Reliability of ADS-B Communications: Novel Insights Based on an Experimental Assessment

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ABSTRACT
The Automatic Dependent Surveillance - Broadcast (ADS-B) technology promises to enhance the safety of civil avionics by diffusing flight data in a more efficient, timely, and easy to access fashion. Moreover, its adoption is mandatory by 2020. However, the quality of the communication is not completely satisfactory. Indeed, packets are lost for a number of reasons, such as obstacles, weather conditions, and by the fact that the frequency band on which ADS-B is intended to work in is the same shared by other legacy communication technologies used by the aircraft.

Leveraging some previous work in the area providing preliminary study of packet loss issues in this specific context, in this paper we analyze the Opensky-network public database to provide more hints and real statistics on both the packet loss characterizing aircraft communications and the overall reliability of the ADS-B technology. Analyzing more than 21 GB of real aircraft-generated traces, we show that models introduced in the last years have severe limitations. This is imputable to several reasons, including the increased throughput and density of the network, as well as — as discovered by our analysis — that there is a not negligible portion of ADS-B implementations that do not follow the standard recommendation.

Overall, this contribution intends to: (i) shed some lights on the current gap in the literature; (ii) provide a new, updated packet loss model for ADS-B communications; and, (iii) motivate further research efforts in the field, toward a precise characterization of the reliability of aircraft communications.

ACM Reference format:

1 INTRODUCTION
Starting from 2020, the Automatic Dependent Surveillance - Broadcast (ADS-B) technology will be mandatory on board of all the aircraft in the US and the EU, operating side-by-side with the other legacy communication technologies such as the Primary Surveillance Radar (PSR) and the Secondary Surveillance Radar (SSR) systems [1]. Moreover, some of the major companies already equipped their aircraft with ADS-B transceivers, including Qatar Airways, British Airways and American Airlines1.

The introduction of ADS-B is expected to improve aircraft navigation in different aspects. Indeed, aerial vehicles will be able to originate messages autonomously, without waiting for polling from ground base stations. In addition, they will be able to exchange information with other aircraft in the communication range, improving the decision making capabilities and autonomously managing self-separation [2].

However, ADS-B is actually far from being an effective and reliable communication technology. Specifically, challenging issues related with the lack of any security mechanism and the low level of reliability of the communication link are actually attracting interests from both academia and industry [3],[4],[5]. As for the reliability of the communication link, some preliminary studies already identified the high packet loss characterizing the broadcast channel [1],[6]. However, these studies analyzed a single communication link, by using data retrieved with a single receiver, usually realized through a Software Defined Radio (SDR). In addition, they often rely on the availability of multiple receivers to promise an increase in the actual reception probability of aircraft-originated packet. Indeed, they do not practically evaluate the redundancy in the reception that can be provided by multiple antennas controlled by the same system owner. In addition, they assumed aircraft to follow the recommendations of the main standardization bodies about the recommended mean packet delivery ratio. All these assumptions proved to be overly optimistic, as shown — backed by data — in the sequel of the paper.

Inspired by the cited gaps, in this paper we investigate the overall reliability and the severe packet loss issues affecting the current deployment of the ADS-B communication technology. Specifically, our contribution is grounded on publicly available data provided by the Opensky-network community2, consisting of a large number of receiving antennas distributed worldwide and continuously gathering data about ADS-B equipped aircraft [6]. We designed a tool able to interface with a consistent portion of the database and to provide results about the lower bound and the mean value of the packet loss. Then, we discuss these results and we demonstrate that packet

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2https://opensky-network.org/
loss issues are more severe than what reported in the literature, severely affecting the reliability of the ADS-B technology.

Overall, the contributions of our paper are the following: (i) to shed some lights on the current gap in the literature; (ii) to disclose a new experimental model for packet loss in ADS-B communications, to be used by industry and academia to study the behavior of new applications and services intended to work on top of the communication link; and, (iii) to motivate and to stimulate further efforts by the scientific and industry community towards the increase of the reliability of the communication link for critical civil applications such as avionics communications.

The rest of the paper is organized as follows: Sec. 2 provides the background on the ADS-B communication technology and some relevant related work, Sec. 3 describes the tool used for our analysis, Sec. 4 provides the results obtained from the sample data, while Sec. 5 discusses the results and illustrates further directions. Finally, Sec. 6 tightens conclusions.

2 BACKGROUND AND RELATED WORK

This section provides details about the functioning of the ADS-B technology and some related work recently published in the area.

