft co-owned by TU Delft and the Dutch Aerospace Laboratory (NLR).

Several days of data are used for the analysis. The first collection of days ranges from 21 to 27 September 2015. As will be explained in the data analysis results section, this set of days proved to have inconsistent ADS-B data. For that reason, a second set of days was obtained, from 11 to 15 January 2016. For the data analysis (i.e. the latency and accuracy of the data) the January dataset will be used. For the signal analysis (i.e. update interval and integrity) both datasets are usable.

To be able to compare the ADS-B data to the radar reference data, which most likely have different sample times and intervals, a reference track is constructed from the reference data using spline interpolation. The reference track gives position as a function of time:

$$\vec{x}_{ref}(t) = (\phi(t), \lambda(t), h(t)) \tag{1}$$

Here, ϕ is the latitude, λ is the longitude, h is the altitude, and t is the UTC time. A third-order spline fit is used to ensure continuity up to the second derivative. Substituting the time stamp of a received ADS-B reports into the spline functions results in a set of reference coordinates to which the reported position can be compared.

B. Dependent measures

Similar to previous studies, this paper distinguishes between data and signal quality. Data quality is assessed in terms of latency and accuracy, and signal quality in terms of update interval and integrity. In addition, this paper also investigates factors that affect the performance of ADS-B. This analysis investigates the reception probability under the effects of frequency congestion and larger ranges, and whether the use of different types of equipment is visible in the ADS-B performance. These measures are described as follows:

1) Latency

A latency, or time delay, exists between position determination on the transmitting side, and signal registration on the receiving side, which means that the received position is in effect an outdated position. This latency is the result of data processing on both sides, and transmission time (where the latter is negligible for the concerned distances). With on-board reference data, latency can be estimated by comparing on-board timestamps to ground-station timestamps for matching position samples. For the radar reference data, time-stamped ADS-B data are compared to the spline-fit of the corresponding radar track, see Figure 1. Here the estimated latency is me minimum least-squares fit of the spline model on the ADS-B data. Note, however that this approach requires an acceptable match between the ADS-B and radar tracks. Large offsets could cause

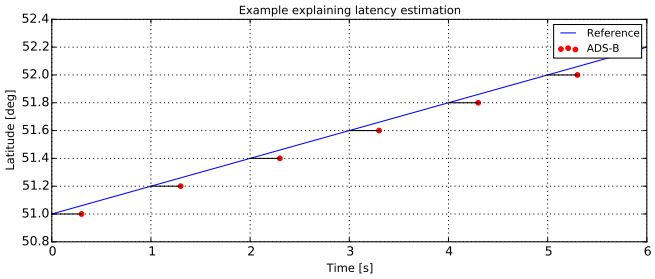

Fig. 1. Example explaining latency estimation

this method to pick an inappropriate reference location on the reference track and calculate an inappropriate latency. To separate the accuracy and latency effects, the top 5 percent of aircraft showing the best correlation with the reference track were therefore selected for the latency estimation.

2) Horizontal position accuracy

The horizontal position accuracy is defined as the 2D offset between the ADS-B report and the reference track, after subtraction of the estimated latency error. Understandably, it is important that the reported position by the aircraft is also the actual position the aircraft is flying (except for the inaccuracy introduced by the inevitable latency and GPS readings). The accuracy of an ADS-B signal is assessed using the root mean square and the average of the position offsets d_i. These offsets are calculated by comparing the timestamped data to the spline functions. The horizontal offset is determined using the spherical law of cosines:

$$d = (R_E + h) \cdot \arccos\left(\sin\phi_1 \sin\phi_2 + \cos\phi_1 \cos\phi_2 \cos\Delta\lambda\right), \tag{2}$$

Here, R_E is the radius of the Earth, h is the altitude of the aircraft, ϕ is the latitude and λ is the longitude.

3) Update interval

The update interval is defined as the time interval between succeeding position reports. This parameter is analyzed by collecting all timestamps from received reports from one specific flight and calculating the time difference between the individual reports:

$$UI = t_i - t_{i-1} \tag{3}$$

It is expected that the reception at the edges of the coverage area is limited, directly influencing the update interval results. Since the analysis should be as independent on ground antenna performance as possible, only reports within a certain range of the antenna are taken. The effects of the Earth's curvature and range are then minimized, resulting in a more accurate analysis of the update interval.

4) Integrity and availability

Each ADS-B position update is provided with a position quality indicator, which indicates the reliability of the reported position. This indicator is called the Navigational Integrity Category (NIC) for ADS-B Version 1 and 2, and can be derived from the messages' type codes. The NIC values relate to a certain Horizontal Position Limit (HPL), which is listed in Table I. En-route surveillance may only be conducted with reports with NIC ≥ 5, TMA traffic with NIC ≥ 6, and traffic on final approach requires NIC ≥ 7 [10]. The *availability* is the percentage of position reports complying to this requirement. For the analysis, every single reported NIC value is collected in order to analyze the availability.

