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Aircraft Surveillance From Space: The Future of Air Traffic Control?

Jan Budroweit, Felix Eichstaedt, and Toni Delovski

In early 2024, the International Civil Aviation Organization (ICAO) announced that global air traffic had essentially fully recovered from the COVID-19 pandemic on most routes and projected a significant increase in air traffic for 2024 and the years to come [1]. Naturally, increased air traffic has to be met with the same amount of appropriate air traffic surveillance, in order to maintain safety but

Jan Budroweit (jan.budroweit@dlr.de), Felix Eichstaedt (felix.eichstaedt@dlr.de), and Toni Delovski (toni.delovski@dlr.de) are with the Institute of Space Systems, German Aerospace Center, 28359 Bremen, Germany.

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also to increase the efficiency of the used airspace and possibly reduce separation distances to allow more aircraft to be safely routed through the same volume.

Automatic Dependent Surveillance–Broadcast for Aircraft Surveillance

One of the elements for air traffic surveillance that is used to achieve this is called Automatic Dependent Surveillance–Broadcast (ADS-B). While originally intended as an air-to-ground system, application of this surveillance mode has been successively moved onto satellite-based systems. This transition brings significant potential advantages and solves some key issues of the original idea of aircraft surveillance but also adds challenges, all of which shall be discussed in this article, including potential new applications on the horizon.

History

Air traffic surveillance has been a key technology since the very beginning of (commercial) aviation. The original way to monitor objects in the airspace was by traditional radar as a very simple yet effective way to detect any object with sufficient radar cross section. *Primary surveillance radar* makes use of the physical properties of wave propagation, determining the position of an airborne object through mere reflection, time of flight, and Doppler shift [2]. While primary radar offered a simple (because it was entirely passive) means of surveillance (no active elements were required aboard the aircraft), it was also inherently limited. For example, beyond simple determination of position and velocity, not much additional information could be retrieved about the detected objects.

This limitation eventually led to the introduction of the *secondary surveillance radar* as a successor of the military *identification friend or foe* system. This technology allowed it to retrieve more detailed information through active responses by the aircraft to requests from an interrogator, requiring each aircraft to carry a transponder that would wait for interrogation messages from ground stations. Being an active radar, it was necessary to determine a common standard/protocol for the interrogator and the aircraft transponder. The first protocols that would implement such a standard were the *Mode A* and *Mode C* protocols, which allowed air traffic controllers to request limited information, such as aircraft identity and altitude, directly from the aircraft. Due to limits in the operational capacity, Mode A and Mode C were succeeded by the Mode S protocol as described in ICAO Annex 10 Volume IV [2], which improved and built upon the existing mechanisms and is still the de facto standard today. In fact, EU Regulation 1207/2011 requires each aircraft entering European airspace under instrument flight rules and operating as general air traffic to be equipped with Mode S transponders. Most countries in the world have similar regulations in place.

ADS-B

Mode S features a large catalogue of applications, in particular, its capability to specifically interrogate a selected aircraft by its unique 24-bit Mode S address. However, one element that has become steadily more popular for air traffic surveillance is called ADS-B. Today, ADS-B is a growing source for aircraft tracking data, used by agencies and researchers, and is available to the general public through various services or through one's own observation.

As opposed to many other Mode S types, ADS-B is a noninterrogation-based service, in which aircraft periodically ("automatically") transmit so-called telegrams, or *squitter* messages, as a broadcast toward any ground (or indeed spaceborne) Mode S receiver in reach. These messages always contain certain fixed types of information, such as the aircraft ID (ICAO address), and varying types of more detailed information depending on the message type, from the airborne position and altitude to the air and ground speed, orientation, and more.

Technical Specification of ADS-B

Each Mode S service operates at a downlink frequency f_{LO} of 1,090 MHz and is one of up to 24 different types, depending on whether they are interrogation-based or not. The type of a specific Mode S message is thereby indicated by its *downlink format* (DF). ADS-B telegrams are marked as DF17, also referred to as "extended squitter" messages, due to their length of 112 bits, as opposed to the 56-bit length, or DF11 "short squitter," of other services.

ADS-B and all other Mode S services utilize a relatively simple modulation scheme called pulse position modulation (PPM). With only two symbols, such as 1 and 0, it is modulated as a sequence of one high pulse followed by a low pulse ("1") or low followed by high ("0"), as indicated in Figure 1.