2.1 Background

The ADS-B technology was originally designed in the early 1990s, to allow an aircraft to autonomously broadcast information about its position, speed and heading. The typical scenario of the communication is depicted in Fig. 1.

![General Scenario of the ADS-B communication technology](image)

The major source for such information is a Global Positioning System (GPS) receiver mounted on-board, that allows the aircraft to obtain its position via satellite navigation [7]. Then, the information is transmitted in broadcast by the aircraft using two possible frequencies. If the height of the aircraft is below the quote of 18,000 feet (i.e., about 5,500 meters), it uses the 978MHz frequency band, in the Universal Access Transceiver (UAT) mode; otherwise it uses the 1090MHz frequency band, in the Extended Squitter - 1090 MHz (ES1090) mode. In both cases, the channel bandwidth dedicated to the transmission is 50kHz. Overall, the maximum theoretical transmission range is 320 Nautical Miles, i.e. 600 km, even if obstacles in the path can reduce the effective range. Practically, the considered reliable transmission range is about 250 Nautical Miles, i.e. approximately 450 km.

ADS-B is also characterized by two different subsystems, that are ADS-B OUT and ADS-B IN. ADS-B OUT allows aircraft to deliver information mainly to ground base stations, as well as the tracking and constant monitoring of the aircraft. ADS-B IN, instead, allows to receive information directly from other aircraft in the area, also regarding weather and traffic conditions.

ADS-B messages are characterized by a different size according to the particular frequency on which they are delivered. UAT messages are 420-bits long, with 272 bits dedicated to the payload, while ES1090 messages are only 112 bits-long, with 56 bits allocated for the payload.

At the data-link layer, ADS-B messages are encapsulated in Mode-S frames, and there is no mechanism to detect or avoid collisions (unlike, e.g., WiFi [8]). Thus, as soon as messages are ready to be transmitted, they are sent in broadcast. Finally, at the physical layer, ADS-B uses Pulse Position Modulation (PPM), with each pulse being 1 µs long [9]. Therefore, ADS-B has a physical data rate of 1 Mbit/s [10].

2.2 Related Work

The amount of the literature around the ADS-B communication technology has been increasing sharply over the last few years. The most pressing concern is on the security features inherent to ADS-B communications, given that they are neither encrypted nor authenticated. For these reasons, many contributions focused on security-related issues, such as location verification, privacy enhancement and broadcast authentication.

As for the location verification, contributions such as [11] and [12] proposed to apply classical localization mechanisms such as multi-lateral to verify the location claimed by an aircraft. A similar approach is also proposed by [13], leveraging the crowdsourcing characterizing modern communications and the well-known k-Nearest Neighbors algorithm.

Towards the enhancement of the confidentiality of delivered messages, some pioneer contributions such as [14] highlighted the feasibility of many vulnerabilities that enable link-layer attacks on the ADS-B technology.

On the one hand, the public availability of data paves the way to interesting studies. To name a few, [15] provides an analysis of movements and distribution of commercial and military aircraft in an area of interest, demonstrating the potential leakages that can emerge from such an open system. Privacy issues are also tackled in [16], with reference to anonymization of contributing receivers. In the same fashion, [17] uses data provided by OpenSky-network to infer meteorological conditions such as air temperature, wind speed, wind direction and atmospheric pressure. Also, annual reports provided by OpenSky-network such as [18] and [19] derive and discuss interesting results on the type of messages delivered by aircraft, the distribution of aircraft using ADS-B and the actual coverage in the deployment of the communication technology.

On the opposite side, some contributions propose novel mechanisms to limit information leakages. In this context, authors in [7] proposed a framework to provide confidentiality of the communications, based on Staged Identity Based Encryption (SIBE). With
the aim of providing authentication of the messages, [20] proposed to replace the Cyclic Redundancy Code (CRC) included in ADS-B messages with a dedicated Hashed Message Authentication Code (HMAC), tying together different consecutive messages. In the same context, [5] recently proposed a method to guarantee broadcast authentication, by limiting the bandwidth overhead generated by the addition of security services. Note that all the previous approaches, leveraging multiple packets to be received consecutively, become ineffective if severe packet loss issues affect the communication link. However, none of them addressed the issue.

