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Analysis of GNSS disruptions in European Airspace

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BIOGRAPHY

Michael Felux is a senior lecturer and leader of the Aviation Infrastructure Team in the Centre for Aviation at the Zurich University of Applied Sciences. He holds a PhD in Aerospace Engineering and has been working on safe and secure navigation for aviation for the past 12 years.

Benoit Figuet is a research associate at the Centre for Aviation at the Zurich University of Applied Sciences and the co-founder of SkAI Data Services. He holds a Master of Engineering from the Grenoble Institute of Technology, France. His research is focused on the application of data science to aviation, specifically in the area of data-driven mid-air collision risk modelling.

Manuel Waltert is a research associate at the Centre for Aviation at the Zurich University of Applied Sciences. He holds a PhD in Transportation Sciences from Cranfield University and has been working on aviation-related research for the the past 10 years.

Patric Fol holds a Bachelor's degree in Aviation and is currently a Master's student at the Centre for Aviation of the Zurich University of Applied Sciences. His thesis is focusing on the identification and operational impacts of RFI on aviation.

Martin Strohmeier is a Senior Scientist at the Swiss Cyber-Defence Campus of armasuisse in Zurich, and also a Visiting Fellow of Kellogg College, University of Oxford. The main focus of his work has been the security analysis of critical infrastructures in the air, in space and on ground. Martin is also a co-founder of the aviation research network OpenSky. He received his MSc degree from TU Kaiserslautern, Germany and joined Lancaster University's InfoLab21 and Lufthansa AG as a visiting researcher.

Xavier Olive is a full researcher with ONERA, the French Aerospace Lab. He graduated from Supaero, Université de Toulouse, France and holds a PhD from Kyoto University, Japan. His research interests include Data Science, Machine Learning and Decision Science applied to aviation, with a particular focus on optimisation, anomaly, and pattern detection applied to air traffic management, operations, predictive maintenance, safety analyses and risk assessment.

ABSTRACT

Global navigation satellite systems have enabled significant improvements in aeronautical navigation over the past decades. However, in recent years a growing number of radio frequency interference events been reported by flight crews rendering this technology temporarily unavailable in large areas. In this paper, we identify these radio frequency interference events and study the impact they have on civil aviation in Europe in more detail. In a first step, radio frequency interference occurrences are identified using crowd-sourced automatic dependent surveillance data collected in the period February to August 2022 for three different regions: the Baltic States and Poland, Eastern Europe bordering the Black Sea and the Eastern Mediterranean. Then, we identify and implement detection schemes in order to assess the extent and duration of the impact of radio frequency interference on civil aviation. The analysis on the three areas of interest show different characteristics, from isolated events to regularly and recurrent disruptions, with up to thousands affected flights daily. We then go on and identify aircraft types affected by jamming and evaluate flight plan data with respect to aircraft navigation equipment in order to identify flights that rely solely on satellite navigation and might need radar assistance from air traffic control in case of a loss of satellite navigation. Finally, we touch on advanced mitigation strategies designed to ensure a safer use of the skies during radio frequency interference events.

I. INTRODUCTION

Today, air traffic is heavily relying on Global Navigation Satellite Systems (GNSS) for accurate and reliable positioning and guidance in most phases of flight, including for departure, cruise flight and during arrivals. For approach and landing, Satellite-Based and Ground-Based Augmentation Systems (SBAS / GBAS) provide corrections for the GNSS signals, yielding improved accuracy. With additionally provided integrity parameters, residual navigation errors can be safely bounded, and the augmented GNSS position information can be used for a variety of applications, such as navigation en-route in airspaces

where performance-based navigation is specified, in terminal airspace and even for precision approach guidance. As GNSS is currently the only means in aeronautical navigation to provide integrity along with the position solution, it is the only means of navigation supporting procedures with a Required Navigation Performance (RNP). Furthermore, GNSS feeds a variety of other aircraft systems, such as for example the aircraft clock, the Terrain Awareness Warning Systems (TAWS) and different surveillance functions of the aircraft as described in an in-service-information by Airbus (2019) on potential cockpit effects in case of loss of GNSS . The Automatic Dependent Surveillance Broadcast (ADS-B) transmits aircraft position information along with parameters regarding the Estimated Position Uncertainty (EPU) and position Source Integrity Level (SIL). These parameters change when GNSS-based navigation is disturbed or interrupted and can thus serve as indicators for determining regions where aircraft are subject to Radio Frequency Interference (RFI). Since the beginning of the conflict in Ukraine in early 2022, there were numerous reports and documented instances where air traffic over Europe was experiencing GNSS disruptions. These incidents were mainly observed over Finland, the Baltic states, the Russian exclave Kaliningrad as well as in Romania, Bulgaria and above the Black Sea. While air traffic being subject to RFI is not a new phenomenon, the extent of disturbances observed over the past months deserves a more detailed analysis. Most large commercial aircraft do not solely rely on GNSS as their exclusive navigation system, but are equipped with high-grade inertial reference systems, other radio navigation equipment, or a combination thereof. But even for those aircraft, loss of GNSS still causes nuisance warnings in the flight deck and thus increases the workload of pilots. It furthermore prevents the use of all procedures requiring GNSS. Besides that, the impact of RFI on GNSS on smaller and less-well equipped aircraft may be more severe as they may require radar assistance from Air Traffic Control (ATC).
In this paper we identify the RFI hotspots in Europe and the timely evolution of RFI affecting air traffic in those regions over the months February through August 2022. The analysis is carried out based on an analysis of transmitted ADS-B parameters. Together with a distribution of aircraft types and equipage information, this study allows for a detailed impact assessments on air traffic, regarding number of affected aircraft, share of affected traffic in a given region, as well as the potential need for ATC support of less-well equipped aircraft and the impact of GNSS unavailability on mid-air collision risks. Finally, the paper discusses the potential impact of these jamming events on global and regional air navigation strategies for the evolution of aeronautical navigation systems.

II. BACKGROUND AND LITERATURE

This section provides an overview of the literature dealing with the detection and localisation of GNSS RFI events on the basis of ADS-B data. Besides that, it presents background information on the effects of GNSS jamming on aircraft systems and concludes with a paragraph on strategies and roadmaps relying on the availability of GNSS for future aeronautical navigation and associated procedures.

