

Jamming a Parked Passenger Jet: Sensitivity of Aircraft to Jamming with Varying Power [†]

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Abstract

GNSS-based navigation is commonly used in aircraft as a source of localization. As reports of pilots about jamming during flights are becoming more frequent, we performed jamming tests with a parked passenger aircraft to assess the criticality of jamming events. We observed the reaction of the aircraft GPS position display in the cockpit and the ADS-B availability during jamming. We analyzed the relative power levels at which the GPS-receivers and the ADS-B broadcasting show negative effects. Beyond other factors, we observed significantly long recovery times for the GPS position display and the ADS-B system. The results give unique detailed facts about the vulnerability of one type of commercial passenger aircraft and emphasize how important it is to raise awareness of this vulnerability in aviation.

Keywords: jamming; aircraft; GNSS; GPS position; ADS-B; aviation safety; interference mitigation



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1. Introduction

Civil aviation is the safest transport mode in the world [1], but it relies on many interconnected systems of information and communication [2,3]. These systems allow information exchange in ground-to-ground, ground-to air, and air-to-air settings. All the communication channels used in these systems can be disturbed by radio frequency interference (RFI).

On board aircraft, GNSS-based navigation is commonly used as a source of localization and timing. Recently, reports by pilots of RFI events during flight have become more frequent. There were even public reports of the spoofing of more than 50 passenger jets in the airspace over the Middle East from the end of September to mid-November 2023 [4,5]. The Guardian reported in April 2024 that about 46,000 aircraft logged problems with GPS over the Baltic Sea after August 2023 [6]. The conflicts in Ukraine and Gaza/Israel have reinforced this development since February 2022.

But interference events have also been observed before. The industry data from Airbus reveal about 10,843 RFI events detected globally in 2021 [7]. This number soared to 49,605 in 2022. The most affected are the Middle East and Eastern Europe, as well as the regions surrounding the conflict zones. The southern and eastern Mediterranean, the Black Sea, the Baltic Sea, and the Arctic area are affected, too [8]. In general, the interference events show continuous increases in the severity of their impact, a growth in their intensity, and the attacks become more and more sophisticated [8].

Jamming and spoofing are real threats to air transport [3,9,10]; the consequences of a successful malicious cyber-attack could be severe [2]. Nevertheless, at the moment, the safety concern about jamming is not considered to be an unsafe condition that would warrant Safety Directive (SD) action [8].

The observed consequences of GNSS degradation are, e.g., the degradation of Satellite-Based Augmentation Systems (SBAS) and Ground-Based Augmentation Systems (GBAS), as well as the failure or degradation of Positioning, Navigation and Timing (PNT) information [8]. This, in turn, can cause, e.g., inconsistent flight guidance, the loss of or misleading of surveillance systems (corrupted Automatic Dependent Surveillance-Broadcast (ADS-B), Terrain Avoidance and Warning System (TAWS), Attitude and Heading Reference System (AHRS), Horizontal Situation Indicator (HSI), wind shear, terrain and surface functionalities, etc.), loss of or misleading time-dependent systems (e.g., clock, fuel computation system, FMS), inconsistent aircraft position and ground display (making arrival and approach procedures unusable, with an erroneous Head Up Display (HUD)), and an inability to conduct or maintain RNAV and/or RNP operations [3,8]. Moreover, the autopilot can fail [11], and even INS might have problems [8] if this is not immediately separated from the other positioning systems in the case of an attack. All these effects can have a considerable commercial impact on flight operators and airport authorities, as they can be detrimental to time-critical airport schedules, resulting in the need to scale down the number of operations and in increased waiting times during the approach of aircraft, raising their fuel consumption [9,12,13].

In order to assess the criticality of jamming events to aircraft, we performed jamming tests with a parked passenger aircraft accommodating 100 to 150 passengers. A clearly defined jamming signal in the L1 band was transmitted with different power levels and from different distances and directions to the aircraft. A reference antenna was placed on top of the aircraft, slightly behind the two GPS antennas of the aircraft. The reaction of the GPS receivers, especially the display of their positioning results as displayed in the cockpit and the ADS-B availability, was observed during jamming.