TABLE I
RELATION BETWEEN TYPE CODES, HPL AND NIC VALUES [11]

TC	HPL limits					NIC
9			HPL	$<$	7.5 m	11
10	7.5 m	$\leq$	HPL	$<$	25 m	10
11	25 m	$\leq$	HPL	$<$	0.1 NM	8
12	0.1 NM	$\leq$	HPL	$<$	0.2 NM	7
13	0.2 NM	$\leq$	HPL	$<$	0.5 NM	6
14	0.5 NM	$\leq$	HPL	$<$	1.0 NM	5
15	1.0 NM	$\leq$	HPL	$<$	2.0 NM	4
16	2.0 NM	$\leq$	HPL	$<$	10 NM	1
17	10 NM	$\leq$	HPL	$<$	20 NM	1
18	20 NM	$\leq$	HPL			0

5) Reception probability

Reception probability directly links to the update interval analysis, but this part of the analysis focuses on the causes of a reception probability drop by analyzing the phenomena of frequency congestion, Earth's curvature and the range between the transmitting aircraft and the antenna. Since the ADS-B frequency is also used for SSR interrogation replies, it may not be unlikely that an ADS-B report is missed due to frequency congestion. Missed ADS-B reports increase the update interval and with increasing air traffic, the phenomenon of frequency congestion can be an issue. To visualize the effects of frequency congestion on the reception probability, the amount of air traffic in the coverage area is compared with the average update interval. It is expected that the average update interval correlates with the number of aircraft in the coverage area. By analyzing the number of received reports as a function of the range will show the effects of the curvature of the Earth and the loss of signal power. By taking a control volume with a sufficient altitude, the curvature effects are eliminated and it can be studied how the range affects the reception probability.

6) ADS-B equipment

There are multiple types of GPS receivers and transponders available for aircraft. This difference in equipment can have an effect on the performance of ADS-B. Aircraft landing and taking off from Schiphol Airport are taken as dataset, in order to have a large variety in aircraft types and airliners, and its performance is analyzed between aircraft types, between airliners, and between aircraft-airliner combinations. It is expected that there will be significant differences in performance when comparing types of aircraft and airliners.

IV. RESULTS

As described in Section III, the results are based on two time periods, one in September 2015, one in January 2016. During the analysis of the September dataset, it was found that the ADS-B timestamps were corrupted. The average time offset between these timestamps and the timing of the reference data was increasing every day with a steady rate of 0.4 seconds per day. After reconsidering the decoding system, it showed that the time synchronization with UTC time was faulty. In order to still analyze the system latency, a new dataset was acquired (the January dataset) together with properly timestamped ADS-B reports. The results are divided into four sections; a summary of the reception statistics, the results of the data analysis in terms of latency and accuracy, the results of the signal analysis in terms of update interval and the integrity/availability, and the results of the performance degradation analysis in terms of reception probability and ADS-B equipment.

A. Reception statistics

Figure 2 shows the number of received messages per update type and Table II shows the number of individual aircraft detected, the number of flight movements, number of received ADS-B position reports and number of decoded position messages per day. Figure 3 provides a density map based on message transmission locations, to give an indication of the distribution of messages within the coverage area.

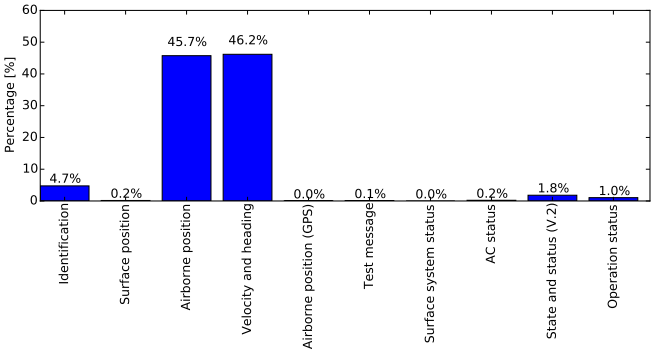

Fig. 2. Distribution of received message update types

TABLE II
NUMBER OF DIFFERENT AIRCRAFT DETECTED, NUMBER OF FLIGHT MOVEMENTS, NUMBER OF RAW POSITION UPDATES, AND DECODED ADS-B POSITION MESSAGES FOR EACH DAY IN BOTH THE SEPTEMBER AND THE JANUARY DATASET

Date	Aircraft	Flights	Raw messages	Decoded
Sept 21	2,159	6,505	5,395,349	1,979,772
Sept 22	2,200	6,399	5,338,961	1,965,201
Sept 23	2,190	6,340	5,205,890	1,789,932
Sept 24	2,237	6,574	5,353,358	2,017,010
Sept 25	2,225	6,697	5,505,487	2,020,401
Sept 26	2,201	6,186	5,550,349	1,912,126
Sept 27	2,283	6,547	5,708,948	1,951,222
Total	*15,495*	*45,248*	*38,058,342*	*13,635,664*
Jan 11	2,000	5,162	5,090,397	1,825,413
Jan 12	1,930	4,707	4,901,541	1,601,414
Jan 13	1,725	4,191	3,896,711	1,476,643
Jan 14	1,971	4,888	4,946,163	1,811,237
Jan 15	1,866	4,905	4,420,649	1,572,143
Total	*9,492*	*23,853*	*23,255,461*	*8,286,850*

About 35% of all received position messages result in a decoded position. This is explained by the fact that for a position to be decoded, two separate position updates are needed: one with an odd frame and the other with even frame (details on how to decode these positions is explained in the Appendix to the paper). Hence, two position updates are required to decode one position. When, for example, an odd-framed message is missed the decoder waits for the next odd frame for decoding the aircraft's position with a maximum waiting time of five seconds. Consider the following reception pattern (with O indicating an odd frame and E indicating an even frame):

O O – E O – E O O – E

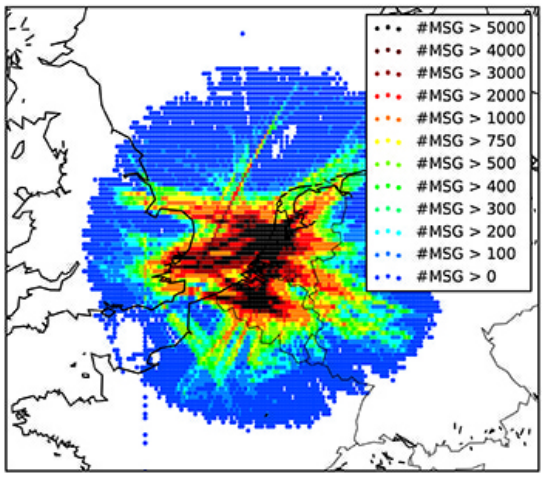

Fig. 3. Density map of message transmissions within the coverage area.