Following several reports about RFI affecting civil air traffic, the European Aviation Safety Agency (EASA) published a Safety Information Bulletin on the 17th of March 2022 describing potential effects on aircraft and outlining suggestions for addressing the issue. The recommendations included that ”Air operators [..] should ensure flight crews and relevant flight operation personnel are aware of possible GNSS jamming and/or possible spoofing” (European Union Aviation Safety Agency, 2022, 2). In order to be able to do so, as well as to maintain a high level of safety in aviation in general, GNSS jamming incidents must be detected and localised in a timely maner. To this end, various detection methods are described in the literature. For instance, Scaramuzza et al. (2015) recorded and subsequently analysed the RFI situation in the Swiss airspace over a period of three years using measuring devices installed on board of rescue and military helicopters. However, such large-scale measurement networks are resource-intensive and often do not allow for a real-time evaluation of an acute RFI situation. To address these limitations, ADS-B parameters such as the Navigation Accuracy Category for the Position (`NACp`) and the Navigation Integrity Category (`NIC`) are often used in the literature for both the detection and localisation of RFI incidents. To this end, Figuet et al. (2022) detected RFI-affected aircraft by evaluating how the transmitted `NACp` values change in zones of active jamming. Put simply, the `NACp` values degrade on entry, while they increase when the aircraft leave the area affected by RFI. Darabseh et al. (2019) compare the `NACp` values transmitted via ADS-B from flights affected by known RFI incidents with the `NACp` values broadcast by unaffected flights. Similarly, Lukeš et al. (2020) employ pattern recognition techniques to detect RFI events on the basis of the fluctuation of `NACp` values. RFI incidents can also be localised by means of the `NIC` parameter in ADS-B messages using mathematical models (Liu et al., 2022) or machine-learning methods (Liu et al., 2021). Finally, RFI incidents can be localised by analysing gaps, i.e., outages, in ADS-B trajectory data by applying the power difference of arrival method (Jonáš and Vitan, 2019) or using convex optimisation models (Liu et al., 2020). A different approach for RFI detection is taken by Murrian et al. (2021). In their work they use a GNSS receiver mounted on the International Space Station to detect an localise large-scale RFI sources from space.

Furthermore, jamming incidents can also be detected by pilots in the cockpit as aircraft affected by RFI often display corresponding advisory and caution messages. However, as Osechas et al. (2021) showed, the effects of jamming may be subtle. As the aircraft starts to be affected by RFI, only a subset of all visible satellites may be affected and become unavailable for navigation. This might initially just decrease the navigation performance but not trigger any alerts in the flight deck. Only after having lost GNSS-based navigation altogether, usually the first warnings that appear relate to a failure to transmit the aircraft position via ADS-B (Fol and Felux, 2022). Navigation-related warnings tend to appear only after the aircraft has been subject to RFI for some period of time. However, short periods where the navigation system may be able to track at least 4 satellites while otherwise flying through an area with active jamming, as well as differences in the hybridisation of different navigation sensors in different aircraft lead to quite different effects for different aircraft types. While the effects differ, they all increase the work load and require attention of the flight crew and adherence to manufacturer recommendations and company standard operating procedures on how to address the warnings.

Apart from the immediate effects visible in ADS-B data and annunciations in the flight deck, frequent unavailability of satellite navigation may also have some consequences for the evolution of civil air traffic and the navigation infrastructure necessary for efficient operations in general. In ICAO's Global Air Navigation Plan (GANP), GNSS is considered a key technology for developing and maintaining an efficient, safe, and interoperable future air navigation system (International Civil Aviation Organization, 2022a). In this context, the availability of GNSS is considered an integral part for numerous elements of the Aviation System Block Upgrade (ASBU) framework defined on the global technical level of the GANP. Moreover, on the basis of the global strategy outlined in the GANP, the European (EUR) Air Navigation Plan (ANP) (International Civil Aviation Organization, 2016) as well as the European ATM Master Plan (Single European Sky ATM Research, 2022) consider GNSS as the primary means to implement performance based navigation (PBN) across Europe. To this end, the implementation of PBN has already been mandated by Commission Implementing Regulation (EU) 2018/1048, which requires the exclusive use of PBN for air traffic management (ATM) and air navigation services (ANS) by the year 2030. With the exception of CAT-II/III landing systems, such as the instrument landing system (ILS) and the GBAS landing system (GLS), conventional, land-based navigation systems shall only be used for back-up purposes in case of GNSS outages in the future. For this reason, only a Minimum Operational Network (MON) of conventional navigation aids shall be maintained, while the remaining infrastructure must be decommissioned at the end of their service life. Consequently, aviation will most probably be even more dependent on the availability of GNSS signals in the future than it is the case today.

III. METHODS

This chapter provides an overview on the methods applied to determine the impact of RFI on civilian air traffic in Europe. In a first step, Section III.1 explains how the ADS-B data set used in this paper was retrieved and processed. Subsequently, Section III.2 illustrates how European geographical areas of interest subject to RFI activities have been identified and selected, while Section III.3 outlines the details of how we classified aircraft to be affected by RFI. Finally, Section III.4 describes the methods used to analyse the data.

1. Data set

This paper makes use of crowd-sourced and publicly available ADS-B data. For an observation period between February 1st to August 31st, 2022, position and status information messages were collected from the OpenSky Network (OSN) database (Schäfer et al., 2014) processed with the `traffic` library (Olive, 2019). As such, aircraft position information was obtained from the `state_vectors_data4` table, while the `NACp` values transmitted by the aircraft were derived by decoding the ADS-B raw messages from the `operational_status_data4` table. Subsequently, the resulting data sets were merged via both the `icao24` code of the aircraft, which is a unique identifier assigned to an aircraft, and the `timestamp` of each message. For the analysis in this paper data of 1,034,455 flights was downloaded and analysed.

2. Selection of areas of interest in Europe

Due to the large amount of data, we restricted the analysis to three geographical regions of particular interest as they were explicitly mentioned by EASA in their Safety Information Bulletin European Union Aviation Safety Agency (2022). Subsequently, we consulted the web page `http://www.gpsjam.org/`, provided and hosted by Wiseman (2022), to cross-check and define areas of interest (AoI) for further analysis. This website provides an overview of the daily aggregated number of flights affected by RFI on the basis of ADS-B data. In the course of this work, three different AoI were selected for the more detailed analysis presented in this paper. The first area, referred to as AoI-1, extends from the southern tip of Finland through the Baltic States of Estonia, Latvia and Lithuania, the Russian exclave of Kaliningrad and Poland into the northern half of the Czech Republic. In East-West dimension, AoI-1 reaches approximately from the German-Polish border to Belarus. AoI-2 is situated mainly around Romania, Bulgaria, Moldavia and the western part of the Black Sea. It also covers part of Ukrainian airspace, however, no traffic was operating in that region during the period we investigated. Especially since the closure of the Russian airspace to most European and Asian airlines, safe and efficient flight operations in AoI-2 is of high interest, as a significant share of the air traffic between Asia and Europe now crosses this sector. Finally, AoI-3 is located in the airspace around Cyprus in the eastern Mediterranean Sea and parts of Southern Türkiye. AoI-3 has been known to be affected by RFI for several years and has already been studied in other scientific papers, e.g., Osechas et al. (2022) or Fol and Felux (2022). The geographical dimensions of the selected AoI are shown in Figure 1.