Each message is further preceded by a preamble to be identified as Mode S and then followed by a set of fields, including a 56-bit-long message field and a

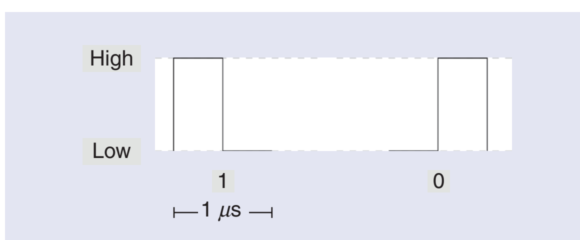

Figure 1. *PPM symbols [3].*

Communication, navigation, and surveillance are key requisites for safe and efficient local and global air traffic.

cyclic redundancy check checksum (Figure 2), allowing a user to discard erroneous messages. The long squitter is transmitted at a sampling rate of 2 MHz, or 2 MSPS (megasamples/s), giving each message a duration of 120 µs, including the 8-µs preamble.

ADS-B telegrams have different types that are sent at different transmission rates. While airborne, a Mode S transponder will send out its aircraft identification (one in five seconds), airborne position and velocity (twice per second each), and different status messages while alternating between the top and bottom antenna of the aircraft.

The total average transmission rate is thus ~6.2 long squitter messages per second (or 3.1 per antenna) [3]. That means that effectively, an observer on ground, or indeed from space, will usually see only one position update every second (depending on pitch and roll angle, both antennas may be visible to an observer), while the channel load at 1,090 MHz is significantly higher due to the different message types and short Mode S as described previously. However, it is important to note that the transmissions of ADS-B messages are not coordinated among aircraft, meaning that from an observer's perspective, they reach the receiver at essentially random intervals and often overlap and interfere with each other (given the usual case in which the observer sees more than one or two aircraft at a time). These interference effects are also referred to as garbling or, in the case of Mode S interrogation, false replies from unsynchronized interrogator transmissions in time (FRUIT). This will be an important consideration especially for space-based observation in the "Challenges of Space-Based ADS-B Receivers" section.

Typical Application and Usage

Communication, navigation, and surveillance are key requisites for safe and efficient local and global air traffic. In this article, we discuss only the provision of surveillance data. From the historical beginnings of commercial air traffic, it became clear that a

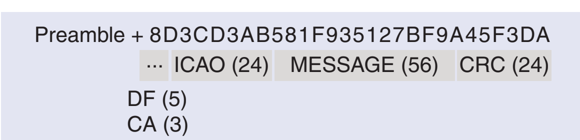

Figure 2. *An ADS-B message example with fields in hex representation [3].*

seamless surveillance of aircrafts was necessary, which was (and still is) typically done with primary and secondary surveillance radars [5]. In the past, typically, only regions with high or medium air traffic density were declared as controlled airspace with a broad network of ground stations that could guarantee minimal separation distances as required by international regulations. In contrast to those regions, low-density air spaces are typically uncontrolled airspace, meaning that air traffic controllers on the ground depend on voice radio contact to pilots and very low to almost no position information and updates in their respective airspace. ADS-B provided the opportunity to deploy ground stations in remote regions without the need for cost-intensive radar networks, making use of the already existing positional information in said Mode S extended squitter. Airservices Australia was one of the first to deploy a huge number of ground stations, which allow them to cover almost 100% of the airspace (as of 2020) at flight level 300 (~9 km altitude) [6]. However, most regions in the world are not only uncontrolled airspace but also barely or not even accessible at all for ground-based systems. This is why the concept of space-based ADS-B has been developed by DLR and SES Techcom and successfully demonstrated on ESA's Earth observation satellite *Proba-V* [7].

Space-Based ADS-B Surveillance

Mode S, and thus ADS-B, has been developed for line-of-sight communication between an aircraft and a radar station on the ground. The restrictive link budget from a distance of several hundreds of kilometers allows only a small margin for a correlation and demodulation function. Additionally, the antennas on commercial airliners are mounted on the top and bottom of the fuselage with an omnidirectional transmission pattern in plane but with a theoretical zero to the zenith (refer to Figure 8). Since the shortest link between an aircraft and a spacecraft is at the same time the worst-case link budget between both, the focus of the world's first space-based ADS-B demonstration was purely to evaluate the feasibility of space-based reception of Mode S squitter. The receiver for the mission was a single conversion superheterodyne receiver with an incoherent detector in the first mission phase after launch, which was updated to a coherent detector during mission time [8]. Due to limited resources on the satellite, a dual right-handed circular polarized patch array with 11.2 dBi was developed for the mission.

Proba-V was injected into a sun-synchronous orbit with 820 km altitude and was launched atop the *Vega* launch VV02 in 2013 May. Due to the natural orbit drift of the satellite, the main mission has been completed, and *Proba-V* is now in an experimental mission mode where the main payload focuses on lunar cycles. The

ADS-B demonstration is still online and providing data to the ground.