The dashes indicate the possibility to decode a position. In this example, it results in three decoded positions whereas 8 messages are received.

B. Data analysis results

Before the data was analyzed, the dataset of ADS-B reports has been filtered. Only aircraft from which, at a certain moment during the flight, more than 30 messages have been received over a timespan of 60 seconds have been included in the data analysis. Data from aircraft with faulty transmissions are also removed before analysis. This occurred for one aircraft. This aircraft performed over 20 flights and its reported ADS-B positions show an impossible flight track, see Figure 4. Here, the reported ADS-B positions (blue) and the radar tracks (red) are clearly inconsistent, where the ADS-B reports, fixed on the prime meridian, are unlikely to be correct. The analysis

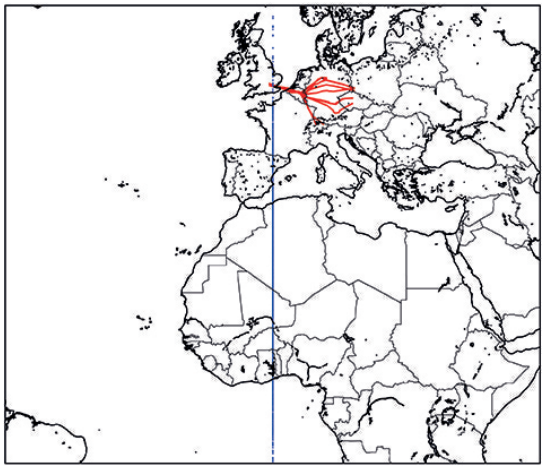

Fig. 4. Reported positions of 4CC0DC in blue, and the radar track in red

of the remaining data includes a least-squares method for the latency and root mean square calculations for the accuracy. In order to have reliable results, the sample size of the tested dataset must be large enough, thereby motivating the choice to remove aircraft from which not enough data points have been received. Since the reception performance is due to the antenna performance and not relating to ADS-B performance, the resulting figures still represent the accuracy of ADS-B.

1) Latency results

Figure 5 shows the distribution of the detected latencies for all analyzed ADS-B reports. The figure shows an asymmetrical distribution, with the peak between 0.2 and 0.3 seconds, with an additional 'bump' peaking between the 1.2 and 1.3 seconds mark. The shape of this distribution matches the Minimum Operation Performance Standards (MOPS) of ADS-B, which states that the transmission of newly computed airborne data must take place within 200 milliseconds (0.2 seconds) of the GPS time mark [11]. When the system is marking the transmission with the GPS timestamp, the information is extrapolated with intervals of one second, which adds up to the 0.2 second transmission boundary, resulting in the additional peak around the 1.2 seconds. The found latency consists of the actual time delay plus an potential induced time offset due to a position inaccuracy bias in the along-track direction. As mentioned, this requires the ADS-B track to closely follow the radar track, and Figure 5 is generated using the 5% best performing aircraft regarding cross-track offset. To view the effects of poorer accuracy performance on the latency, Figure 6 shows the calculated latency distribution in case the best 5%, 10%, 20%, 50%, or 100% of all flights are included. The position inaccuracy is visible in the latency data but the effects are minimal as the peak around the 0.2 second mark is still present.

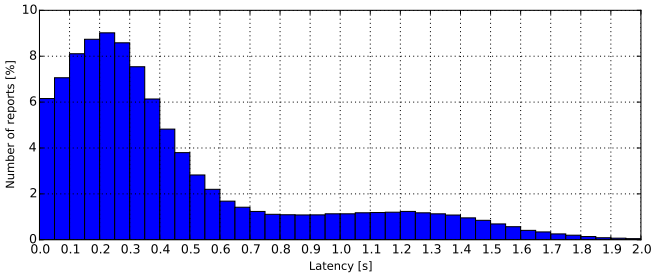

Fig. 5. Histogram showing the distribution of the detected latencies

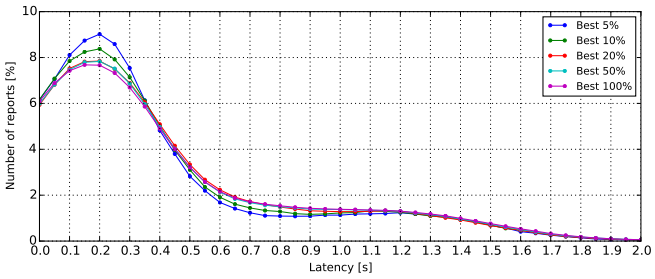

Fig. 6. Histograms showing effects of position accuracy variation on latency calculation

The most exact figures regarding the latency are obtained if on-board GPS data from an aircraft is available, and by examining the recorded GPS data it can be pinpointed which GPS locations relate to which ADS-B report. But even if this on-board data is available, the problem of time-synchronization can induce uncertainty in the measured data. To this end, this study also used the on-board data from the Cessna Citation II to determine ADS-B latency. A flight on the 16th of September 2015 was recorded, and it is assumed that the timing issues with the September dataset have had limited to no effect on the

received ADS-B times, since the system did not accumulate that much time offsets on that day. The timestamps of both the on-board GPS dataset and the received ADS-B reports have a resolution of one second. During the analysis it turned out that the ADS-B timestamps required a better resolution, but for this flight it was unfortunately not possible to acquire this higher resolution. The expected latency results are therefore expected to consists of either zero seconds or one second of latency. Averaging these individual latencies results in a general latency of 0.21 seconds for the entire Citation flight, which corresponds well to the estimated latencies in Figure 5.