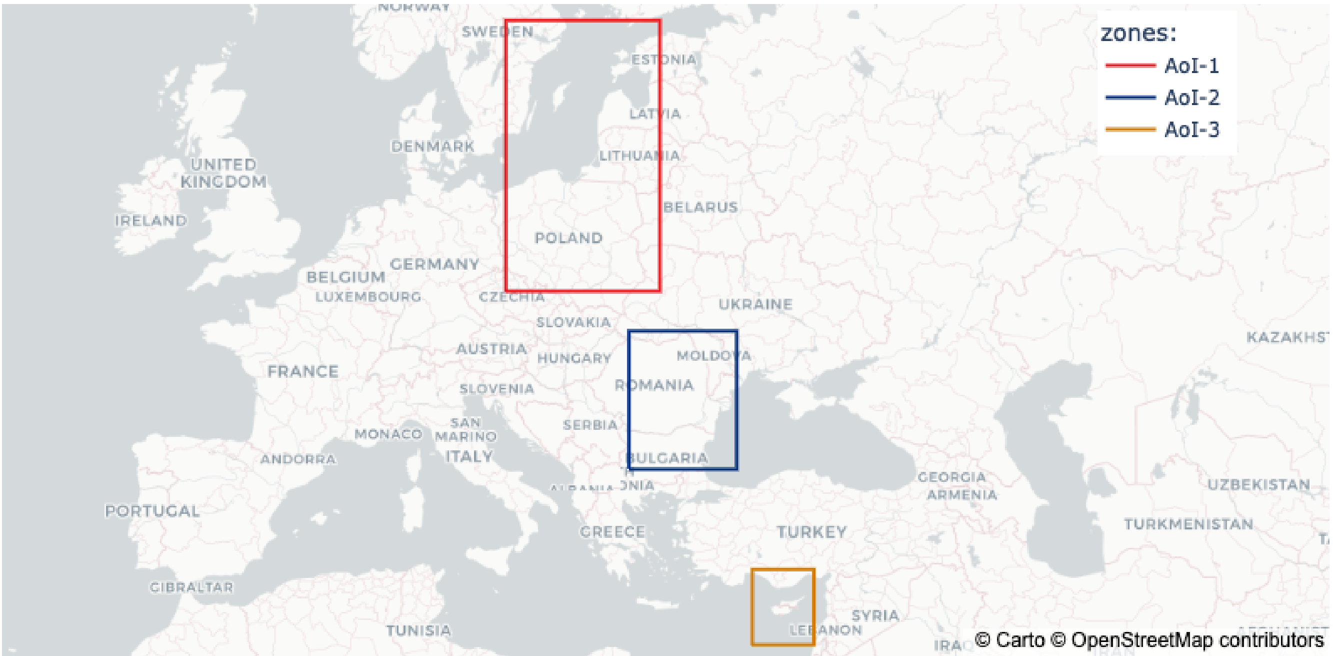


Figure 1: AoI for which ADS-B data have been collected.

3. Detection of aircraft affected by RFI

To detect aircraft subject to GNSS RFI, the method described in Figuet et al. (2022) is adopted in this paper. Based on the `NACp` value sent via the ADS-B messages, this method aims to determine whether an aircraft is jammed or not. As shown in Table 1, the `NACp` value provides an indication for the Estimated Position Uncertainty (EPU) determined the navigation system of an aircraft. To this end, high `NACp` values suggest that the positioning accuracy is high, while low `NACp` values indicate the opposite.

Table 1: `NACp` and corresponding EPU values. From Sun (2021).

`NACp`	EPU
11	< 0.00162 NM
10	< 0.0054 NM
9	< 0.0162 NM
8	< 0.05 NM
7	< 0.1 NM
6	< 0.3 NM
5	< 0.5 NM
4	< 1 NM
3	< 2 NM
2	< 4 NM
1	< 10 NM
0	> 10 NM or unknown

(Darabseh et al., 2019) and (Lukeš et al., 2020) suggest that a degradation from `NACp` values of 8 or above to a value of 0 occurs when an aircraft is affected by RFI. By the same logic, if the `NACp` value transmitted by an aircraft increases from 0 to a value of 8 or more, an aircraft can be assumed to have left a zone of active RFI and GNSS is being used as primary means of navigation again. Consequently, in this paper aircraft are labelled as being affected by GNSS RFI by examining the `NACp` values emitted in the AoI determined above for significant changes. To this end, we consider an aircraft being present in one of the AoI to be jammed (i) if it transmits a `NACp` value of zero cumulatively for more than one minute, and (ii) if it transmits a `NACp` value greater than 7 cumulatively for more than one minute within the entire period of observation. By requiring both condition (i) as well as condition (ii) to occur for at least one minute each, outliers in the data set can be excluded.

4. Analysis of RFI activities in AoI

A number of analyses were carried out in order to evaluate the impact of RFI activities on aircraft operating in the AoI defined above. This includes (i) an analysis of the number and share of flights affected by RFI as well as the timely evolution of RFI occurrences, (ii) an analysis of aircraft type-specific influences of RFI activities, and (iii) an analysis of aircraft equipage-specific influences of RFI activities.

Once specific portions of flights are identified as being affected by RFI, the impact of jamming activities on air traffic can be investigated further. Most simply, the cumulative number of aircraft affected by RFI per day over the period of observation is determined. Since the cumulative number of affected flight movements depends both on the geographical extent of the AoI as well as on the amount of traffic passing through that region, we also considered the relative share of flights affected by jamming on a day-by-day basis. Moreover, to identify potential patterns in the timely evolution of GNSS interruptions, we fine-screened the entire observation period by analysing the number of affected aircraft in 30 minute intervals.

As mentioned above, the reaction of an aircraft to RFI depends heavily on the architecture of the on-board navigation sensors. Hence, we investigated what types of aircraft were affected by RFI and how the aircraft types relate to the observed flights showing a degradation of the `NACp` value within the selected AoI. The aircraft type of each flight was identified using the OpenSky aircraft database, which maps the unique `icao24` code of each aircraft to an aircraft type. This information is used to compare the traffic share of all flights passing through the AoIs and jammed flights with respect to the aircraft type and helps to potentially identify which aircraft types are more robust to RFI.