Commercial Usage of Space-Based ADS-B

After the first successful in-orbit demonstration of ADS-B surveillance from space as presented in the section "Space-Based ADS-B Surveillance," other space missions have proven the reception of aircraft transmitted signals from space. According to [10], at least six different companies have either entered the demonstration phase or moved into active services. In Table 1, these are listed and compared with regard to status, service level, coverage, and equipage.

As can be seen, commercial markets have already emerged. In particular, the Iridium-NEXT fleet opened a call for a dedicated ADS-B hosted payload on their 66 satellites, which was won by Aireon. Since 2019, the new constellation has been operating in orbit, offering 100% globe coverage. The hosted payload has a mass of 52.5 kg (including the antenna) and requires about 80 W of power [11]. With the Iridium communication network, received and demodulated ADS-B messages are transferred over crosslinks among Iridium satellites and downlinked to the ground. Aireon proposes a target report delay of about 1.5 s (from capture to the ground) and a probability of update of >96% for an update interval of 8 s [12].

Globalstar is another constellation that equipped 24 satellites with the ADS-B Link augmentation system (ALAS) that were launched and deployed back in 2016. The ALAS system guarantees an availability of >99.999% and offers an update rate of 1 s and a latency of <200 ms from the aircraft to the ground and <300 ms end to end [13]. ALAS needs specific hardware for the communication between the aircraft and the constellation and does not evaluate the Mode S transponder signal. A real performance analysis of the Globalstar equipped ALAS service has not been published with in-flight data.

Challenges of Space-Based ADS-B Receivers

Even though space-based ADS-B offers a lot of opportunities and has a huge impact toward air traffic control and security, satellite data from ADS-B Over Satellite on *Proba-V* reveal that capturing aircraft signals from space is quite challenging. The main reason is the large field of view that comes naturally due to the large altitude of the spacecraft (820 km at 98° inclination) and the relatively small antenna (dual patch antenna) with a half-power beamwidth (HPBW) of about 33° through 73° ($HPBW_{AZ} \times HPBW_{EL}$) and a gain of about 11 dBi. For small satellites, such apertures are quite common since space and weight on the spacecraft are limited. Based on the antenna and the given orbit, the footprint for capturing aircraft signals is about 1,200 km in longitudinal and 500 km in lateral extension to the satellite's flight direction, and due to the pulse-based noncoordinated transmission of ADS-B signals, collisions of data cannot be avoided. The best way to express the space-based receiver performance and potential areas where signal collision and signal quality issues occur is the probability of detection (PoD).

With the Iridium communication network, received and demodulated ADS-B messages are transferred over crosslinks among Iridium satellites and downlinked to the ground.

The PoD is explained by the ratio of correct decoded ADS-B messages to the expected amount of received data. Aircraft transmit ADS-B position messages with a frequency of 2 Hz alternating between the top and the bottom antenna, as explained in the section "Technical Specification of ADS-B." Since we assume that signals can only be received from the top antenna, a position update is expected to be received once per second. To give an example of how such tracking works, we depicted one aircraft descending toward London Heathrow (LHR) airport in Figure 3.

Green dots/lines in Figure 3 represent a correctly received message from the aircraft. As we know that the aircraft transmits messages every second via its top antenna, we can interpolate the missing telemetry here as red dots/lines.

TABLE 1. A space-based aircraft tracking and surveillance market comparison [10].

Companies	Status	ATS Service Level	Coverage	Equipage
ADS-B Systems				
Aireon	Active	Surveillance or tracking	Global	Uses existing
Globalstar	Demo	Tracking	No polar coverage	Need ALAS transceiver
Spire	Active	Tracking	Planned global	Uses existing
GomSpace	Demo	Tracking	Demo in Arctic region	Uncertain
Automatic Dependent Surveillance–Contract Systems				
Inmarsat	Active	Tracking	No polar coverage	31% aircraft equipped
Iridium	Active	Tracking	Global	Aireon system