As for the packet loss, some previous contributions such as [6], [1] and [21] already pointed out the issue. However, those contributions first evaluated the packet loss by considering that, on average, 21 messages every 5 seconds are delivered by an aircraft. In addition, they provided packet loss statistics only with reference to a single receiver, while statistics for a pool of receivers in the reception range of an aircraft are not discussed. Finally, the transmission rate of the aircraft is never considered in the analysis.

With respect to those valuable contributions, we further extend the analysis and we hereby investigate the packet loss by considering a pool of receivers in the transmission range of the aircraft.

3 EXTRACTING PACKET LOSS STATISTICS FROM THE OPENSKY-NETWORK DATABASE

The aim of this paper is to investigate on the reliability of the ADS-B technology and on the feasibility of current packet loss models, based on real data available through open-source databases, such as Opensky-network.

To this aim, we designed a dedicated tool, tailored to the structure of the data included in the Opensky-network database. Specifically, the tool processes the raw data provided by the Opensky-network and provides useful statistics about the lower bound and the mean value of the packet loss. The pseudo-code of the tool is provided in the following Alg. 1.

Specifically, the data provided by the Opensky-network are released in the form of an avro file, in which data acquired from each sensor have been serialized. The data used in this paper are publicly available at the following link: https://opensky-network.org/datasets/raw/.

Our tool accepts in input the whole avro file, and it first converts the input file in the JavaScript Object Notation (JSON) format, through the tool avro2json. Each row of the converted file indicates a reception of a message from a sensor connected to the distributed Opensky-network deployment, and contains the following information:

- **SensorType**: it identifies the manufacturer of the ADS-B sensor capturing the message;
- **sensorSerialNumber**: it uniquely identifies the particular receiver of the message;
- **SensorLatitude**: latitude coordinate of the receiving sensor;
- **SensorLongitude**: longitude coordinate of the receiving sensor;
- **SensorAltitude**: altitude of the receiving sensor;
- **timeAtSensor**: it indicates the time at which the sensor received the message, in seconds;
- **timestamp**: it indicates the hardware reception timestamp of the sensor, in nanoseconds;
- **timeAtServer**: it identifies the time at which the Opensky-network database received the message from the sensor;
- **rawMessage**: encoded content of the ADS-B packet
- **RSSIPacket**: indication of the Received Signal Strength of the packet on the receiving sensor, computed over the whole ADS-B message;
- **RSSIPreamble**: indication of the Received Signal Strength of the packet on the receiving sensor, computed over the 8 bits representing the physical preamble (similarly with the techniques used for the Wi-Fi);
- **SNR**: estimation of the overall Signal-to-Noise Ratio (SNR) of the received packet.

Our tool also identifies all the receivers whose received data are included in the database and whose position is reported. Note that this step is necessary because some receivers chose to maintain anonymity of their position, and so the values in the columns related to their position are empty. On the data provided by the remaining receivers, the tool identifies a pool of receivers that are very close to each other (i.e., the maximum distance between a couple of receivers in the pool is less than or equal to 70 kilometers), in order to focus on data that are highly correlated. This is achieved by identifying the number of receivers falling in a circle centered in the position of a receiver and having a diameter equal to 70 kilometers. In this way, it is possible to increase the probability that a given packet is received by the system, given that an higher number of receivers can potentially receive it.
On the remaining data, sorted by the reported reception time, the tool can compute the packet loss both in the form of a lower bound or as a mean value, as specified in the input. In case the lower bound is required, for each of the remaining unique messages, the tool evaluates which receivers did not receive them, and computes the distance between the position of the given receiver and the position reported by the aircraft. If such a distance is less than the maximum practical transmission range of the ADS-B technology (250 Nautical Miles, i.e. approximately 450 km), then the event is classified as a packet loss. Note that the results achieved through this procedure represent a lower bound on the overall packet loss, given that we cannot have any data regarding packets that are not received by any of the receivers. In addition, for each packet loss event, the tool evaluates how many planes are located in the proximity (i.e., less than 20 km) of the receivers, in a way to provide data useful to deduce the presence of congestion phenomena (more details will be provided in Sec. 4.2).

In case the tool is instructed to provide the mean value, it computes the mean number of packets delivered by each of the aircraft in a time-window of 5 seconds, in line with other contributions in the literature [6]. Then, it evaluates the mean message loss on each receiver, assuming the number of messages to be transmitted by each aircraft equal to the maximum number of messages received by the whole system from a given aircraft. Indeed, even if this is not a precise estimation, such a procedure provides a realistic upper bound on the mean packet loss on the communication link. Results and discussion will be provided in Sec. 4.