RFI activities can affect aircraft differently. For example, aircraft that exclusively rely on GNSS for navigation will most likely be more affected by RFI activity than aircraft that are equipped with a number of different navigation sensors. In case of RFI, such aircraft may need ATC assistance and thereby increase the work load of controllers. In case of multiple aircraft needing assistance simultaneously, this may reduce the capacity of ATC sectors. When filing a flight plan, operators have to indicate the navigation equipment they carry on board in accordance with ICAO's Procedures for Air Navigation Services - Air Traffic Management (PANS-ATM) International Civil Aviation Organization (2022b). Among others, operators shall indicate whether the aircraft is equipped with Distance Measuring Equipment (DME), GNSS, and/or inertial navigation equipment. For this study we considered aircraft that indicate GNSS equipage but neither inertial navigation nor DME capability, as these are the ones likely to lose navigation capability and requiring assistance in a zone of active RFI.

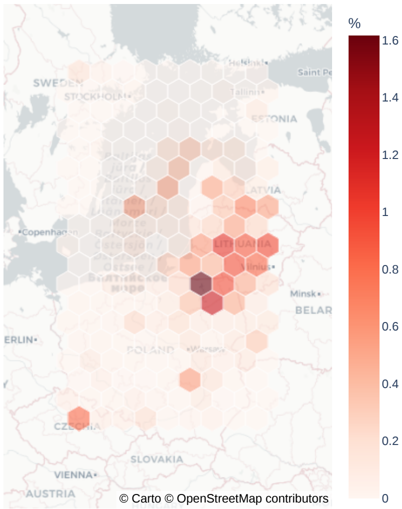
IV. RESULTS

In this chapter, the results are presented. To this end, Section IV.1 deals with both the localization of RFI activities in each AoI and the determination of the number of flights affected by jamming. Section IV.2 contains statistics on the duration of the impact of RFI activities on flights. Finally, Sections IV.3 and IV.4 illustrate which aircraft types have been affected by GNSS jamming and investigates the aircraft navigation equipage.

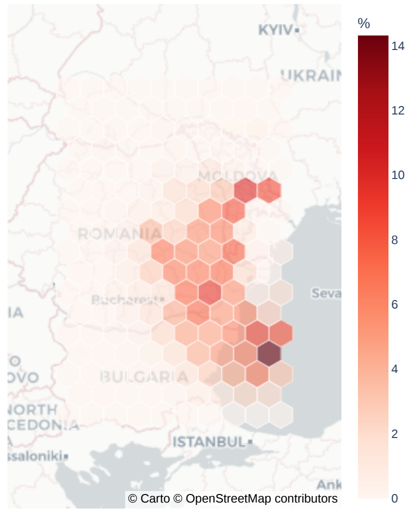
1. Number and share of affected aircraft

For the selected observation period from February 1st to August 31st, 2022, data for 511,195 flights were collected for AoI-1 (Baltic States and Kaliningrad area), of which 3,422 were identified as being impacted by RFI. Similarly, 428,118 flights have been collected for AoI-2 (Romania, Bulgaria area), of which 22,565 were identified as impacted by RFI. And finally, in AoI-3 (Cyprus area) 95,142 flights were collected, out of which 42,904 were identified as being impacted by RFI. Figure 2 depicts the percentage of flights affected by RFI for the selected observation period and for each of the AoI in hexagonal bins. For AoI-1, the area most affected by RFI is the region around Kaliningrad, the southern half of Lithuania and the north-eastern part of Poland. Another area that shows increased levels of jamming is located over the Baltic Sea, between Latvia and Sweden. In AoI-2, the most significantly affected area extends from over the Black Sea off the coast of Bulgaria in a north-westerly direction towards central Romania. High levels of jamming are also observable for flights into Moldova. For AoI-3, high levels of jamming activities were observed especially in the area between southern Türkiye, along the coast of Syria and Lebanon, up to the Israeli border. Throughout AoI-3, a decreasing impact of RFI from east to west can be observed.

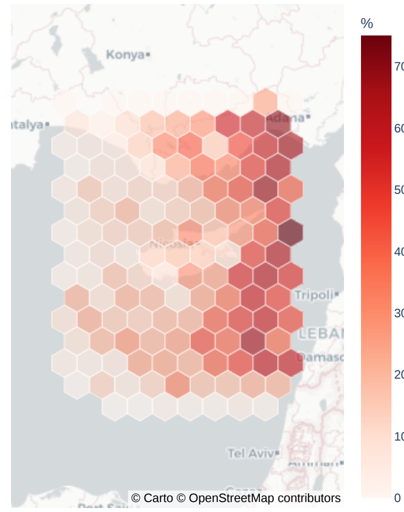
When comparing the percentage of flights jammed over the whole observation period, it can be observed that the maximum percentage of flights affected by RFI varies significantly across the three AoIs. Indeed, the maximum share of affected flights is just 1.6% in AoI-1, about 14% in AoI-2 but over 70% in AoI-3. In order to put those numbers into context, Figure 6 shows the the total number of aircraft affected by jamming in each AoI, along with the relative share of flights within the AoI being affected for each day. For AoI-1, the the largest peak occurred in early March where about 25% of all flights were affected. The maximum share of affected aircraft reached just over 50% in AoI-2 ane went up to almost 80% in AoI-3. For a more in-depth analysis, Figures 3, 4, and 5 depict the intensity of RFI activities, quantified by means of both the relative and absolute number of aircraft labelled as being jammed, in intervals of 30 minutes duration over the entire observation period.
In AoI-1, a period of intensified jamming activities can be clearly identified from March 4th to 6th, 2022. This phase is followed



(a) AoI-1.

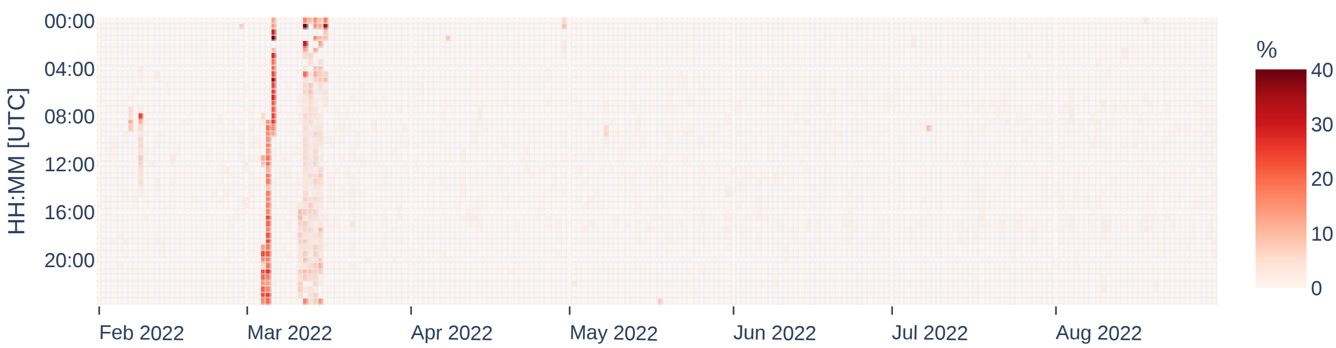


(b) AoI-2.