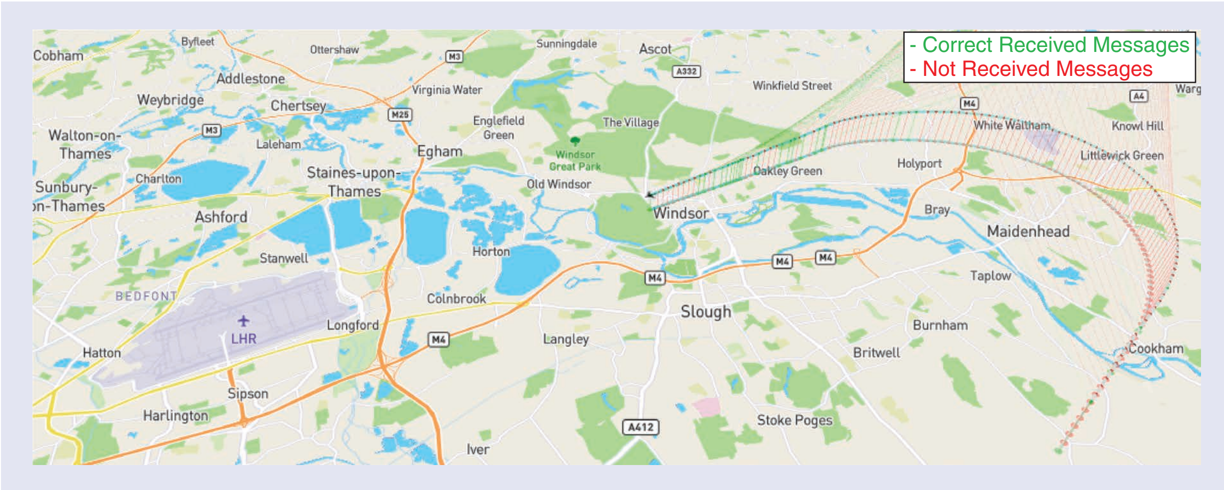

Figure 3. *An aircraft in descend mode toward LHR airport, captured from the Proba-V ADS-B receiver. (Source: OpenStreetMap.)*

If we transfer this method on a global scale, we can see the aircraft messages received, or to be received, on the satellite track as being depicted in Figure 5 for roughly four orbits (orbits 1–4 in Figure 4). This illustration already shows that the PoD over the Atlantic Ocean looks fine but becomes of more concern if we look closer at the land site, such as the eastern United States.

This is something that would be expected as most air traffic is over land. To show the air traffic on a global scale, we accumulated the amount of received ADS-B messages for a one-month period of continuous tracking plotted on the Earth map (Figure 5).

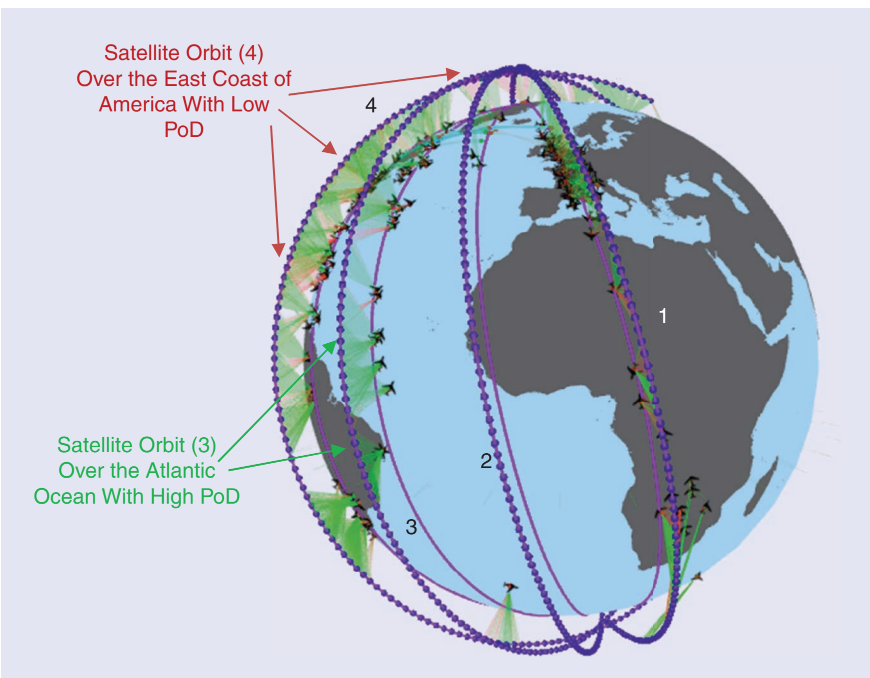

Figure 4. *Received and not received messages for four orbits.*

Here we clearly see certain hot spots, somewhat as expected in the United States, Europe, South America, and Asia, where many large airports are located. Another interesting perspective is the PoD that is plotted on the same map for the same period. This heat map is presented in Figure 6.

One would expect that the PoD would be in line with the map illustrated in Figure 5 for the accumulated received messages, but the hot spots show more accurately where signal interferences are of concern. These hot spots are still in areas with large airports, such as London, Paris, and Frankfurt in Europe or Washington, New York, or Boston in the United States, but they do not completely match with the previously shown heat map. More critically, these areas with a low PoD are always located on the coasts to transoceanic routes. These areas are critical for air traffic control and security maintenance as the aircraft will leave the ground-based controlled area and will hand over to a fixed given flight track, e.g., into the so-called *North Atlantic Organised Track System* (*NAT-OTS*). These tracks are of concern not only for safety reasons but also for commercial aspects as aircraft flying in the NAT-OTS must maintain fixed separation minima, e.g., one degree of latitude lateral separation (which equates to 60 nmi (nautical mile) or even 25 nmi for eligible aircraft (see Figure 7).