The described tool has been implemented through a combination of programming languages, such as Python and MySQL. To help researchers to reproduce our results and further work on them, the source code of the tool, as well as of the other tools used to obtain the results reported in the paper, have been released as open-source at the following link: https://github.com/adsbreliability/adsb-reliability-tools.

## 4 ADS-B PACKET LOSS EVALUATION

In this section we provide some results about the packet loss rate and the packets sending ratio of ADS-B equipped aircraft, based on real data. This contribution focuses on data provided by the Opensky-network project, and publicly available[^1]. The dataset refers to communications that took place in the summer of 2017, in different parts of the world, including Europe, US and Asia. It includes 21.5 GB of data, related to the reception of 231 receivers (over an actual total number of 543 receivers), worldwide distributed. Overall, a total number of 255,960,868 messages are included in the file.

We ran the tool described in Sec. 3 over these data. Results about the lower bound of the packet loss are reported in Sec. 4.1, while some considerations about the effects due to the congestion on the communication link are included in Sec. 4.2. In addition, the results about mean packet loss and the packet sending ratio on the equipped aircraft are discussed in Sec. 4.3.

### 4.1 Packet Loss Rate

As discussed in Sec. 3, the tool has been designed to identify pool of receivers located in the same geographical area. Indeed, several pools can be identified, consisting of a different number of receivers. For our analysis, we selected the pool composed of the highest number of receivers. This is located in an area coincidental approximately with the Switzerland. An illustrative map is shown in Fig. 2, providing the exact location of the receivers and their unique identifier.

![Figure 2: Map of the receivers considered in our analysis — scale 1:500000.](image)

It is worth noting that even if the following analysis is focused on a limited area, the seven receivers together cover an area of approximately 750km², centered in the central Europe, i.e., an area characterized by a dense traffic almost at all time of the day. Thus, the data provided hereby are representative of a consistent portion of the daily flights and the results achieved on these data can be easily generalized to other areas in the world showing similar characteristics.

Focusing on this pool, the first metric we investigated is the number of receivers receiving a given message. Indeed, when a message is broadcasted from the aircraft, all the receivers can potentially receive it, provided that their distance from the emitting source is less than the maximum transmission range of the ADS-B technology. In Fig. 3 we depict, for each distinct ADS-B message logged in the database, how many receivers received it.

The figure shows that most of the messages are received only by a single receiver, while few messages are received by a larger number of receivers. This is in line with the expectations, given that the areas in which a given pool of receivers can receive a packet is smaller when considering more receivers.

Starting from these data, we restricted the analysis only to messages that could have been received by all the receivers (based on the distance of the emitter from the receiver and the constraints of the ADS-B technology), and we evaluated how many receivers actually received them. Results are reported in Fig. 4.

While all the messages could have been received by all the receivers, only 3.25% of the messages were correctly received by all

[^1]: [opensky-network.org/datasets/raw](https://opensky-network.org/datasets/raw/)
of them. This brings to light the issue of packet loss on ADS-B communications. Most of the messages, i.e., 54.5% were still received by a single receiver, and this highlights the presence of phenomena that insist on the single link between the aircraft and the receivers, and that can likely bring to the loss of the packet. Given that the Opensky-network database provides only data about packets that have been received by at least one of the receivers, these data represent a lower bound on the probability of correct reception from a given number of receivers. In practice, the real packet loss will be even worst, because of messages that have not been received by none of the receivers and that are not reported in the database.

To provide further insights, we investigated the existing relationship between the distance transmitter-receiver and the packet loss event. Specifically, for each packet loss event, we computed the distance between the position reported by the aircraft in the message and the particular receiver that should have received it, but that failed in doing so.

Note that, in case the message (detected as lost by some receiver, but received by at least one of them) did not report a position, we considered the last valid position reported by the same aircraft as its position at the sending time. Fig. 5 depicts the Empirical Cumulative Distribution Function (ECDF) of the packet loss with respect to the distance between the transmitter and the receiver (straight black line).

The ECDF exhibits a slow start and then a linear increase, toward the 100%. This suggests that the packet loss is limited in the proximity of the receiving sensors, then it increases quickly and finally remains constant independently from the distance transmitter-receivers. Indeed, Fig. 5 also shows that to improve the reception probability of 50%, a receiver should be located no farther than 150 km from the transmitting aircraft.

To further investigate the relationship between the packet loss and the distance, we also considered the received packets, and we computed the packet loss percentage with increasing distances. Results are reported in Fig. 6.