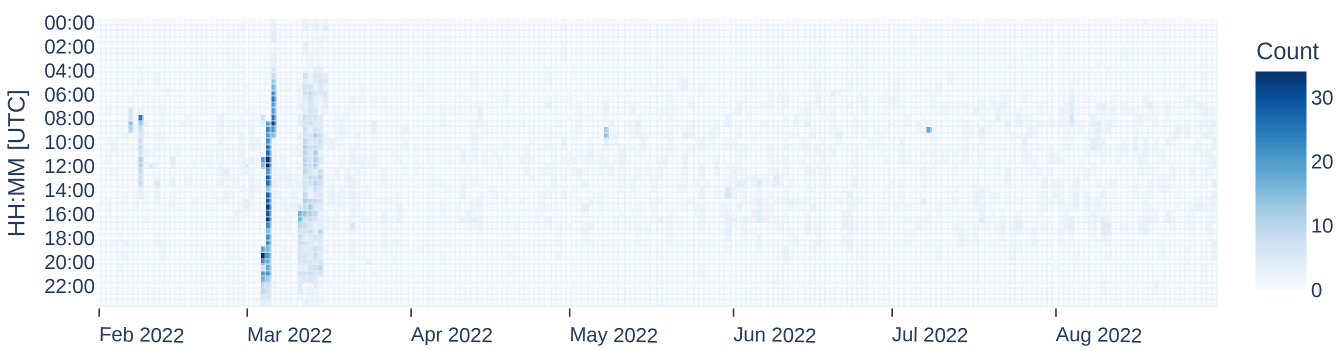


(c) AoI-3.

Figure 2: Percentage of aircraft affected by RFI per hexadecimal bin between February and August 2022.



(a) Relative share of aircraft being subject to RFI.

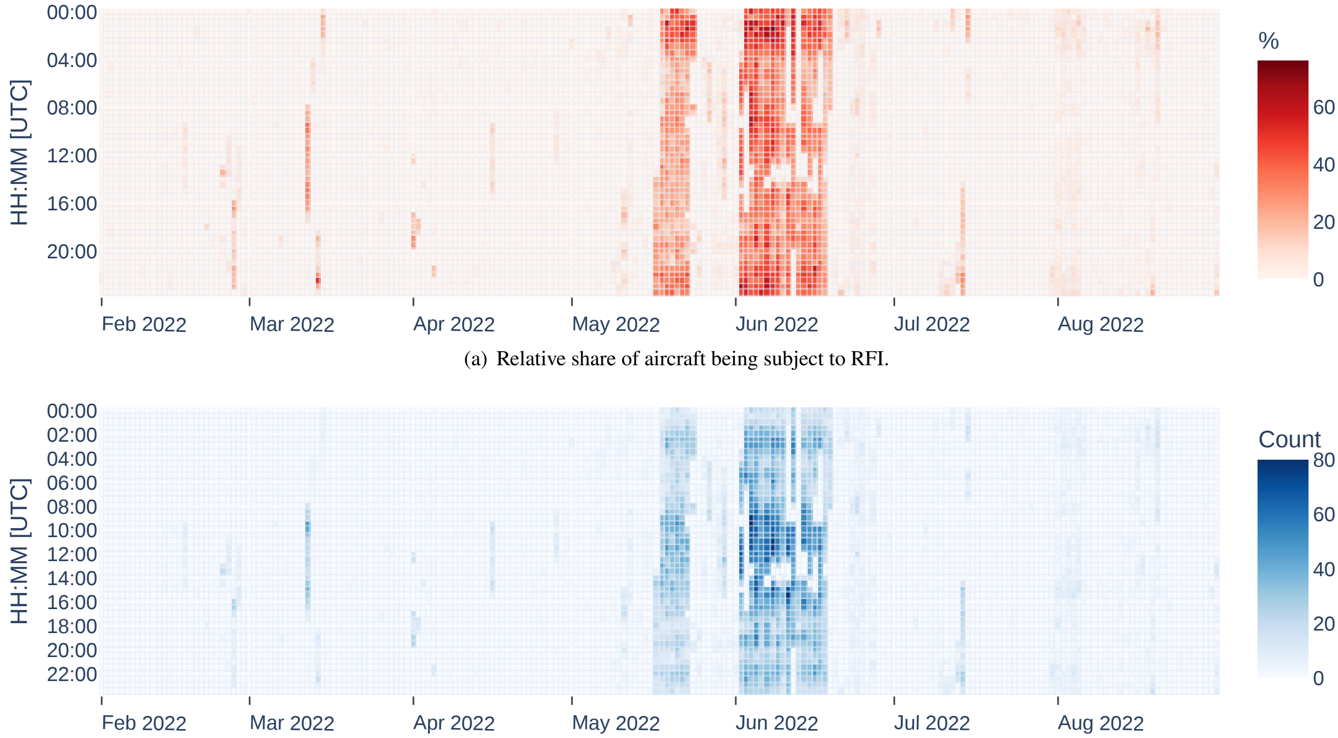


(b) Absolute number of aircraft being subject to RFI.

Figure 3: Jamming activity for AoI-1 for 30 minute intervals covering the entire observation period. The colour of each cell corresponds to the relative and absolute number of flights impacted by RFI within the 30 minute intervals.

by a 5-day period with less intense interference. Apart from a half-day impact in February, only isolated RFI events are observed in AoI-1 for the remainder of the observation period.

Concerning AoI-2, segregated events were identified until mid-May 2022. A period with relatively high intensity of RFI activity was observed between May 17th and May 24th, followed by the most intense one in the observation period on the days from June 2nd until June 19th. In that period, up to 80 flights per 30 minutes interval were identified as being affected by RFI.



(a) Relative share of aircraft being subject to RFI.

(b) Absolute number of aircraft being subject to RFI.

Figure 4: Jamming activity for AoI-2 for 30 minute intervals covering the entire observation period. The colour of each cell corresponds to the relative and absolute number of flights impacted by RFI within the 30 minute intervals.

