OpenSky Report 2023: Low Altitude Traffic Awareness for Light Aircraft with FLARM

Xavier Olive, Martin Strohmeier, Junzi Sun, Giorgio Tresoldi

OpenSky Report 2023: Low Altitude Traffic Awareness for Light Aircraft with FLARM

Xavier Olive*†, Martin Strohmeier*‡, Junzi Sun*§, Giorgio Tresoldi*‡

*OpenSky Network, Switzerland
lastname@opensky-network.org

†ONERA, Université de Toulouse
Toulouse, France

‡armasuisse W+T
Switzerland

§Faculty of Aerospace Engineering
Delft University of Technology
Delft, The Netherlands

***Abstract*—Established in 2013, The OpenSky Network, a crowdsourced network of ADS-B receivers, has consistently collected surveillance data from equipped aircraft and made it available for science. Coverage has steadily improved, boasting more than 6000 registered sensors worldwide today. This platform has aided numerous researchers in publishing studies across fields such as air traffic management, security, environment, and radio frequency interference. Following the 2020 mandate, most aircraft flying at high altitudes in Europe or Northern America are within range of one of the network's ADS-B receivers. To complement existing research using OpenSky data, this paper focuses on lower altitude coverage, including light aircraft, general aviation, gliders, and ultralights, which are not required to carry ADS-B transponders. Instead, these often use, esp. in Europe, another traffic awareness and collision avoidance technology known as FLARM. The OpenSky Network has been gathering FLARM messages since 2018, and now enough data is available for a detailed analysis. The aim of this report is to present OpenSky's FLARM data, explain the workings of the technology, and highlight potential uses of this data for future research.**

I. Introduction

The availability of open access data, particularly ADS-B aircraft trajectory data through platforms like The OpenSky Network, has been a game-changer for academic research in aviation. With a facilitated access to such crowdsourced data, researchers have been improving the reproducibility of data-based studies for optimizing operations, reducing the environmental impact of air travel or enforcing security in communications.

The European Commission issued Regulation 1207/2011 mandating the Single European Sky [1]. As part of this, ADS-B out usage is mandated on aircraft built after January 8, 2015, and for all aircraft by December 7, 2017. Regulation 1028/2014 later modified this, pushing the deadline to June 2020 [2]. Later, the deadline was pushed back again by Regulation 2020/587 [3], adding a transitional period and exemptions for older aircraft, up to 2023 and 2025, respectively. The European Commission's mandate applies to most commercial aviation (with maximal take-off mass exceeding 5700 kg or maximal cruise speed greater than 250 knots) but many light or slow aircraft remain unequipped.

Light aircraft flying at lower levels, when cooperative for traffic awareness and collision avoidance, may also be equipped with Mode A/C, Mode S or ADS-B compliant transponders but other technologies such as Wi-Fi for drones or FLARM, originally designed for glider activities (mandatory in some countries) dominate these segments.

FLARM (a portmanteau of "flight" and "alarm") is, along with TCAS (traffic collision avoidance system, [4]), one of the most widespread technologies for traffic awareness and collision avoidance in smaller aircraft. It is a system used to prevent potential aviation collision and to raise awareness of the pilot, initially tailored for gliders, light aircraft, rotorcraft, and drones. FLARM obtains its position and altitude readings from an internal GPS (or potentially other GNSS) and a barometric sensor. It then broadcasts these readings together with forecast data about the ownship's future 3D flight track, calculated considering its speed, acceleration, track, turn radius, wind and other parameters. Similar to other aircraft communications, the wireless nature of FLARM allows for the reception of signals in a crowdsourced fashion, and the OpenSky Network [5] has been collecting such messages since late 2018.

Recently, there has been preliminary work with FLARM data from OpenSky on security [6] or for collision risk models at very low levels [7], [8]. While statistical data and literature about trajectories of flights conducted according to Instrumental Flight Rules (IFR) is widely available, little or no work is available about aeroplanes flying according to Visual Flight Rules (VFR) as these small aircraft often do not turn on their transponder or are not equipped with one.