As air traffic is increasing, reducing these separation minima and having control of the air traffic increases the number of aircraft to be handled and increases efficiency at the end with the same level of safety as required by international regulations. This is why satellite-based air traffic control becomes so important. However, the data shown in the "Challenges of Space-Based ADS-B Receivers" section indicate that there is still a bottleneck to be overcome to improve space-based ADS-B receiver systems.

A simple solution would be to build antenna arrays with beam-forming capability to narrow the field of view, but due to the fairly low center frequency of ADS-B (1,090 MHz), such architecture becomes very large and hard to integrate in small satellite missions. Before we introduce another approach in the section "The Multichannel Receiver Approach," we want to take a close look at the PoD again and explain where these hot spots came from.

As has been said, ADS-B is a pulse band, noncoordinated transmission, and due to the large field of view, data collision may occur, especially in areas with a large density of aircraft in operation. However, the PoD has its worst level around coast areas, and we noticed that also, at areas over the ocean but close to the land site, the PoD drops. One needs to mention that the land site in this scenario is not directly in the field of view of the

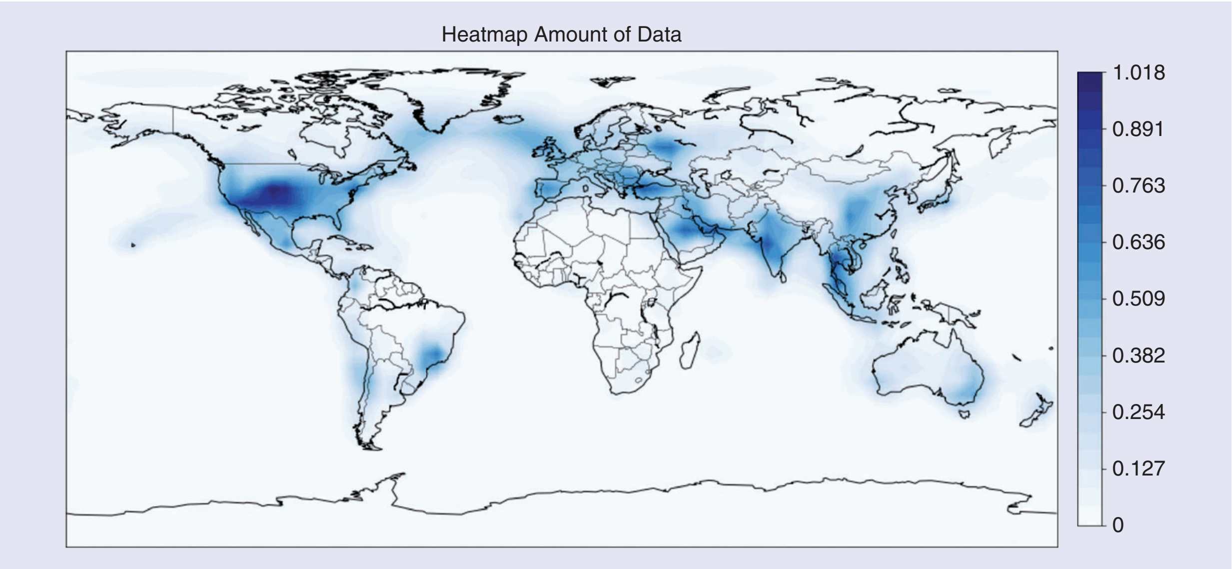

Figure 5. *The number of ADS-B signals received and the PoD on Proba-V from 31 January 2017 to 31 January 2018.*