The details of the measurement setup will be explained in Section 2 and the outcomes and results will be discussed in Section 3. Section 4 provides a summary and draws further conclusions for aviation safety.

2. Experimental Setup

As already stated in Section 1, we performed jamming tests with a parked passenger jet, namely an Embraer 195 from Austrian Airlines AG. This aircraft was parked in the airport Graz Thalerhof in September and October 2023 and jamming tests were performed during the night, when the airport was closed and no air traffic was in motion. The Embraer 195 acquires GPS L1 signals via two antennas and the signals are processed by two receivers to two different position solutions, called GPS 1 and GPS 2.

In coordination with the Austrian frequency authority and the Austrian armed forces, a jamming device was made available on loan. This was an SDR-based circuit; Figure 1 presents a block diagram of it. The transmission antenna was a hemispherical, omnidirectional antenna from TECOM (Omni Conical Spiral Antenna, Type Nr. 201143).

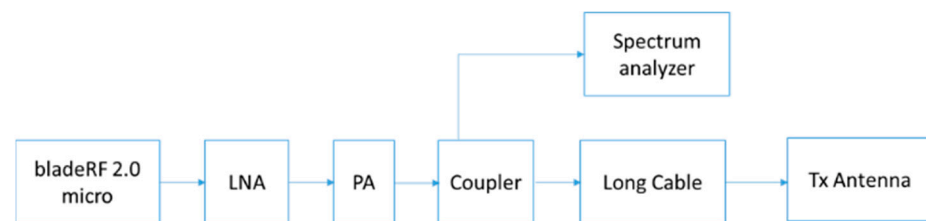


Figure 1. Block diagram of transmitter (LNA—noise amplifier; PA—power amplifier).

The jamming signal was generated in the L1 band with a center frequency of 1575.42 MHz and a bandwidth of 8 MHz. It was a linear chirp signal, where the instantaneous frequency alternated periodically between -4 MHz and 4 MHz, initially increasing from -4 MHz to 4 MHz and then decreasing from 4 MHz to -4 MHz. The chirp rate was 1×10^{12} Hz/s. The sampling rate of the generated signal was 10 MSPS (mega samples per second).

Within this configuration, the transmission power of the jamming device was adjusted by manipulating the gain value within the bladeRF SDR. In the tests, the power transmitted from the jammer varied from 20 dBm to 25 dBm (equivalent isotropically radiated power, EIRP).

To assess and analyze the impact of jamming on the aircraft, a GNSS reference antenna of type UBlox ANN-MB Multiband [14] was also attached to the aircraft. It was placed in line with the GPS antennas of the aircraft, being slightly behind them on top of the fuselage (Figure 2, left picture). Below the aircraft, a sensor box was placed (Figure 2, right picture), containing a GNSS receiver module of type Septentrio mosaic-X5 [15]. This was connected to the reference antenna and could be monitored via a WLAN connection from a laptop inside the aircraft.



Figure 2. (Left): Positioning of GNSS reference antenna on top of aircraft. (Right): Sensor box below aircraft, placed on a table and connected via cable to GNSS reference antenna.

Inside the cockpit of the aircraft, a Sony Alpha 6400 camera was installed on a tripod to film several displays of interest. In particular, the GPS navigation solutions, given in standard and fine resolutions as well as the ADS-B (Automatic Dependent Surveillance-Broadcast) display of the aircraft, were in the focus of the camera.

With this setup, the aircraft was jammed from different distances, ranging from a few meters to about 180 m, from different directions (cross-shaped around the aircraft, as well as in an angle of about -34°), and using different transmitter powers from -20 dBm to 25 dBm EIRP.

During the tests, the GPS position data of the aircraft were recorded along with the videos from the camera, and the data of the reference receiver were logged.