Compared to ADS-B and Mode S data, the FLARM data collected by OpenSky thus offers an untapped potential for an extended analysis of the activity of lighter flying crafts such as general aviation planes, gliders, helicopters, gyrocopters, paragliders, ultralight, and drones. The present paper demonstrates or refers to first analyses that can be performed with such data, and it suggests potential research questions and room for future analyses. This includes:

- behaviour of light aircraft at low altitude [7];
- planning drone BVLOS operations at low altitude [8];
- security of the FLARM protocol [6];
- detection of areas with favourable thermal conditions for gliders based on vertical profiles (Section IV-A);
- quality of the GNSS signals (Section IV-B);
- identification of hotspots with higher risks of collision (future works).

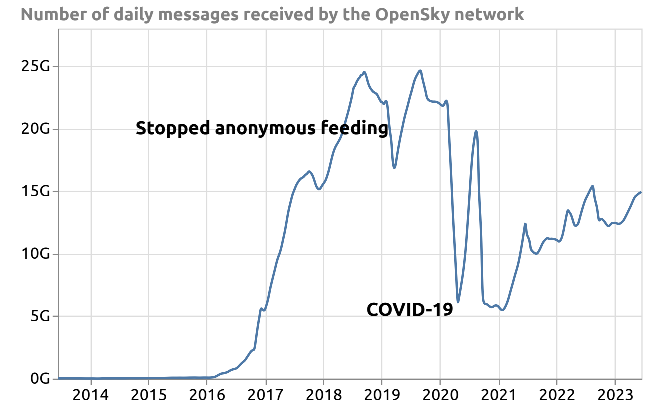

Fig. 1: The growth of OpenSky's dataset over time from 2013 to 2023

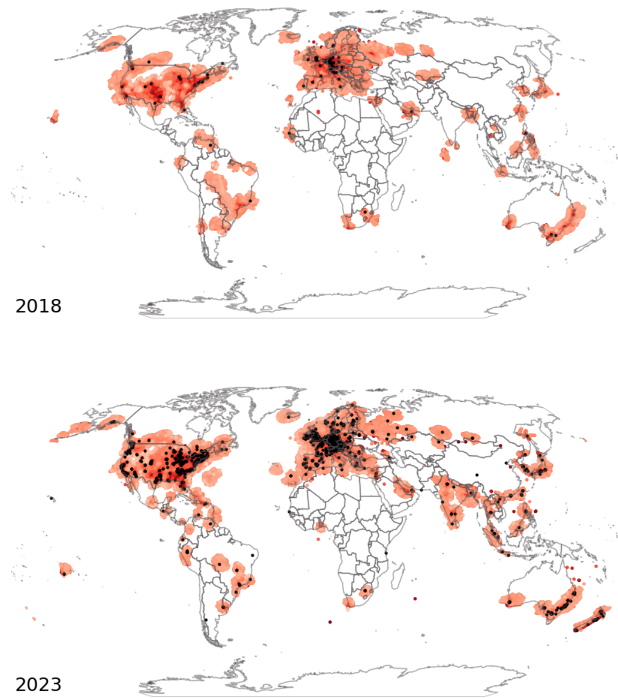

Fig. 2: OpenSky's global coverage in 2018 and 2023

The remainder of this paper is structured as follows. Sections II and III present the necessary background information about the OpenSky Network, the FLARM technology and the collection of those messages. Section IV showcases first analyses that can be performed with such data. Section V suggests some possible research questions and room for future analyses before we conclude in Section VI.

II. The OpenSky Network

The OpenSky Network is a collective sensor network that gathers surveillance data for air traffic control (ATC) purposes. Its primary aim is to provide the general public with access to real-world ATC data and to facilitate the advancement and enhancement of ATC technologies and processes. Since 2013, the network has been continuously collecting air traffic surveillance data. In contrast to commercial flight tracking networks like Flightradar24 or FlightAware, the OpenSky Network preserves the original Mode S replies received by the sensors in a vast historical database, which researchers and analysts from various fields can access.