2) Accuracy results

Figure 7 shows the resulting root mean square accuracies, mean accuracies, and cross-track accuracies of the January dataset, respectively. The RMS accuracies show that there

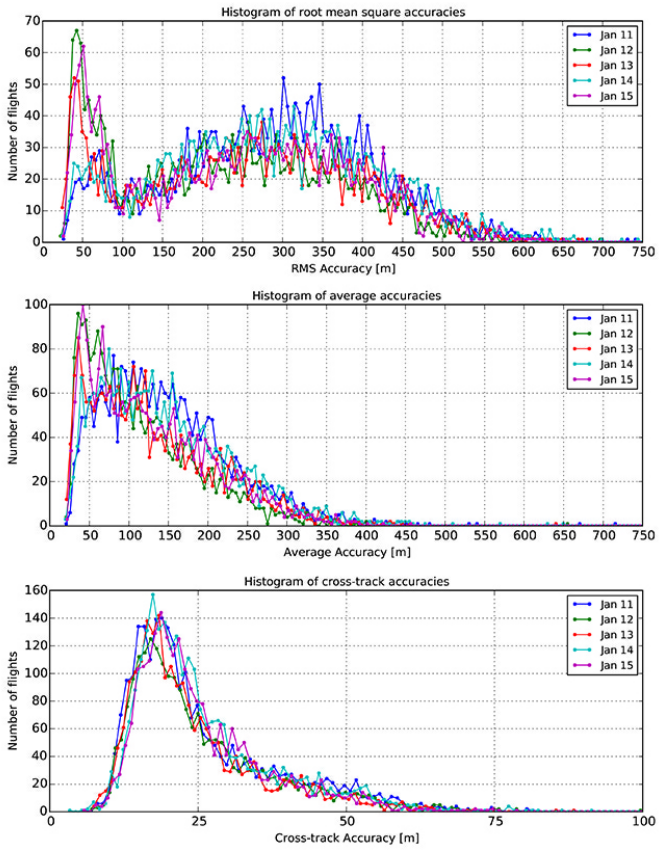

Fig. 7. Histograms showing the calculated root mean square accuracies, mean accuracies and cross-track accuracies of the dataset

is a peak around the 50 meter mark, but the remainder of the flights show larger inaccuracies. When calculating the root mean square of a set of values, any extraordinary large values cloud the resulting RMS. The concentration of flights around the 50 meter mark is there because these flights had little to no messages showing a large offset. The effects of corrupted messages with a very large error is far less visible when the mean of the individual offsets is calculated. The peak around the 50 meter accuracy remains, after which the amount of flights steadily decreases when the mean accuracy increases. The resulting RMS and mean accuracies are the direct offsets between the reported position and the reference position on the track. When analyzing the flight paths of the aircraft together with the ADS-B reports, it is visible that many aircraft show a large correlation with their reference track. The cross-track error, i.e. the offset perpendicular to the reference track, is therefore also an interesting parameter to investigate. Comparing the cross-track accuracies with the mean accuracies, it can be seen that the cross-track accuracy is much better than the mean accuracy. To see the differences between the three ways to look at the accuracies, Figure 8 shows the cumulative distributions of the RMS accuracy, mean accuracy and cross-track accuracy of the entire January dataset. From this figure, it can be concluded that 95% of the analyzed flights show a root mean square accuracy better than 472.29 meters (0.26 NM), a mean accuracy better than 281.77 meters (0.15 NM) and a cross-track accuracy better than 51.83 meters (0.03 NM).

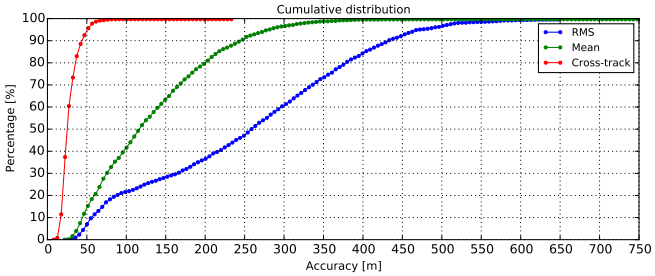

Fig. 8. Cumulative distribution of the RMS accuracy, mean accuracy and cross-track accuracy

Figure 9 shows the direction of the cross-track offset for all flights departing and arriving from Schiphol on January 11th, 2016. In the plot, some spikes are visible, each spike originating from a single flight. This indicates that a number of flights show a constant directional bias. The red dot indicating the average offset (16.06 m in the Eastern direction and 13.83 m in the Southern direction) shows that the reported position can show a bias, but it is not certain where the origin of this bias lies. However, when comparing the average offset as if it was the off-set w.r.t the center point of a typical sized aircraft, e.g. the Boeing 787 Dreamliner, it can be seen that this bias is insignificant with respect to the current separation criteria.