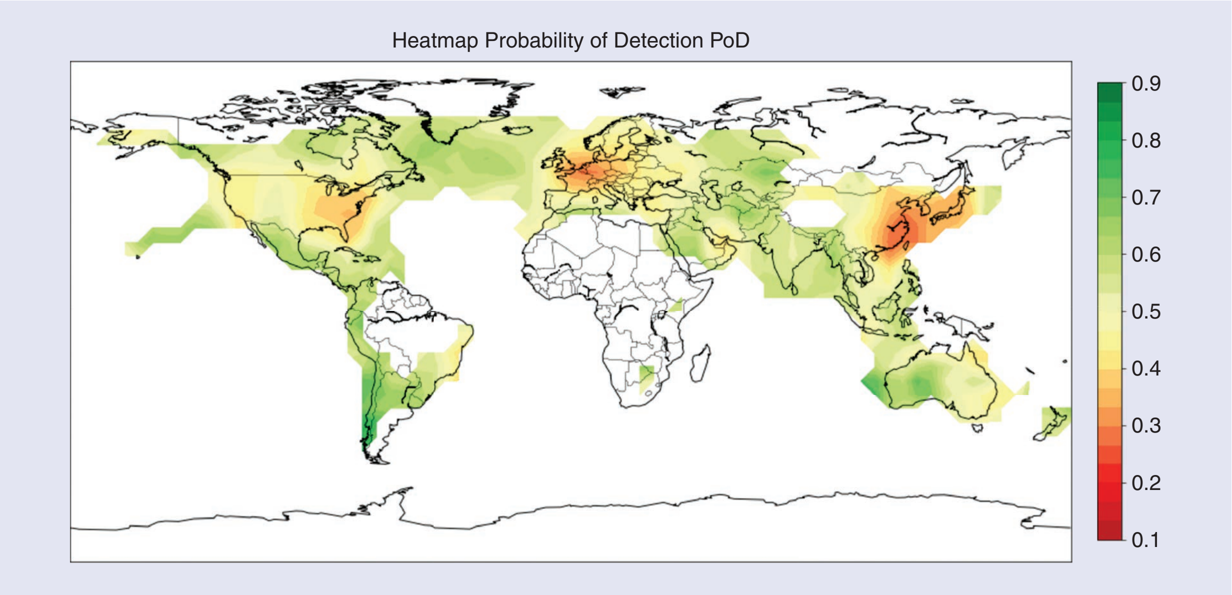

Figure 6. *The PoD on Proba-V from 31 January 2017 to 31 January 2018 on a world scale.*

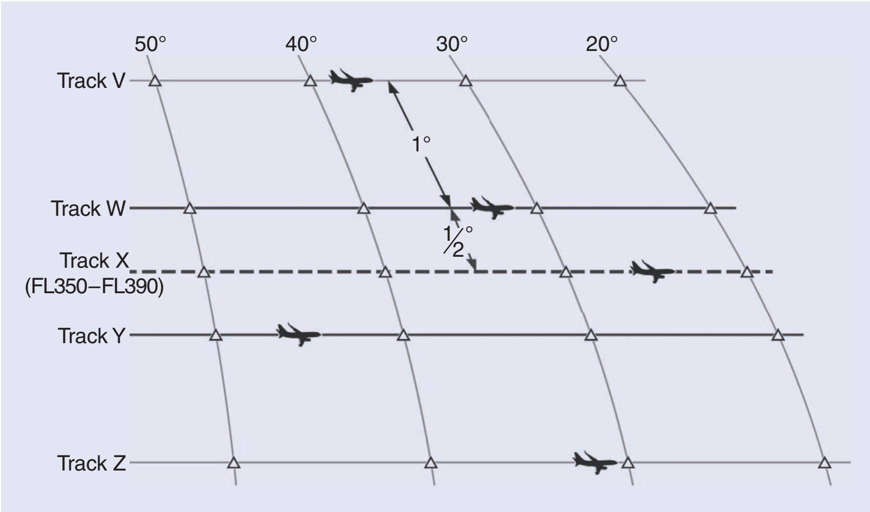

Figure 7. *The NAT-OTS track separation with track X having half-degree separation (Source: ©NATS/EUROCONTROL.)*

satellite, but the PoD decreases where typically, PoD values over the ocean are >90%. While analyzing the *Proba-V* data, we determined that the reason for such PoD drops was because of the nearby aircraft density, specifically at large airports. The weaker signals from the landsite (red dashed line in Figure 8) interfere with the receiver, so that the strong signal from the aircraft underneath (green bolt line in Figure 8) is not correctly detected. Moreover, one can see that the antenna on top of the aircraft has a nonhomogeneous pattern shape, and higher gain is achieved at 40° (and 80°) elevation, whereby the lowest gain is in the boresight.

This condition explains the observed phenomena on *Proba-V* and the quite low PoD at these coast site areas. In addition to that, the ADS-B receiver was designed to be very sensitive, is capable of receiving those weak signals, and is blocking the receiver to stronger ones as identified in the findings.

To mitigate those effects, one can use a steering type of antenna with high gain properties, but as mentioned, those structures become very large and inappropriate for small satellites. Another solution, also to further study these effects, is to use a multichannel receiver system with independent and parallel signal processing capacities that can face in different directions with dedicated antennas. This architecture was already proposed in [14], [15], [16], [17], and [18] and should allow weak signal blocking compared with the *Proba-V* configuration and characterize such phenomena in more detail to propose new solutions for space-based ADS-B receivers.