Initially, the non-profit network consisted of eight sensors located in Switzerland and Germany. However, it has grown to encompass over 6000 registered receivers situated worldwide. As of now, OpenSky's dataset contains over 10 years of ATC communication data. While the network initially focused solely on ADS-B, it expanded its data range to include the complete Mode S downlink channel in March 2017. More recently, it incorporated other technologies such as FLARM and VHF. The dataset currently comprises more than 35 trillion Mode S replies and experiences a peak influx of over 20 billion messages per day.

Figure 1 displays the growth and evolution of the network in recent years, which involved the inclusion of dump1090 and Radarcape feeding solutions, as well as the integration of non-registered, anonymous receivers. However, this practice was discontinued in early 2019 to ensure the consistent quality of the feeder data. In March 2020, the number of daily flights decreased by approximately 30% compared to previous levels, reflecting the reduction in air travel worldwide caused by the COVID-19 pandemic.

The global data reception of the OpenSky Network relies entirely on its crowdsourced network of receivers, primarily consisting of enthusiasts, academics, and other supporting institutions. The coverage provided by each individual sensor is limited by the range of the antennas' line ofs ight, typically around 400–500 km for the best-performing antennas that reach the radio horizon. The main areas of organic growth of any such crowdsourced network effectively serve as a proxy for densely populated and wealthier regions worldwide. Between 2018 and 2023, the network's global coverage (see Fig. 2) reached a saturation point, with most new sensors significantly enhancing reception at lower altitudes in areas already covered in Europe, the US, and other developed countries. However, notable coverage expansions can still be observed in the Middle East, South Asia, and New Zealand. Geographical regions such as deserts and oceans naturally lack ground-based coverage due to physical constraints. To address this limitation, commercial ADS-B providers partially rely on space-based ADS-B or ADS-C data.

In addition to the payload of each Mode S downlink transmission, OpenSky also stores supplementary metadata. This metadata includes precise timestamps (suitable for multilateration), receiver location, and signal strength, depending on the receiver hardware. For further details on the history, architecture, and use cases of OpenSky, please refer to [4], [9]–[11] or visit the website https://opensky-network.org.

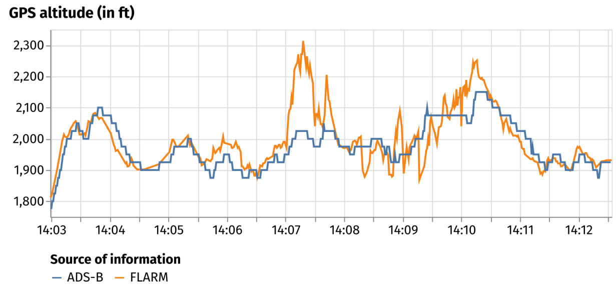

Fig. 3: Aircraft F-JVZB (identifier 394f3c) is equipped with both ADS-B and FLARM. Different GPS altitude data is however emitted: ADS-B broadcasts the aircraft current position, while FLARM estimates the position of the aircraft two seconds in the future for collision avoidance purposes. Extract from [7].

III. FLARM

A. The FLARM Technology

FLARM is an aviation safety system that prevents collisions and increases pilot awareness. Along with TCAS [4], it is one of the most widespread technologies for traffic awareness and collision avoidance, initially designed for gliders, light aircraft, rotorcraft, and drones. It thus features low power consumption, is cost-effective to purchase and install, and avoids unnecessary warnings for close proximity between light aircraft where collision risk is low.

FLARM obtains its position and altitude from a GPS antenna and an internal barometric sensor, and it then broadcasts this information together with a forecast 3D flight track. At the same time, its receiver listens for transmissions from other FLARM devices and processes the information received.

In contrast to ADS-B, the FLARM radio protocol features message encryption in order to ensure integrity and confidentiality. However, implementation and encryption keys are widely available and enable both compatible receivers and downstream applications [6]. The Open Glider Network (OGN) maintains a tracking platform with the help of many receivers, mostly co-located with flying clubs operating light aircraft at local airfields. The OpenSky Network also collects and stores raw FLARM messages and provides access to this data to researchers.