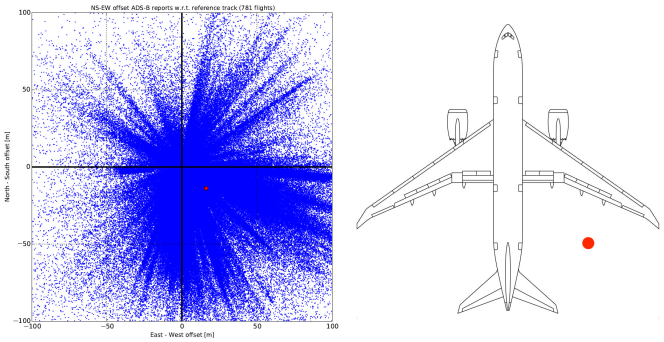

Fig. 9. Directional offsets for all flights departing and arriving at Schiphol airport on Jan 11th, 2016, with the red dot indicating the average offset compared to the center point of a Boeing 787 Dreamliner

C. Signal analysis results

1) Update interval results

Figure 10 shows the distribution of the update interval in a histogram and a cumulative distribution. In the histogram it can

be seen that the update interval results are divided over evenly-spaced peaks, which correspond to multiples of the declared transmission rate of ADS-B reports. For position updates this transmission rate is varying between 0.4 and 0.6 seconds, resulting in an average transmission interval of 0.5 seconds [6]. The possibility of receiving a position update within a certain time interval increases with that same interval, hence the sharp declining trend. The update intervals in Figure 10 include every single position update received by the antenna, regardless of integrity and decoding probability. Poor reception from aircraft on the borders of the coverage area would result in higher update intervals. The effects of geographic location of the aircraft is therefore investigated in Section IV-D1. From the cumulative distribution it is visible that 50% of all position reports are updated within 1.5 seconds and about 90% are updated within 10 seconds. 80% of all received position updates fall within the update interval of radar surveillance ($\pm$ 4 seconds).

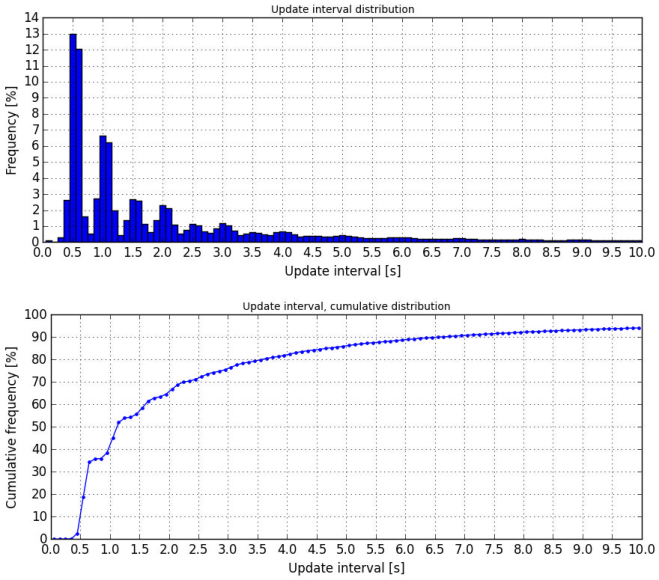

Fig. 10. Histogram and cumulative distribution of received update intervals from the January dataset

2) Integrity/availability results

With every position message, the integrity level (NIC value) is included, which indicates the radius of confinement of that particular position. Collecting every single NIC value results in the distribution shown in Figure 11. Around 11.5% of all messages show the lowest integrity value possible: NIC = 0. After examining the aircraft which reported these low integrity values, it was found that in the January dataset alone, there were 868 individual aircraft (together accounting for 9.84% of all flight movements) that only report NIC = 0. This can have various reasons, ranging from equipment issues to water in the antenna. From 2020, all aircraft will have to be properly equipped for ADS-B transmissions, so when these faulty aircraft are removed from the dataset, one gets availability figures which simulate future operations. The resulting availability, before and after removal of the unfit aircraft, are given in Table III.

From this analysis it can be concluded that at this moment, there are still a large number of aircraft which prove

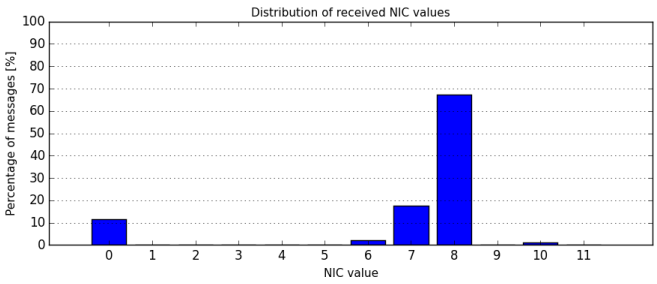

Fig. 11. Received NIC values

TABLE III
AVAILABILITY RESULTS BASED ON RECEIVED NIC VALUES BEFORE AND AFTER AIRCRAFT REMOVAL

	Availabilities [%]	
NIC	Initial	After
0	100.00	100.00
1	88.44	99.97
2	88.44	99.97
3	88.42	99.94
4	88.37	99.89
5	88.33	99.84
6	88.28	99.78
7	86.21	97.44
8	68.57	77.51
9	1.21	1.37
10	1.12	1.26
11	0.14	0.16

themselves unfit to transmit proper ADS-B position updates. Because the implementation program is still underway, the assumption that in the future every aircraft will be equipped properly is made and this results in improved availability results, where 99.84% of all ADS-B reports are suitable for en-route surveillance, 99.78% for TMA traffic, and 97.44% for traffic on final approach.