Indeed, the trend suggested by the ECDF in Fig. 5 is confirmed by Fig. 6. In fact, the packet loss remains almost contained at low distances, up to 30 km. Then, it starts increasing linearly up to 250 km. Finally, it settles at a level of about the 73%, up to very high distances.

With reference to the reported results, we also obtained the fitted linear model that depicts the experimental packet loss percentage with increasing distances. Specifically, the model obtained by using the real data provided by the Opensky-network has been obtained...
by using the `fitlm` tool provided by Matlab®, and assumes the form in Eq. 1.

\[ y = 65.366 + 0.020319 \times \text{distance}[\text{km}] \]  

(1)

Fig. 7 shows both this experimental model and a model obtained by the related work [3], by using data in the same geographical area but related to a single receiver.

As resulting from Fig. 7, the current model reported in [3] (that is also the most updated realistic model for ADS-B communications) seems quite far from catching the real behavior of packet loss, as it under-estimates the loss for shorter distances, while for distances greater than about 425 km it over-estimates the actual entity of the packet loss. Especially for shorter distances, the model in [3] is very far from the results obtained by our study, as the packet loss is almost double.

Overall, the results reported in this subsection further motivate the need of new, updated and realistic packet loss models to characterize ADS-B communications, as well as the need to re-consider previously published approaches leveraging stable communication links between ground stations and the aircraft.

4.2 Considerations on Congestion

In this section we focus specifically on packet loss due to the congestion on the communication link. Our aim is indeed to investigate if there is a relationship between the packet loss rate and the number of aircraft in the close proximity of the receiving antennas.

Specifically, with reference to both packets received and lost by the receivers in the considered scenario, we evaluated the packet loss percentage with respect to the number of airplanes in the close reception range of each receiver (no more than 20 km), for each of the receivers considered in our analysis. Fig. 8 reports the results for a specific receiver in our scenario, i.e., the one having ID 954778341 and located nearby the town of Zug. The same results for all the other receivers, instead, are shown in Fig. 9.

The trend shown in Fig. 8 would lead to the immediate consideration that the packet loss increases due to the number of aircraft in the close reception range of the sensor, as reported in previous related work [21]. Indeed, there are two effects that would support such a claim and to induce an high congestion on the communication link. First, the higher the number of aircraft, the higher the probability for the transmitters to choose overlapping transmission time windows. Second, transmissions from aircraft in the close reception range of the receiving sensor are characterized by higher levels of received power, thus destroying packets coming from longer distances. However, as it emerges from Fig. 9, such a trend is not evident for all the other six anchors considered in our analysis. For all these anchors, we notice almost a (very high) constant packet loss, also considering few aircraft in the close proximity. This can be due either to the geometry of the geographical area tackled by the analysis (shadowing and obstacles throughout the path between the senders and the receivers, caused by a not optimal placement of the receivers), or to an high level of interference on the same frequency used for communications. Further deep investigations on this phenomena are needed and are left as part of our future work.

4.3 Packets Sending Ratio

To obtain the estimation of the average packet loss of the ADS-B technology, we need to provide an estimation of how many packets are actually transmitted by the aircraft in a time unit. For this
ADS-B technology in the area, assuming a transmission rate of each message characterized by the mean packet loss. This, in addition to the assumptions made before about the transmission rate of the aircraft, provides a practical upper bound on the mean packet loss characterizing ADS-B communications.

Switzerland is a geographical area mainly composed of mountains, characterized by at least a single receiver in a time window of 5 seconds. Results are reported in Fig. 10, considering all the 841 unique aircraft whose messages are received for more than 30 seconds. Note that each aircraft has been associated to an anonymous unique identifier, from 0 to 840, to properly anonymize it.

![Figure 10: Mean number of packets delivered by the aircraft in 5-seconds time windows.](image)

A striking result is that there are a number of aircraft actually exceeding the recommended transmission rate, transmitting more than 21 messages in 5 seconds. Specifically, there are 58 out of 841 exceeding this limit, that is 6.89% of our sample. Moreover, the same data can be used to obtain the mean packet loss of the ADS-B technology in the area, assuming a transmission rate of each aircraft equal to the maximum mean transmission rate between all the vehicles, that is 33.05 messages every 5 seconds. Averaging over all the 841 aircraft whose messages have been received for more than 30 seconds, we obtained the results reported in Tab. 1.

