Large-Scale ADS-B Data and Signal Quality Analysis

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Automatic Dependent Surveillance Broadcast (ADS-B)

A

D

S

B

TU Delft
GPS positioning

Aircraft to aircraft

ADS-B over satellite

ADS-B, ADS-B re-broadcast
ADS-B message contents

- **Capability (CA, 3 bits)**
- **Downlink format**
  - DF, 5 bits
  - 11: Acq. Squitter
  - 17: ADS-B
  - 18: TIS-B
  - 19: Military
- **Aircraft (ICAO) address**
  - AA, 24 bits
- **ADS-B data**
  - ME, 56 bits
- **Parity check and address**
  - PI, 24 bits

Diagram showing the structure of an ADS-B message, including a Preamble and a Data Block with specific timing and format details.
## ADS-B message contents

<table>
<thead>
<tr>
<th>Type Code</th>
<th>Message type</th>
<th>Transmission rate [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 4</td>
<td>Aircraft identification</td>
<td>5</td>
</tr>
<tr>
<td>5 - 8</td>
<td>Surface position</td>
<td>0.5</td>
</tr>
<tr>
<td>9 - 18</td>
<td>Airborne position (barometric altitude)</td>
<td>0.5</td>
</tr>
<tr>
<td>19</td>
<td>Airborne velocity and heading</td>
<td>0.5</td>
</tr>
<tr>
<td>20 - 22</td>
<td>Airborne position (GPS altitude)</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Test message</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Surface system status</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Extended squitter AC status</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Target state and status (V.2)</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Aircraft operation status</td>
<td></td>
</tr>
</tbody>
</table>
ADS-B out mandatory from 2020

Initial applications

- ADS-B in non-radar airspace (ADS-B NRA)
- ADS-B in radar airspace (ADS-B RAD)
- Airport surface surveillance (ADS-B APT)
Benefits of ADS-B

Safety

Efficiency

Cost
ADS-B limitations

- **Truncation** (accuracy of 9 - 17m)
- **State accuracy** (GPS $\leq$ 8m)
- **Update rate and latency**
- **Signal range**
- **Interference / frequency congestion**
ADS-B performance studies
Latency: 0.6 - 1.8 sec

Accuracy: <150m: 66%, <925m: 99%

Update interval: <10sec: 99%, <2.8sec: 95%

Based on data from few aircraft
Large-scale ADS-B analysis

**ADS-B Measurement data:**
- 2 weeks, single receiver
- ± 69,000 flights

**Reference ‘truth’ data**
- Eurocontrol MUAC radar data
- On-board data from Cessna C550 flight
Approach

Analysis in terms of:

- Data quality (latency, accuracy)
- Signal quality (Update interval, integrity)
- Performance degradation
Distinguishing latency and accuracy
Distinguishing latency and accuracy

- 3rd order spline interpolation of reference

\[ S(t) = \begin{cases} 
S_0(t) & t \in [t_0, t_1] \\
S_1(t) & t \in [t_1, t_2] \\
\vdots & \vdots \\
S_{k-1}(t) & t \in [t_{k-1}, t_k] 
\end{cases} \]

\[ \vec{x}_{ref}(t) = (S_\phi(t), S_\lambda(t), S_h(t)) \]

- Result is position as function of time
Distinguishing latency and accuracy

• Minimise difference to find latency

\[
\min_{\Delta t} \sum_{i=0}^{k} (x'_{ADS-B[i]} - x_{ref}(t_i - \Delta t))^2
\]

• Assumption: latency is constant
Distinguishing latency and accuracy

- Accuracy: remaining latency-corrected error

\[ \bar{x}_{ref}(t - \Delta t) \]
Data quality results: latency

- Citation test flight latency: 0.21 sec
- MOPS required latency: 0.2 sec
Data quality results: Accuracy

Histogram of average accuracies

Histogram of cross-track accuracies
Data quality results: Accuracy

NS-EW offset ADS-B reports w.r.t. reference track (781 flights)
Data quality results: extreme cases

- Sometimes, aircraft don’t make sense.
Data quality results: extreme cases

- Sometimes, aircraft don’t make sense..
Signal quality: update interval

- Update interval based on position reports
- 2 reports are needed for position report:

O O—E O—E O O—E
Signal quality: integrity

• Navigational Integrity Category (NICₚ)