The Multichannel Receiver Approach

DLR has since conducted several experiments in order to verify the multichannel ADS-B receiver approach including radio and antenna front end [14], [15], [16], [17], [18]. As a practical demonstration platform, a special quad-channel communication platform for small satellites was developed at DLR, as described in [14], along with a custom quad-channel ADS-B antenna [17], [18]. This research so far has shown the feasibility of this receiver design, which has been shown to be capable of

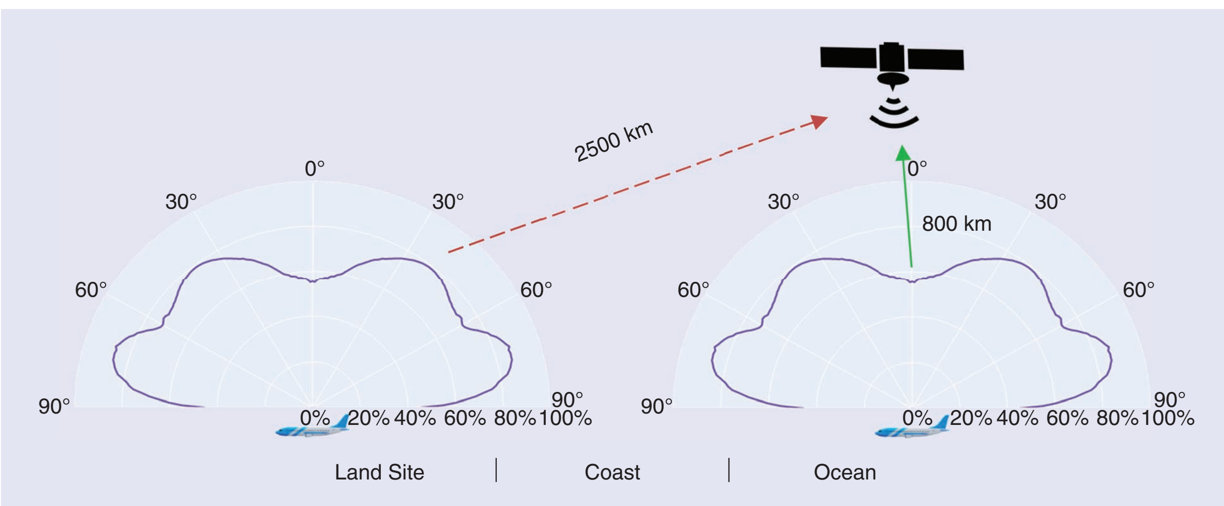

Figure 8. *An illustration of the signal arrival on a satellite as seen from a land site, the coast, and the ocean, which causes bad PoD.*

receiving ADS-B signals independently on four channels at the same time and at real-time speeds [4]. Further, the directional sensitivity has also been verified both in the lab and in a real-world ground-based field test.

The most important advantage proposed by this quad-channel design lies in the fact that based on the previous observations of low PoD over near-coastal regions, it might be beneficial to dismiss simple boresight observation in favor of multiple smaller antennas directed more laterally. This would ideally both mitigate interference effects from medium- or high-density airspace over coastal regions, with interfering aircraft in the peripheral view, and at the same time benefit from the higher gain of the aircraft's upward antennas at 40° and 80°.

Figure 9 shows some ground-based field test observations from 2022 [15] in different ways. In Figure 9(a), received messages from one receive channel have been decoded by their contained aircraft positions, with each dot in 3D space representing a single received positional ADS-B message. Figure 9(b) shows the same channel with the respective positions on a map. When