![Table 1: Mean Packet loss on the considered ADS-B system.](image)

<table>
<thead>
<tr>
<th>Mean Packet Loss</th>
<th>69.56%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower 95% confidence interval</td>
<td>68.61%</td>
</tr>
<tr>
<td>Upper 95% confidence interval</td>
<td>70.51%</td>
</tr>
</tbody>
</table>

It is worth noting that, even if such statistics are related to a limited geographical area, they are indeed very useful. In fact, the Swiss area is well-known for its mountains, that somehow worsen the quality of the communication links, especially for transmitters that are located far from the receivers. This, in addition to the assumptions made before about the transmission rate of the aircraft, provides a practical upper bound on the mean packet loss characterizing ADS-B communications.

5 CURRENT LIMITATIONS AND FURTHER DIRECTIONS

The analysis reported in Sec. 4 brings out the severe packet loss issue affecting the operations of the ADS-B communication technology. Indeed, almost 70% of the packets transmitted by the aircraft are lost, hindering both a precise and continuous monitoring of aircraft and the implementation of any reliable service based on the data provided by the aircraft.

For instance, the presence of such a high packet loss severely hinders the deployment of services based on the reception of multiple, even consecutive, packets from the aircraft. This is the case for most of the approaches dealing with the provisioning of security services. In fact, because of the limited payload size of ADS-B messages (56 bits), the addition of authenticity tags and signs often requires a single message to be amortized over multiple packet transmissions, as in [7], [20], [23], [24]. Even being valuable, these approaches would not work as intended in practice, because of the high message loss showed in previous sections that would hinder the reception of the needed cryptographic elements needed to carry out the specific procedures. Effective strategies, instead, should commit to reduce at minimum the bandwidth overhead derived by the inclusion of security services, thus mitigating the side effects due to the bad quality of the communication link.

Even if we are not the first one to spot this problem, we are the first one to quantify it and to point out, supported by data, that the issue is even worse than highlighted by previous contributions. In fact, previous contributions [6] assumed lower transmission rates by the aircraft, in compliance with the ICAO standards. Unfortunately, this is not the case, and the increase in the transmission rate by the aircraft further worsen the issue, given that the broadcast nature of the communication and the absence of any coordination increase the congestion of the communication link. Moreover, we are also the first one to provide useful bounds on the packet loss for a realistic scenario.

The reported results emphasize the need to develop new, accurate models for the ADS-B communications, taking into account the severe packet loss affecting the link. Indeed, these models can be useful to plan the deployment of receivers and implement advanced and reliable services based on received data. Moreover, the results demonstrate the need for a more reliable communication technique. In this context, Carrier Sense Multiple Access (CSMA) techniques have the potential to ameliorate the packet delivery ratio, providing well-known mechanisms for the collision avoidance. While this can potentially reduce the number of packets injected in the system by an aircraft in a given time frame, it can drastically improve the probability to successfully receive a packet. In addition, reported results can be used by system owners to improve the overall resiliency against packet losses. In fact, the receivers can be deployed and positioned in a smart fashion, with a mutual distance able to reduce at minimum the probability that a single packet is not received by any of the receivers. For instance, by positioning receivers in a way that the maximum distance between an aircraft and a receiver is 150 km, the packet loss probability can be improved by 50% on a single link, allowing any service that is built on top of such a system to work as intended. Indeed, deploying collision avoidance techniques and reducing the transmission rate could provide better performances and, thus, lower deployment costs.

Finally, it is worth noting that from the Opensky-network database it is possible to only deduct a lower bound on the packet loss probability, as well as some indicative statistics about the mean packet loss. Instead, precise models are possible only by knowing...
the effective packets transmitted by the aircraft. Thus, collaboration in this field by the major avionics firms is indeed necessary to better understand the underlying phenomena and to improve the reliability of communications.

6 CONCLUSION
In this study, analyzing more than 21GB of real aircraft-generated data traces, we have shown that packet loss in ADS-B communications is a serious issue, and, moreover, that current models are not very close to the reality of data. While this latter phenomenon can have several different causes (e.g. congestion, not compliance with the standard, interferences), for this technology to keep its promises, it is necessary that both the academic and the industrial community put more effort in characterizing packet loss and in providing solutions to the issues at stake.

Future work include verifying our model on other geographical areas with a sufficient number of receivers, deepening the investigations on the congestion phenomena, as well as the formulation of a statistical model to motivate theoretically our findings.

REFERENCES