3. Results and Discussion

From the observations in the cockpit of the aircraft as well as the recorded data, the sensitivity of the aircraft receivers was analyzed. In particular, the availability of GPS

positions, the ADS-B displayed to the pilots, and recovery times of GPS and ADS-B were investigated. As the aircraft was jammed from different sides of the aircraft, also shadowing effects due to the aircraft fuselage were examined.

GPS positions availability and ADS-B availability fail when the aircraft is jammed with enough power. The pilots recognize this from the cockpit display of these values, as can be seen from Figures 3 and 4 (left panel). In the two pictures on the left of Figure 3, the display from the tablet can be seen, showing GPS positions with standard (LAT and LON in degree, accuracy 1×10^{-7} degrees) and very fine accuracy (LATFINE, LONGFINE in degree; must be added arithmetically to LAT/LON coordinates; accuracy 1×10^{-8} degrees to 1×10^{-14} degrees). In case of jamming with sufficient power, LATFINE/LONGFINE becomes unusable, which is indicated via red numbers on the tablet, as shown in the second panel of Figure 3. In the two panels on the right, the Multipurpose Control and Display Unit (MCDU) can be seen, which is directly integrated into the cockpit and shows positions derived from GPS 1 and GPS 2 receivers (cf. Figure 2). When jamming with sufficient power, the GPS 1 and GPS 2 display on the MCDU disappear, as can be seen from the panel on the right.



Figure 3. Display of GPS positions in cockpit.



Figure 4. (Left): Display of ADS-B and RAAS availability in cockpit. If jamming with enough power, “ADS-B NOT AVAIL” and “RAAS NOT AVAIL” are displayed in green color, as can be seen from the lower panel (no better picture quality possible). (Right): “Center” position of jammer below the aircraft.

We analyzed the GPS positions’ availability on two different test nights. On night one, the jammer antenna was mounted at approximately the same height as the GPS antennas on top of the fuselage (about 5.2 m). The jammer was brought to three different positions: in front of the aircraft at a horizontal distance of 70.5 m from the GPS reference antenna, to the right of the aircraft at a distance of 63.1 m, and diagonally left of the aircraft at an angle of about -34° (relative to the front direction) and a distance of 174.9 m. On night two, jamming was performed with the transmitter antenna mounted on a roll plate that could be moved on the bottom (see Figure 4, right panel). Jamming was operated from below the aircraft (called “center” in the diagrams), which was a position right behind the turbines of the aircraft in the center of the fuselage; see Figure 4, right). It also occurred in a cross around this center at distances of 3 m, 6 m and 10 m to the “left” and/or “right” of

this center point (which was also left/right of the aircraft), 3 m, 6 m and 10 m in “front” of the nose of the aircraft, and 3 m, 6 m and 10 m behind the “rear” of the aircraft.

The availability of GPS positions in the test cases described above are displayed in Figure 5, with the left-hand side showing the results of night one, and the right-hand side showing the results of night two. A value of 3 means that the GPS position was fully available (both GPS receivers worked fine), a value of 2 means that only the GPS 2 receiver position information was available, a value of 1 means that only the GPS 1 receiver position information was available, and 0 means that no GPS position information was available at all during jamming. The nominal signal power at the reference antenna (x -axis) was calculated from the EIRP transmitted omnidirectionally by the jammer via the subtraction of the free space loss between the transmitter position and reference antenna position. Signal shadowing due to the fuselage was not taken into account; the distances between reference receiver antenna and aircraft antennas were also neglected as there was no accurate position information about the aircraft receiver antennas available, as this drifted before starting the experiment (for an unknown reason). Hence, this is no measured value, but a nominal calculated link-budget value, which gives the nominal power in the distance of the reference antenna.