Afterwards, only mild activity has been observed until the end of the observation period.
In AoI-3, the RFI activity is more or less constant through the entire observation period, with up to 20 flights being affected by RFI within the 30 minutes intervals.

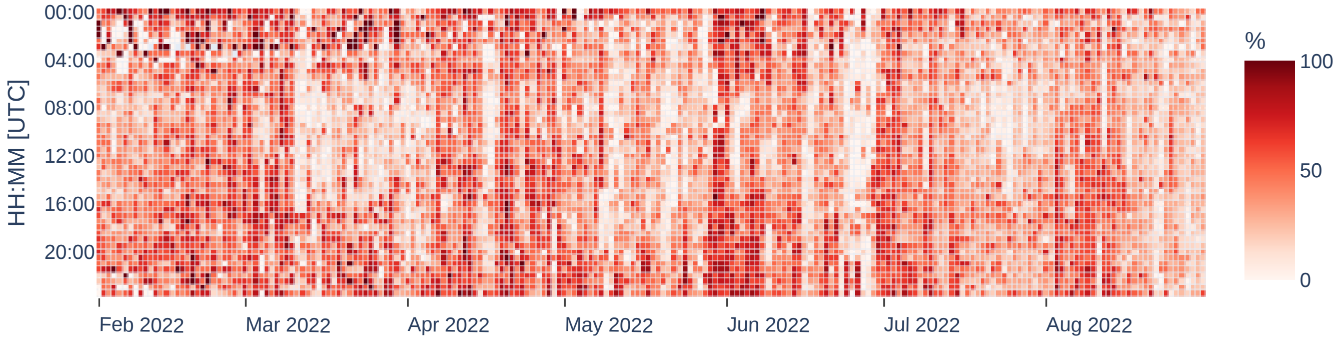
Additionally, Figure 7 contains a box plot of the number of simultaneous flights being affected by RFI when at least one flight was identified as affected. For AoI-1, slightly less than two flights were affected by RFI at the same time on average, while the number increases to 3 for AoI-3, and to 6 for AoI-2. It is important to note that the number of flights affected by RFI can vary depending on the jamming intensity, the amount of traffic, the geometric dimension of the AoI, as well as the ADS-B coverage in an AoI.

2. Duration for which aircraft are impacted

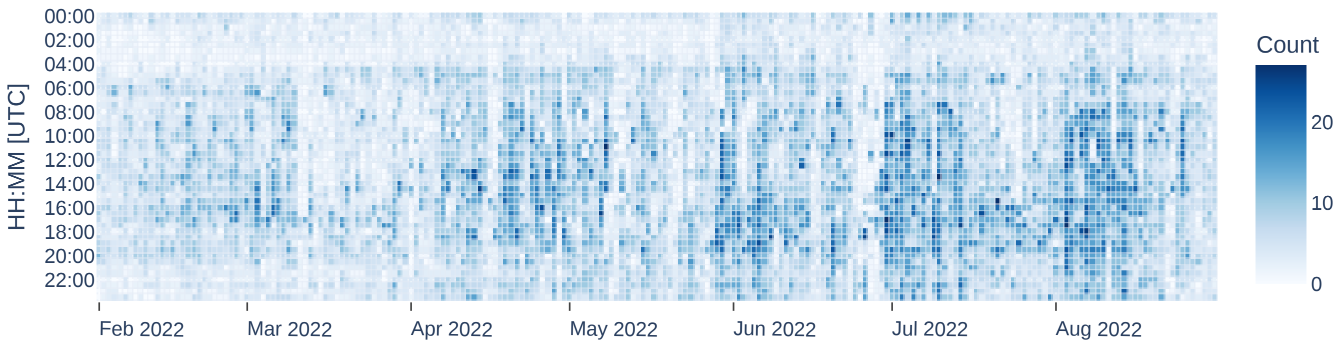
For every flight affected by RFI, the duration for which the transmitted `NACp` value is equal to zero was calculated. As previously mentioned, most large airliners are equipped with high-grad Inertial Reference Systems (IRS) coupled with the GNSS. In case of loss of GNSS the aircraft is thus able to continue to navigate autonomously using just the inertial information (and/or other radio navigation equipment where available). However, the IRS drifts with time resulting in a slow degradation of the navigation accuracy. Thus, it is crucial to monitor for how long an aircraft is exposed to RFI. As shown in Figure 8, the duration of jamming interference affecting flights range from a few minutes to more than an hour. Moreover, significant variations are evident between the AoIs, as they differ in terms of their geography, geometrical dimensions, and ADS-B coverage.

3. Aircraft type-specific behaviour

In order to analyse potential aircraft type-specific patterns, we identified and grouped the aircraft affected by jamming according to aircraft families. For each AoI, the blue bars in Figure 9 indicate the proportion of the 10 most frequently observed aircraft families in relation to all traffic observations. Moreover, the red bars in the same figure indicate the share of the aircraft families that were labelled as jammed. With a traffic share between 20% and 40%, aircraft of the Airbus A320 and Boeing B737 families accounted for most traffic in all three AoIs. In AoI-3 the Airbus A320 family and the Boeing B737 family have a similar share of the total traffic and the percentage of jammed fights. Contrary, in AoI-1 and AoI-2 the share of jammed flights with A320 and



(a) Relative share of aircraft being subject to RFI.



(b) Absolute number of aircraft being subject to RFI.

Figure 5: Jamming activity for AoI-3 for 30 minute intervals covering the entire observation period. The colour of each cell corresponds to the relative and absolute number of flights impacted by RFI within the 30 minute intervals.