D. Performance degradation analysis

The performance degradation analysis comprises of the investigation on the effects of reception probability and the effects of different types of ADS-B equipment on the reported integrity categories.

1) Reception probability analysis results

The reception probability is assessed by investigating the effects of frequency congestion, the curvature of the Earth and the range equation. The number of reports being sent over the 1,090MHz frequency increases with increasing air traffic. The possibility of frequency congestion therefore exists, and in order to see whether this has an effect on the reception of ADS-B reports, the number of aircraft in the coverage area is correlated with the average update interval. Figure 12 shows the distribution of visible aircraft over time, together with the average update interval over time. The number of aircraft and average update interval reach their minimum during curfew hours, and start to increase when aircraft start to depart and/or arrive at the larger hub airports. From these distributions a strong correlation is already visible. When the amount of air traffic is plotted against the average update interval, one

gets the relation as shown in Figure 13, validating the strong correlation seen in Figure 12.

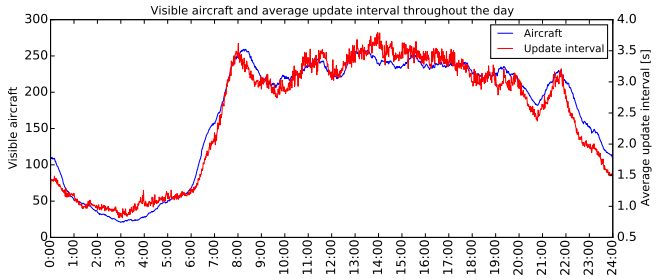

Fig. 12. Number of aircraft in coverage area and average update interval as a function of time

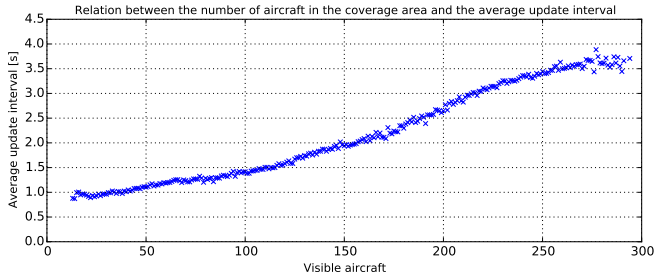

Fig. 13. Relationship between the amount of air traffic and average update interval

The correlation coefficient of both parameters is calculated using a linear regression model:

$$R^2 = \left(\frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}} \right)^2 \quad (4)$$

Here, n is the sample size, and x and y represent the two parameters which are compared. For this correlation analysis, it is calculated that the (linear) correlation coefficient is $R^2 = 0.971$, indicating a strong correlation. It is, however, visible that the correlation does not follow a linear distribution, but it is concluded that the amount of air traffic and the effect of increased amount of reports sent over the frequency decreases the reception probability, due to the large correlation coefficient.

To see the effect of the curvature of the Earth, Figure 15 shows the minimum detected altitude as function of horizontal range. It also includes the theoretical horizon constructed with the round Earth assumption, with an Earth's radius of 6,375km. The antenna's elevation is estimated at 50m, resulting in a visibility horizon of 25.2km. The minimum altitude as function of range is then calculated using the geometry given in Figure 14. Angle Θ can be calculated using:

$$\Theta = \frac{X}{R_E} \quad (5)$$

Here, X is the horizontal distance from the horizon and R_E is the Earth's radius. The problem then reduces to a simple triangle and the minimum detectable altitude h_i is then

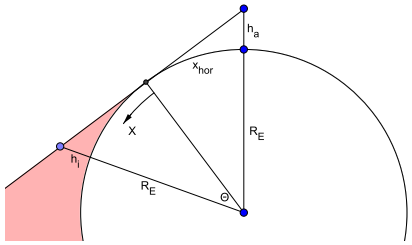

Fig. 14. Geometry of Earth's curvature estimation

calculated as:

$$\cos\Theta = \frac{R_E}{R_E + h_i} \quad \Rightarrow \quad h_i = \frac{R_E}{\cos\Theta} - R_E \quad (6)$$

The resulting theoretical altitude (after converting from meters to flightlevels) is shown in Figure 15. The detected minimum altitudes do not follow the theoretical horizon and this is probably due to the fact that the Earth is not perfectly round and the reported flightlevel is based on barometric pressure, rather than actual height. However, it is visible that the curvature of both distributions are similar, showing that the decrease of the altitude band with increasing range is indeed due to the curvature of the Earth. The small discontinuity between 0 and 50 km distance from the antenna is caused by aircraft arriving and departing from Rotterdam-The Hague Airport, and blocking of the signal by surrounding structures. Since the altitude bandwidth decreases with increasing range, the number of received messages is also a function of range, as is shown in Figure 16. Again, the large amount of Schiphol traffic is visible at the 50 km range mark.