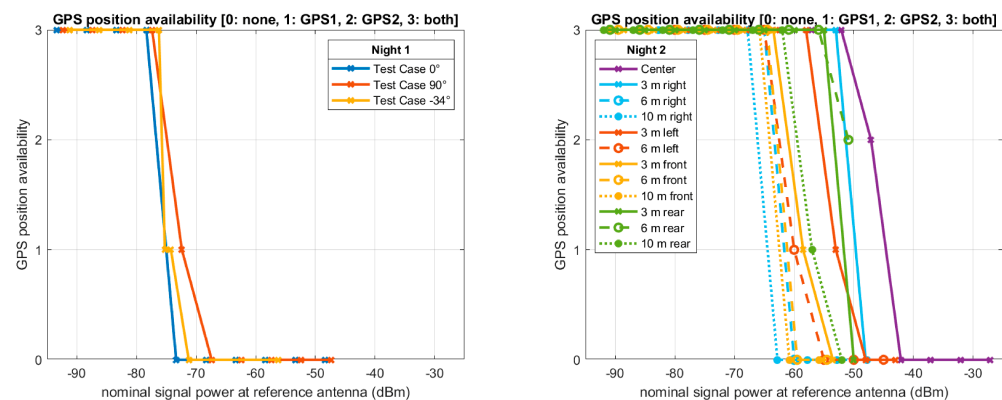


Figure 5. Availability of GPS positions depending on relative jammer signal power at reference receiver site on night 1 (left) and night 2 (right). “Front” means position in front of the nose of aircraft, “right” is right of the center point below fuselage, “left” is left of this center, and “rear” is behind the rear of aircraft.

As can be seen, for lower jammer signal powers reaching the receiver, the acquisition of GPS positions was clean, whereas for higher jamming powers, all the GPS positions were lost. The transition area in between, where the aircraft was struggling with acquiring GPS positions—resulting sometimes in the availability of only either GPS 1 or GPS 2 positions—was quite narrow in night 1, ranging from about -67 dBm to -79 dBm. In night 2, however, the transition area was much broader, ranging from about -42 dBm to -70 dBm, and the relative power was also higher, meaning that GPS positions were available at higher jamming powers as compared to night 1. This is probably due to shadowing effects of the aircraft, as the jamming in night 2 was performed from below the aircraft, where the fuselage of the aircraft was in between the transmitter and the receiver antennas on the top of the fuselage. In night 1, however, the transmitter was brought to almost the same height as the receiver antennas, which is why there was a free line of sight between the transmitter and receiver antennas there.

The broadness of the transition area in night 2 probably resulted from the different strengths of shadowing from the different positions below the aircraft. However, unknown reflection effects from the bottom and other facilities in the airfield can have a minor influence. The shadowing effect seems to be highest for the transmitter located in the

center below the fuselage of the aircraft (violet), a bit lower for the transmitter located at a distance of 3 m to the right (blue, dashed) and left (orange, dashed), and again lower for the transmitter located 3 m in front of the cockpit (yellow). The shadowing from the aircraft when the transmitter was located 3 m behind the *rear* (green) of the aircraft seems to be comparable to the shadowing to the right and left. If you move further away from the aircraft, at a distance of 6 m (dashed lines), the shadowing effect seems to be reduced again for the positions right and left, whereas it remains similar to the 3 m distance in the *rear* of the aircraft (green dashed). In front of the aircraft (yellow dashed), the shadowing has already weakened at 6 m and weakens insignificantly further at a distance of 10 m (yellow dotted). The shadowing in these two distances in front of the aircraft seems to be very small, considering the fact that the relative signal power reaches values comparable to the free-line-of-sight case (night 1). Behind the rear of the aircraft, however, the shadowing further decreases at a distance of 10 m (green, dotted) but seems to be still available at this longer distance, as the full GPS position is also available for comparably high relative signal powers. The shadowing to the left (orange) and right (blue) seem to be similar; no significant difference can be determined.

Figure 6 shows the recovery times of the GPS positions after being lost due to jamming for the two measurement nights. The values were derived from the observation of the GPS 1 (top) and GPS 2 positions (bottom) displayed on the MCDU (cf. Figure 3) in the cockpit. The recovery times typically increase with increasing jamming power, while the increase is steep in the middle, and flattens for lower and higher jamming powers. Recovery times can be significant and reached up to 44 s in cases with high jamming power and long jamming duration (cf. Figure 6, night 1, where jamming duration was always 4 min). Moreover, the recovery times of GPS 1 and GPS 2 can differ significantly, as is the case for the 0° scenario in night 1 at lower powers (blue lines on the left panels of Figure 6).