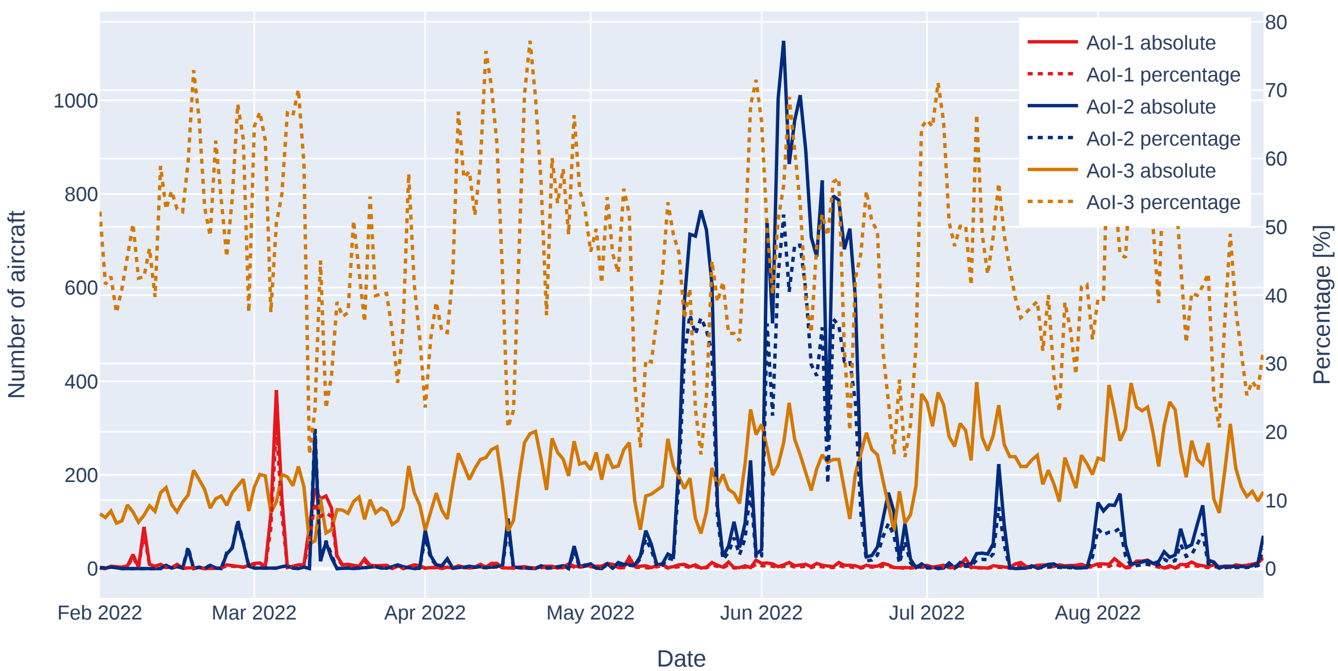


Figure 6: Daily number and percentage of flights affected by RFI for all AoI.

B737 is smaller than the share of the total traffic. While for the most part traffic share of the total number of flights and share

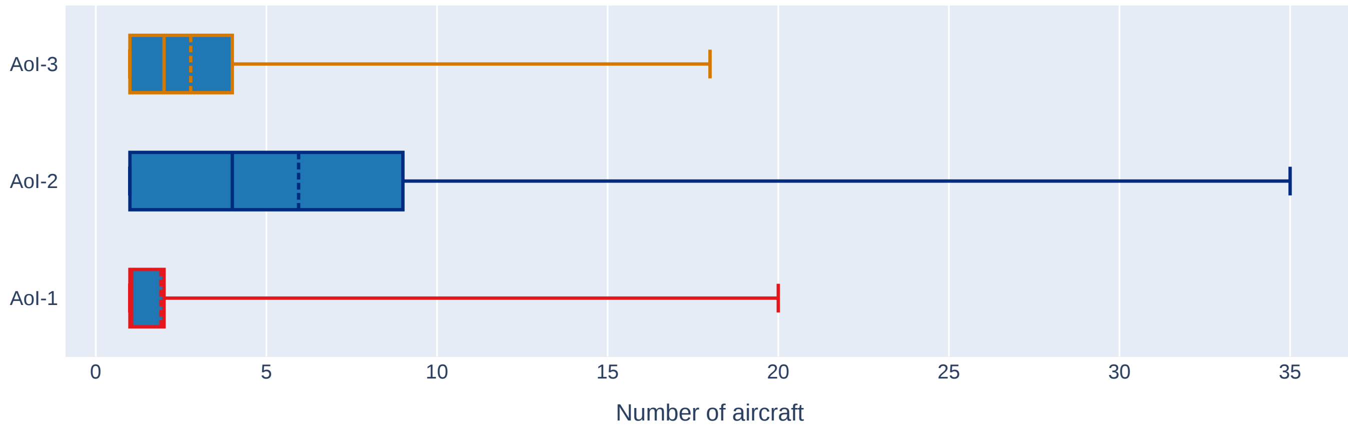


Figure 7: Box plot of the number of aircraft affected simultaneously by RFI for each AoI. The plain vertical bars indicate the minimum, first quartile, median, third quartile and maximum number (from left to right), while the dashed vertical line represents the mean value.

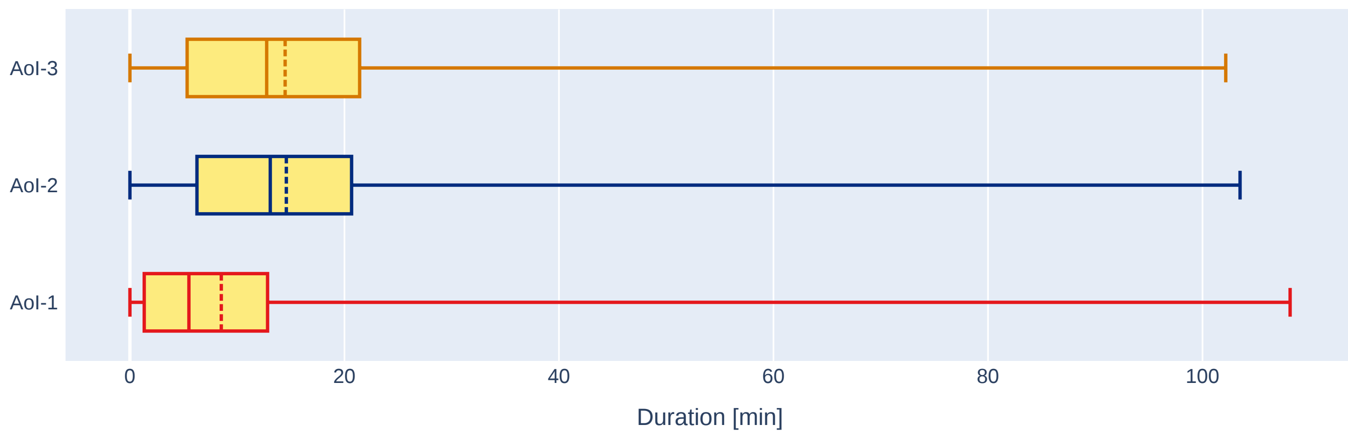


Figure 8: Box plot of the duration during which aircraft affected by RFI transmit a `NACp` value of 0. The plain vertical bars indicate the minimum, first quartile, median, third quartile, and maximum duration (from left to right), while the dashed vertical line represents the mean value.