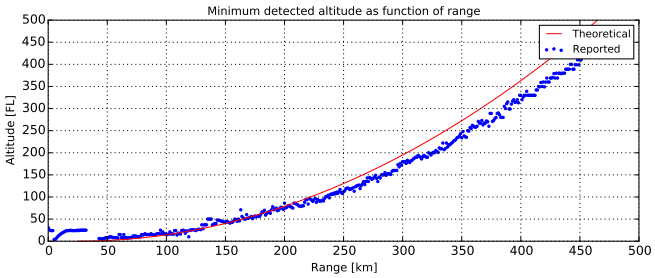

Fig. 15. Minimum reported altitude as function of range, together with the theoretical horizon

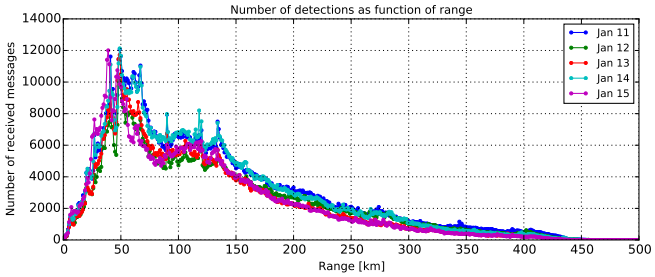

Fig. 16. Number of received messages as function of horizontal range

The decreased visibility due to Earth's curvature is clearly

visible. The decrease in messages at the edges of the coverage area can also be caused by poor reception due to far-away aircraft. Referring to Figure 3, it is visible that areas in the vicinity of Delft are showing a large number of reports, whereas the edges of the coverage area have a lower message density. By taking a control volume around Delft, the effects due to Earth's curvature are eliminated. Looking at Figure 15, it is clear that messages from within a circular control volume with a (horizontal) radius of 350km and an altitude band between FL300 and FL450 will not suffer from reception loss due to Earth's curvature. Figure 17 shows the relation between the slant range (i.e. distance between aircraft and receiver) and the number of messages received. Up to a slant range of around 130 km the message count is dominated by flight operations around Schiphol and standard air routes. Increasing the range with respect to the receiver, the numer of received messages is decreasing steadily.

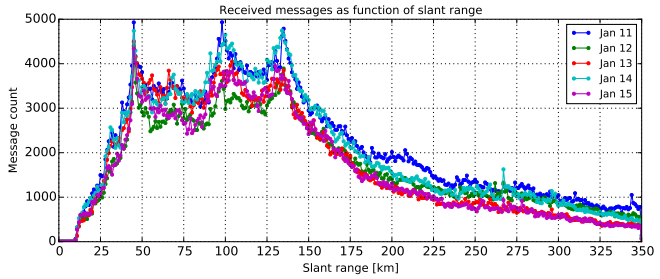

Fig. 17. Number of received messages in the control volume as function of slant range

As expected, the Earth's curvature and the effects of increased range are visible in the data. It is also visible that the reception probability depends on the amount of air traffic in the coverage area. When setting up a surveillance system using ADS-B as primary source of surveillance data, it is therefore important that the reception performance of the antennae with increased amount of air traffic is also taken into account, in addition to the geographical limitations of receiving ADS-B reports, possibly by increasing the number of antennae to increase the probability of detection. Furthermore, the reception probability can also be affected by the possible shielding of the aircraft antenna during turns and other unforeseen effects, such as weather conditions.

2) ADS-B equipment results

To see whether different types of aircraft and airliners perform differently regarding ADS-B, the reported NIC values and calculated cross-track offsets are collected per aircraft type and airliner for all flights in- and outbound of Schiphol Airport. First the differences between the reported NIC values: Figure 18 shows the boxplots for the received NIC values for the 20 most-seen aircraft types and airliners at Schiphol. It is visible that the majority of the aircraft types are conservative in reporting NIC values higher than 8. The majority of the aircraft are reporting an average NIC value of 8, except for the B738, B739 and A318. Looking at the different airliners, significantly better NIC values have been received from all Lufthansa flights arriving and departing from Schiphol, with an average NIC value of 10. Zooming in on the Lufthansa aircraft, it is found that the airliner most often operates with the A319 and E190 on Schiphol. The remainder of the top 20 airliners show a similar pattern regarding the NIC values sorted by aircraft type. However, as mentioned in the integrity/availability results, there are numerous aircraft reporting only NIC = 0 integrity values. Examples of such aircraft are the Fokker 70 and Fokker 100 operated by KLM Cityhopper. When these types of aircraft are taken into consideration, the aircraft type definitely can have an influence of the usability of ADS-B. With the same argumentation as used in the results section of the integrity and availability, in an envisioned future where aircraft are properly equipped these situation no longer occur, and more than 99% of all messages are usable for surveillance purposes. The conclusion therefore is that the ongoing implementation program causes some aircraft to still be unequipped with the proper protocols and present day operations would be influenced by these aircraft/airliners. In the Appendix, a more elaborate list is given regarding the aircraft types which reported only NIC = 0 reports.

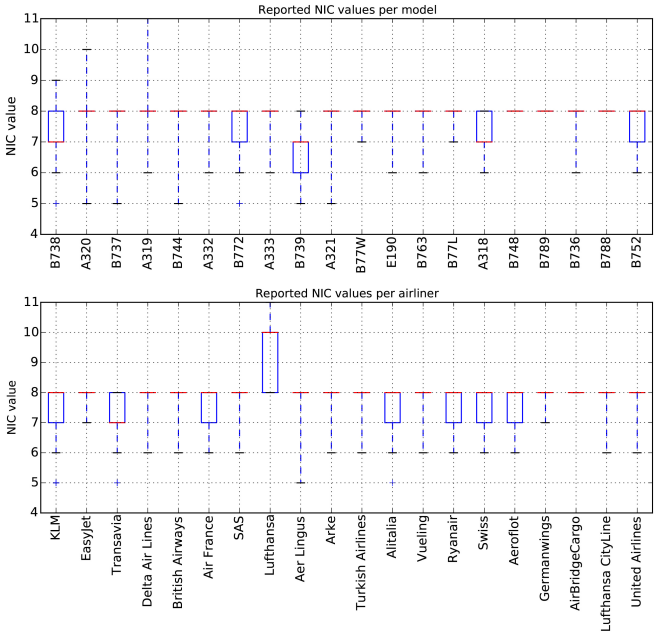

Fig. 18. Boxplots showing the received NIC values of the 20 most seen aircraft types and airliners at Schiphol airport