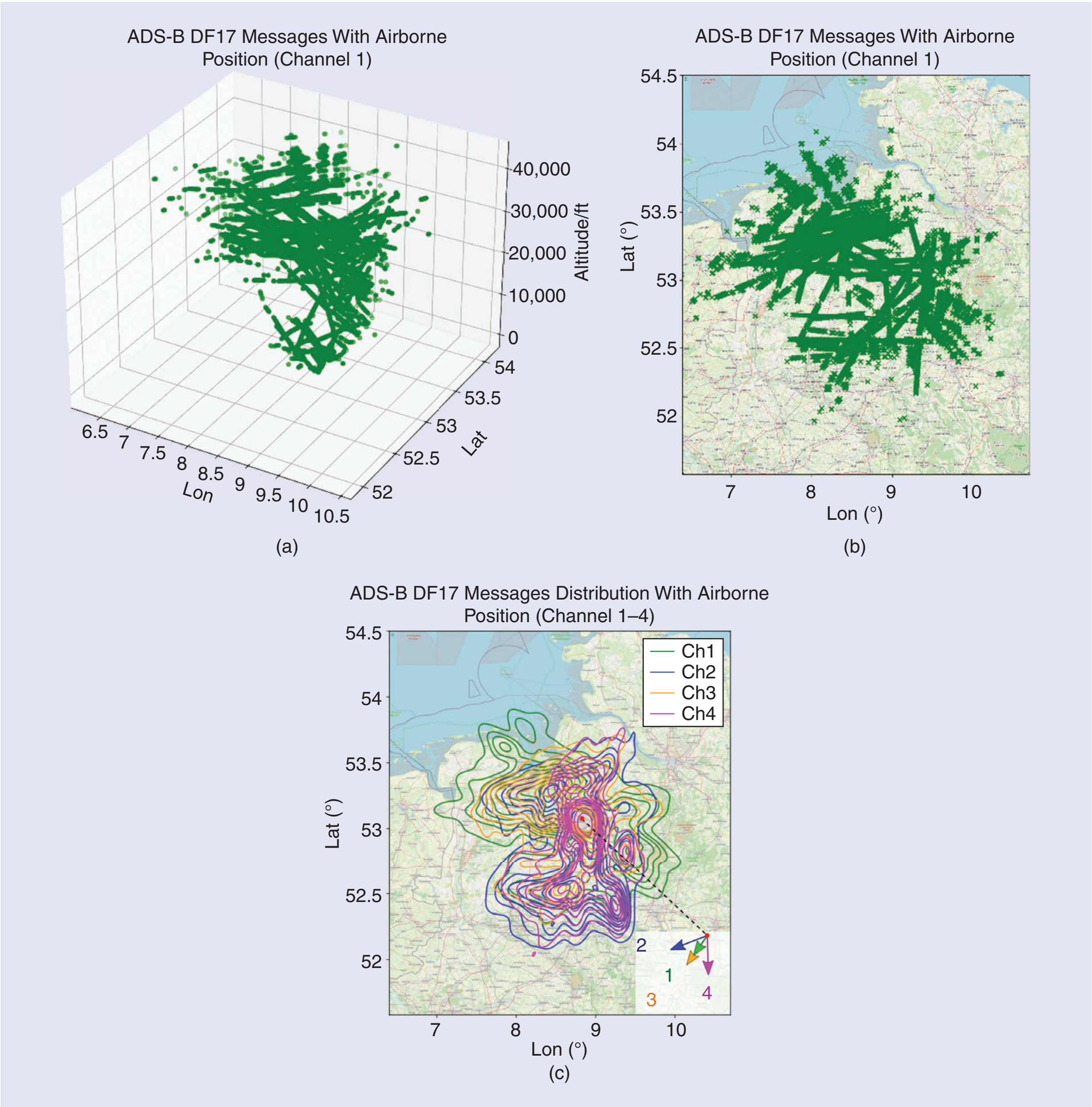

Figure 9. *The field test data of ADS-B telegrams [15]. (a) The decoded ADS-B aircraft positions on a single channel (ch1) in a 3D view. (b) A top-down view of the map. (c) A contour plot of the ADS-B positional message distribution based on message density, for all four receive channels. (Map data source: OpenStreetMap.)*

A clear pattern emerges, which is of course biased by the position being on ground but gives a preview of the clearly distinct receive characteristic of such a multichannel approach.

processing the received message patterns based on spatial density for all four channels [Figure 9(c)], a receive pattern becomes visible that varies, depending on the antenna directions, indicated by the arrows. Antennas 1 and 3 faced upward and up-forward, and antennas 2 and 4 faced sideways. A clear pattern emerges, which is of course biased by the position being on ground but gives a preview of the clearly distinct receive characteristic of such a multichannel approach.

An in-orbit demonstration mission of the proposed solution is already planned and will show the power of such a quad-channel receiver on a small satellite architecture, as another viable contribution to ADS-B surveillance from space.

Conclusion

In this article, we showed the demand and performance of space-based aircraft surveillance. Due to the increased aircraft traffic, there is a need for advanced tracking systems to maintain security and optimize flight route allocations. Transoceanic areas are typically not covered with surveillance systems. Thus, satellite-based ADS-B systems are capable of providing surveillance data and ensuring global coverage. However, the analysis of existing in-flight data on the first in-orbit demonstration mission of *Proba-V* revealed the technical difficulties that come with space-based tracking systems. Nevertheless, there are already constellations of satellites operating aircraft surveillance as commercial services, with great performance at least on global coverage. Real performance reports in terms of update rates and the delay time between reception and the ground infrastructure are limited, and specifically, the here-mentioned PoD data are not presented. Moreover, we presented new approaches to improve and further analyze the behavior of the PoD issue with a multichannel ADS-B receiver system that is intended to be launched into space in the middle of 2025 and at the end of 2025.

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