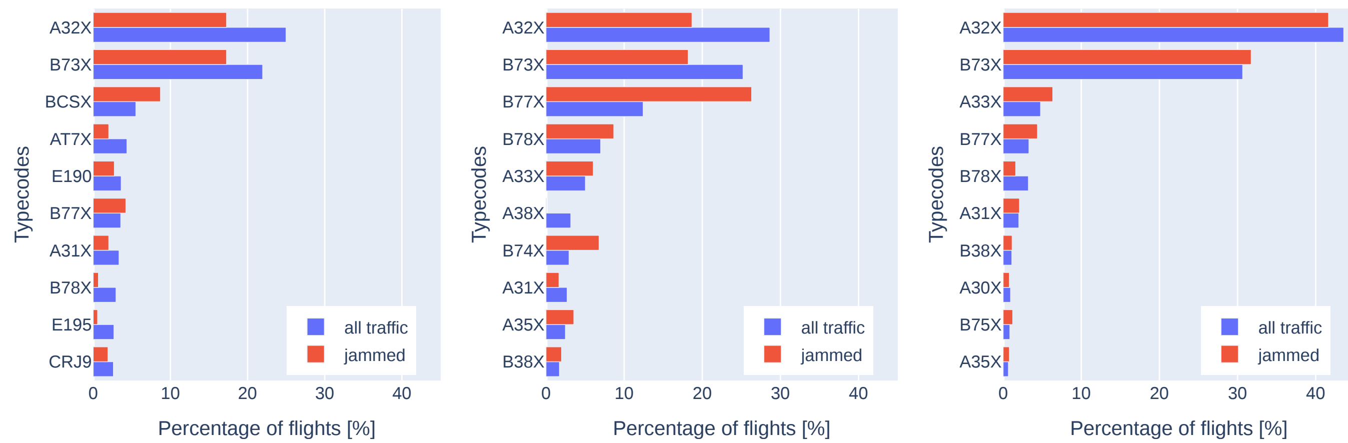
of the jammed flights is similar, in AoI-2 the B777 and B747 account for significantly larger shares of the jammed flights than their share of the total numer of flights. However, in AoI-3 this result for the B777 family could not identified with the same significance. For the B747 there were not enough data available for a meaningful analysis. Finally, in AoI-1 the B787 familiy and the Embraer E195 family account for a significantly smaller share of the number of jammed flights than their share of the total flights. For the B787 aircraft, a similar behaviour can be observed in AoI-3 but not in AoI-2.

4. Aircraft equipage to determine potential impact for ATC

Finally, information about the navigation equipment available on board each aircraft was retrieved from flight plan data. Based on the data available, the aircraft type could be identified for about 90% of the flights in the data set. Particular attention was given to those aircraft that indicated being equipped with GNSS navigation but not with IRS or DME. Table 2 shows for each AoI the number and the aircraft types of flights impacted by RFI with this combination of equipment according to flight plan data. A total of 5 flights affected by RFI and having GNSS as the only navigation solution were identified in AoI-1, 12 in AoI-2 and 36 in AoI-3. The types of aircraft indicate that business jets such as Learjet 35 or Embraer Phenom 300 make up a large proportion of these.

V. DISCUSSION

The results of the analysis showed that a significant number of flights was affected by RFI. As the absolute number of affected aircraft alone depends on the size of the area under investigation and the amount of traffic flowing through, the numbers were normalised by the total number of aircraft. In this way, the share of aircraft affected by jamming could be identified. We



(a) AoI-1. (b) AoI-2. (c) AoI-3.

Figure 9: Comparison of aircraft type share between the whole traffic and the RFI impacted flights.

Table 2: Number of occurrence of flights affected by RFI for which no inertial nor terrestrial navigation capabilities have been reported.

Aircraft Type	Count		
	AoI-1	AoI-2	AoI-3
LJ35	0	7	13
E55P	1	2	16
S22T	0	2	0
C68A	0	1	0
LJ55	0	0	3
C510	2	0	5
EC45	2	0	0
EA50	0	0	1

discretised the AoIs into smaller hexagons to eliminate (to a large extent) the dependency on the chosen size of the AoI. Finally, a dependence on the observation period yields different shares of the total percentage of the traffic affected if jamming occurs sporadically.

Thus for a more detailed analysis of periods when jamming was observed we discretised the observation period into 30-minute intervals. Thereby, different days with high levels of RFI could be identified. The periods with high RFI seemed to follow no particular pattern regarding day of months, day of week or time of day. The periods with high levels of RFI differed between all three AoIs without any obvious similarities. The duration during which aircraft were subject to RFI differed from several minutes to about half an hour. It should be noted, however, that for AoI-2 and AoI-3 the regions with high levels of jamming were at the borders of the AoIs. Hence, it is likely that the jamming impact was longer for many aircraft as they would continue flying though RFI affected areas outside the AoIs selected for our investigation.

Regarding differences between aircraft types the share of the individual aircraft types of all flights corresponded roughly with the share of the individual aircraft types of all jammed flights. For some aircraft types large differences between those shares could be seen in one or two AoIs but never in all three AoIs. Hence, based on these results no obvious relation between aircraft type and likelihood of being jammed could be determined. However, there were several flights that, according to flight plan data, were only equipped with GNSS but not with IRS or DME. These aircraft would likely require assistance from ATC. However, their number was rather small, indicating that the probability that the workload for ATC in a given sector due to many aircraft requiring simultaneous assistance is rather small.

VI. CONCLUSIONS AND OUTLOOK

This paper showed that GNSS jamming is an ongoing issue affecting a significant share of flights. While most aircraft have other alternatives for navigation (either by inertial sensors or by conventional ground-based navigation aids), a GNSS outage generally produces alerts to the flight crews and increases their work load. While flying en-route, this might not be a big issue, however, during times of high work load, such as during arrivals and departures, such alerts may distract the crew also during more critical phases of flight. From an operational perspective, the operational impact of GNSS outages should be kept to a minimum. This, however, contrasts with the road maps regarding a modernisation of the ATM system. The main strategies and implementation activities increasingly rely on performance-based navigation in order to make operations as efficient as possible. One key element in that navigation strategy is the use of GNSS. In order to continue with the much needed modernisation of ATM to keep up with the increasing traffic volumes, safe, secure and reliable navigation is crucial. Solutions to the GNSS jamming issue should thus be based on a variety of different measures, such as (i) increasing the robustness against RFI of the onboard GNSS receivers, potentially by using advanced signal processing and antenna/receiver technology, (ii) integrate GNSS more with other sensors and thus reduce the dependency on a particular navigation system, (iii) retaining a ground-based network of radio-navigation aids, such as DMEs, with improved performance and the potential to support the same or similar levels of accuracy and integrity as currently achieved by GNSS and (iv) measures to prevent harmful interference in the first place to the extent possible.

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