The calculated cross-track offsets of all flights of the 20 most seen aircraft and airliners at Schiphol are shown in Figure 19. A large variety can be observed: it can be seen that airliners, and especially low-cost carriers like EasyJet and Ryanair, which operate with a fleet of similar aircraft also have a more narrow concentration of the data. KLM and Air France, examples of airliners operating with a variety of aircraft types from both Airbus and Boeing, have a large spread of accuracies showing that the accuracy indeed is dependent on equipage.

V. Discussion

The aim of this study was to investigate whether ADS-B can serve as a primary means of surveillance, by analyzing the ADS-B performance based on raw messages. This was done by analyzing four parameters linked to ADS-B that play an important role in surveillance. These are latency, accuracy, update interval and integrity/availability. From the analysis of the results it follows that the applied methods allow to assess the performance of ADS-B quite closely, even though some uncertainties still remain. The latency estimation proves to

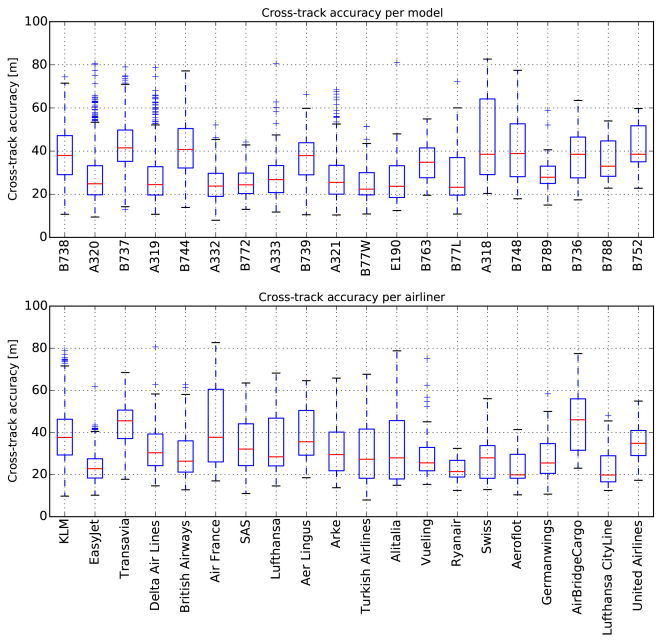

Fig. 19. Boxplots showing the calculated cross-track offsets of the 20 most seen aircraft types and airliners at Schiphol airport

be difficult without on-board data, since the applied method requires the reported position to actually represent the aircraft's real position. Depending on the latency of the reference that was used in this study (radar track data), the latency is therefore an underestimation of the true latency.

Even though the applied methods have their limitations, the analysis shows promising results. When the cross-track accuracy is taken, it can be seen that for the vast majority of all flights, the ADS-B track closely follows the reference track, with 95% of all flights showing a cross-track accuracy better than 51 meters. The update interval of the received position updates is largely dependent on the reception probability. Because in this study, only a single antenna was used to receive ADS-B data, the effects of range and frequency congestion are clearly visible. The conclusion for the update interval is therefore that future systems should closely look at the reception probability and strategically plan their antenna placement, in order to assure safe flight operations. The integrity and availability of the ADS-B reports show that a number of aircraft are not properly equipped yet, but based on the results of the remaining aircraft it is assumed to be sufficient when in the future every aircraft operating under IFR rules is properly equipped with the right ADS-B protocols.

Based on the results it can be said that ADS-B is indeed a promising technology, and it can serve as a very important element in the surveillance system. However, as is also found in the analysis, the uncertainty of reception and performance of individual aircraft is difficult to asses, making it difficult to prove whether ADS-B can ever serve as a sole means of surveillance. An extreme example was already mentioned in the results section, where one aircraft continuously reported an impossible position. This aircraft was not included into the results, but it highlights a problem which is still at hand: namely that ADS-B operations can only be considered safe when every single aircraft is reporting its position properly. Hence, when ADS-B is to be implemented as primary means of surveillance, back-up systems should be available (e.g., conventional radar systems or multilateration systems), in order to track all aircraft, even when their broadcast position cannot be trusted.

VI. Conclusions

This study aimed to provide a contribution to the question whether ADS-B is fit to serve as primary means of surveillance. This was assessed by analyzing the latency, accuracy, update interval, and integrity/availability of raw-received ADS-B reports. Latency and accuracy were determined by comparing the reported position with radar data provided by MUAC. The update interval and integrity/availability were determined by analyzing the ADS-B timestamps and reported integrity values respectively. The study also includes an analysis on reception probability and the effects of different aircraft types on ADS-B performance. It was found that the vast majority of aircraft shows acceptable performance for their ADS-B reports to be used as means of surveillance. The study also makes clear that ADS-B based operations heavily rely on the performance of the corresponding ground system and individual airborne systems, with aircraft 4CC0DC as example. However, since ADS-B is still in its implementation phase, and future equipages are expected to perform accordingly, it can be concluded that in the future, ADS-B will be a valuable asset in air traffic management.

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