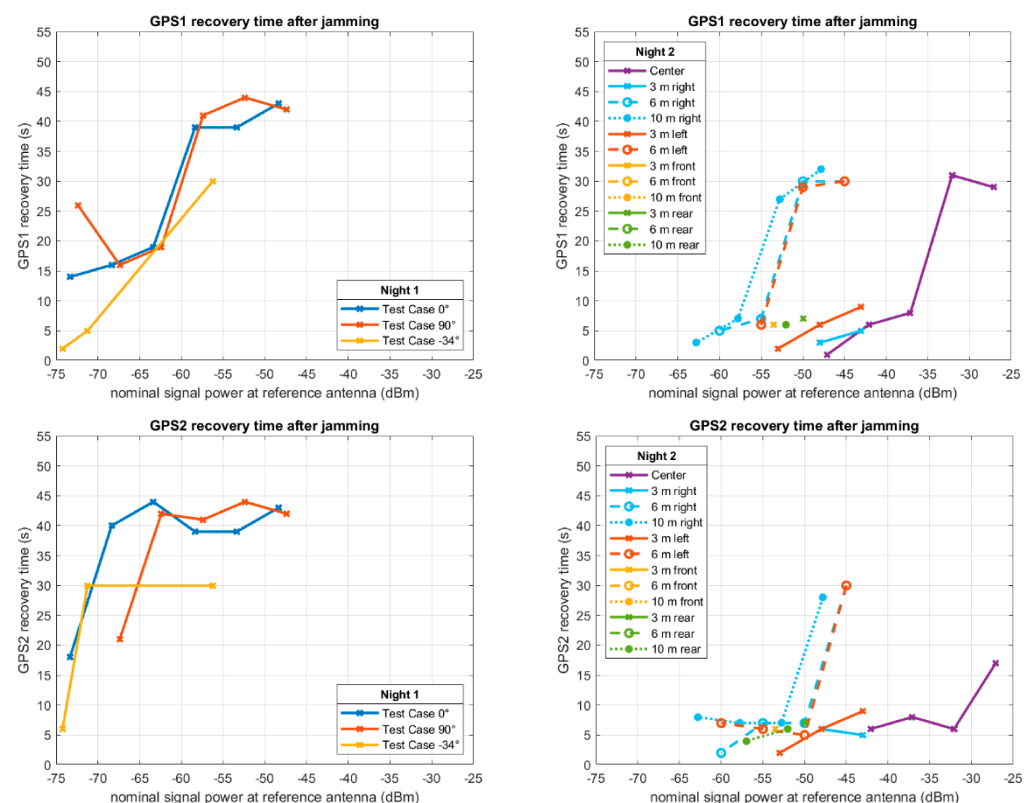


Figure 6. Recovery times of GPS 1 position (**top**) and GPS 2 position (**bottom**). Data derived from status shown in MCDU display of cockpit.

During night 2, the jamming duration was varied arbitrarily, which was why the relationship between recovery time and signal power was less distinct than on night 1 (cf. right panels of Figure 6).

The recovery times of highly resolved latitude (LATFINE) and longitude (LONGFINE), which are displayed on the tablet in the cockpit, are shown in Figure 7. Typically, the fine position recovers in a similar time to the GPS 1 and/or GPS 2 position of the MCDU display, mostly within one second earlier.