• Represents Horizontal Position Limit

<table>
<thead>
<tr>
<th>TC</th>
<th>HPL limits</th>
<th>NIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>7.5 m</td>
<td>11</td>
</tr>
<tr>
<td>10</td>
<td>7.5 m</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>25 m</td>
<td>8</td>
</tr>
<tr>
<td>12</td>
<td>0.1 NM</td>
<td>7</td>
</tr>
<tr>
<td>13</td>
<td>0.1 NM</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>0.5 NM</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>1.0 NM</td>
<td>4</td>
</tr>
<tr>
<td>16</td>
<td>2.0 NM</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>10 NM</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>20 NM</td>
<td>0</td>
</tr>
</tbody>
</table>
Signal quality results: update interval

Figure 12. Cumulative distribution of the RMS accuracy, mean accuracy and cross-track accuracy

Figure 13. 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

The reason for looking at cross-track accuracy is first because there are no issues regarding time anymore. As mentioned in the latency results section, small differences in the two timing systems can occur, and these timing issues are prone to have its effect on the accuracy estimation. Second, it's because it represents the offset of the actual track. Along-track offsets lie, as the name implies, along the track and the aircraft's position along the track can be derived using the reported position, speed and heading. The cross-track offset is therefore the part which represents the diversion from the reference track, something which is interesting to know when smaller separation criteria are to be applied in the future.

C. Signal analysis results

1. Update interval results

Figure 14 shows the histogram and cumulative distribution resulting from the update interval analysis. Clearly visible is the periodic behavior of the histogram, with peaks every half a second. These peaks can be explained by the 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. 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 14 are including every single position update received by the antenna, regardless of bad integrity and/or decoding possibility. 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 investigated in Section IV.

D. 1. From the cumulative distribution it is, for example, visible that 50% of all position updates are received within 1.5 seconds and about 90% of all messages are received within 10 seconds. 80% of all received position updates are received with an interval less or equal than the update interval of radar surveillance (being about 4 seconds).

Figure 14. 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 indicating the radius of confinement of that particular position. Collecting every single NIC value results in the distribution shown in Figure 15. 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 is found that in the January dataset alone, there were 868 individual aircraft (together accounting for 9.84% of all flight movements) who only reported NIC = 0. This can have various reasons, ranging from equipment issues to water in the antenna. In the future, all aircraft will 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 4.

Table 4. Availability results based on received NIC values before and after aircraft removal

<table>
<thead>
<tr>
<th>NIC</th>
<th>Initial</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>1</td>
<td>88.44</td>
<td>99.97</td>
</tr>
<tr>
<td>2</td>
<td>88.44</td>
<td>99.97</td>
</tr>
<tr>
<td>3</td>
<td>88.42</td>
<td>99.94</td>
</tr>
<tr>
<td>4</td>
<td>88.37</td>
<td>99.89</td>
</tr>
<tr>
<td>5</td>
<td>88.33</td>
<td>99.84</td>
</tr>
<tr>
<td>6</td>
<td>88.28</td>
<td>99.78</td>
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<tr>
<td>7</td>
<td>86.21</td>
<td>97.44</td>
</tr>
<tr>
<td>8</td>
<td>68.57</td>
<td>77.51</td>
</tr>
<tr>
<td>9</td>
<td>1.21</td>
<td>1.37</td>
</tr>
<tr>
<td>10</td>
<td>1.12</td>
<td>1.26</td>
</tr>
<tr>
<td>11</td>
<td>0.14</td>
<td>0.16</td>
</tr>
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From this analysis it can be concluded that at this moment, there are still a large number of aircraft which prove themselves...
Signal quality results: integrity

- High number of NIC=0 only aircraft

![Distribution of received NIC values](image)

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Performance degradation

- Frequency congestion
- Signal strength
- Line of sight
Reception probability due to frequency congestion

![Graph showing visible aircraft and average update interval throughout the day.](image)

![Graph showing relation between number of aircraft in coverage area and average update interval.](image)

$R^2 = 0.971$
Reception probability due to signal range

Minimum detected altitude as function of range

Number of detections as function of range
Conclusions

- Majority of flights shows high accuracy
- Update interval dependent on frequency congestion
- A number of aircraft not yet sufficiently equipped