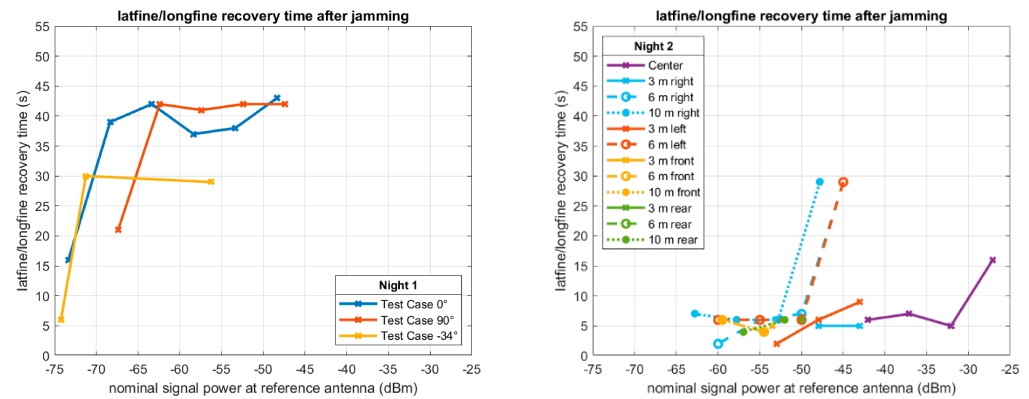


Figure 7. Recovery times of highly resolved latitude (LATFINE) and longitude (LONGFINE) depending on relative signal power. Data is recorded from tablet in cockpit.

The higher the relative signal power, the longer the recovery times for ADS-B availability, as can be seen in Figure 8. Typically, the recovery times are slightly longer compared to the recovery times of the position solutions, sometimes by even up to 10 s.

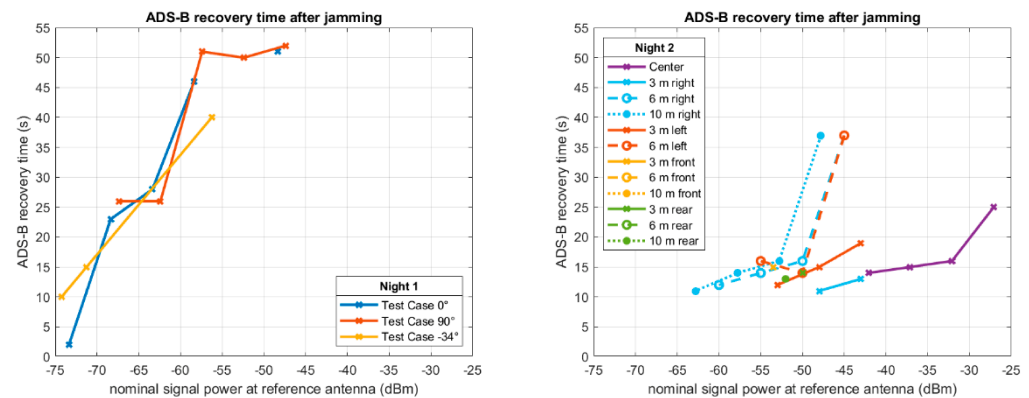


Figure 8. Recovery times of ADS-B availability depending on relative signal power.

As stated above, the recovery times observed in night 2 show a less clear dependency on the relative signal power, which is why we also investigated the dependency of the recovery times on the jamming duration, which was diverse on night 2 (arbitrarily ranging from 28 s to 240 s). The dependencies of fine latitude and fine longitude, as well as ADS-B recovery times, on the jamming duration in night 2 are shown in Figure 9. The relationship between these variables is not very distinct, but there is a tendency where longer jamming durations also result in longer recovery times.

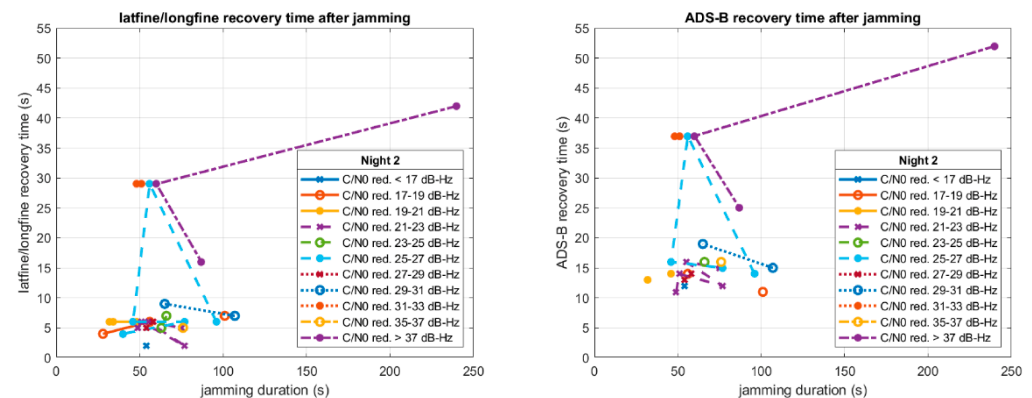


Figure 9. Recovery times of highly resolved latitude (LATFINE) and longitude (LONGFINE) (**left**) as well as of ADS-B availability (**right**) depending on jamming duration in night 2. Different colors and line styles combine measurements with similar C/N0 reduction as recorded by reference receiver. This grouping should make it easier to analyze relationships.

4. Summary, Conclusions and Outlook

From the results shown in Section 3, one can summarize that Embraer 195 shows clear impairments due to jamming. The display of the GPS position information on the MCDU of the aircraft failed during jamming with enough power, showing that the GPS receiver lost track of the signal. Also, the display of the highly resolved fine latitude and fine longitude failed during jamming. ADS-B availability and RAAS availability dropped out too. The recovery times of the GPS position display after jamming were unexpectedly long in some cases and took up to 44 s in cases with higher jamming power. The recovery times of the highly resolved latitude (LATFINE) and longitude (LONGFINE) display were similar; these two values always recovered simultaneously. The recovery times for the ADS-B availability were longest, usually about a few seconds to 8 s longer than the GPS position recovery, and reached up to 52 s in the worst cases.

The recovery times of the GPS positions (MCDU and fine display) and ADS-B availability in the cockpit show a clear dependence on the jamming power, resulting in longer recovery times with stronger jamming power. In addition, the jamming duration has an influence on the recovery times, even if this effect is less distinct than the dependency on the jamming power. When jamming with median powers caused the C/N0 of the receivers to collapse, one of the two GPS position displays recovered much faster than the other (with differences in recovery times of up to 25 s).

When jamming from below the aircraft, shadowing effects appear, which are highest when the jammer is located directly below the fuselage in the center location (described in Section 3 above). Behind the rear side of the aircraft, the shadowing is greater than for left and right. In front of the aircraft, shadowing is lowest. Shadowing to the left and right of the aircraft are similarly pronounced.

These results underline how GPS jamming can pose considerable challenges to the pilots in the cockpit, especially during the approach phase to an airport. The long recovery times are particularly critical in this respect, not least because the causes are still unclear. Further investigations should be carried out to uncover the essence of this.

The results shown in this paper need to be scaled when drawing conclusions about aircraft flying in the air. Generally, we expect the same effects in the cockpit for the same jammer power reaching the aircraft receivers, but the power diminishes with the distance from the jammer. The influence of reflections (multipath) due to the bottom and the fuselage itself are also different for aircraft in the air. Their effect also depends on the soil conditions (asphalt, concrete, meadow, etc.; dry, wet, etc.), the environment (buildings, mountains, etc.), and hence on the resulting additional power incidence on the antennas.

The effects on the aircraft depend on the actual hard- and software installed in the aircraft. To prevent impairments due to jamming, we recommend the use of multiband receivers and the elaborated automated coordination of the interaction of different sensors (sensor fusion) for position determination. Our measurements build a well-documented database, which is suitable for deriving requirements for the implementation of suitable mitigation measures (an insight into countermeasures and mitigations technique can, e.g., be found in [3,10,16,17]). The results could be of particular value, especially for the design of flight-certified sensor implementation. This involves techniques such as signal authentication, multi-sensor fusion or jamming, and spoofing mitigation techniques. The results can also aid the development and installation of interference monitoring systems in airports to contribute to preserving the integrity of airport communications.

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