Similar to ADS-B, FLARM is also a broadcast-based surveillance technology. However, it is a proprietary technology that is optionally used by lighter aircraft. FLARM also actively listens to the broadcast of other aircraft, akin to the capability of *ADS-B In* on aircraft, which is not mandatory (unlike *ADS-B Out*).

Similar information is transmitted by both ADS-B and FLARM, which includes identification, position, altitude, speed, heading, vertical rate. Additionally, FLARM transmits turn rate, and detailed aircraft type information. Table I provides the complete structure of a FLARM message and its contents. Table II show the main difference between ADS-B and FLARM technologies.

Figure 3 reflects the difference in philosophy between ADS-B and FLARM technologies: ADS-B is a surveillance technology where aircraft broadcast their current position; FLARM is a collision avoidance technology where aircraft estimate their future position. Reported GPS altitudes (FLARM only reports GPS altitude, using the metric system) may not match, as they do not represent the same estimation.

The detection range of ADS-B receivers at high altitudes can come close to 400 km, especially when it is not surrounded by higher buildings or relief. Most FLARM-equipped aircraft (e.g. gliders), however, stay below 4000 meters. As with ADS-B, low altitude range is shorter and typical maximum FLARM reception on the ground is around 100 km. Figure 4 plots a distribution of distances between the FLARM transceiver and the receiver with respect to the GPS altitude, illustrating this point.

B. Information Security

From 2008 onwards, FLARM Technology, the company behind the FLARM protocol, encrypted all transmissions for safety, integrity, and privacy. This differs fundamentally from

TABLE I: FLARM packet structure and functions. Adapted from [6]

	Bits		Function
0	DDDD	DDDD	Device address
1	DDDD	DDDD	
2	DDDD	DDDD	
3	00BB	0000	BB = 10 or 01
4	VVVV	VVVV	Vertical speed
5	RRRR	RRVV	Stealth mode, No track
6	GGGG	GGGG	GPS status, quality
7	TTTT	GGGG	Plane type
8	LLLL	LLLL	Latitude
9	LLLL	LLLL	
10	AAAA	LLLL	
11	AAAA	AAAA	Altitude
12	NNNN	NNNN	Longitude
13	NNNN	NNNN	
14	RRRR	NNNN	Reserved / Unused
15	MMRR	RRRR	Multiplying factor
16	HHHH	HHHH	Horizontal
17	SSSS	SSSS	speed (N/S) for
18	KKKK	KKKK	collision
19	TTTT	TTTT	forecast
20	EEEE	EEEE	Horizontal
21	WWWW	WWWW	speed (E/W) for
22	PPPP	PPPP	collision
23	QQQQ	QQQQ	forecast

TABLE II: Comparison between ADS-B (out) and FLARM

Parameter	ADS-B (out)	FLARM
Aircraft	"Commercial aviation" (heavy and fast aircraft)	"Light aviation" (gliders, UAVs and more)
Communication	Broadcast	Broadcast, actively listen
Frequency	1090 MHz / 978 MHz	868 MHz / 916 MHz
Range	long (ca. 400 km)	medium (ca. 100 km)
Privacy	Open	Optional encryption
Regulation	Mandated [1]–[3]	Partly mandated

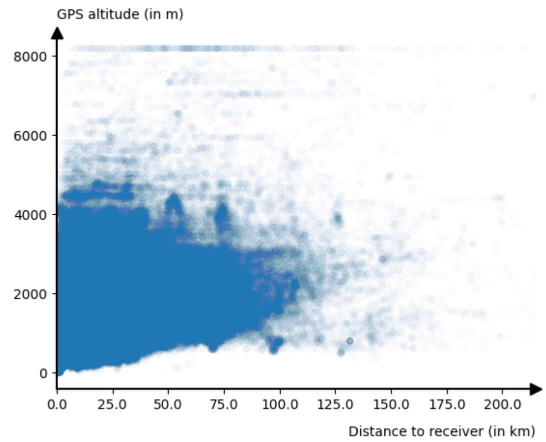

Fig. 4: Every dot represents the distance between the aircraft and the receiver on the x-axis, and its altitude on the y-axis.

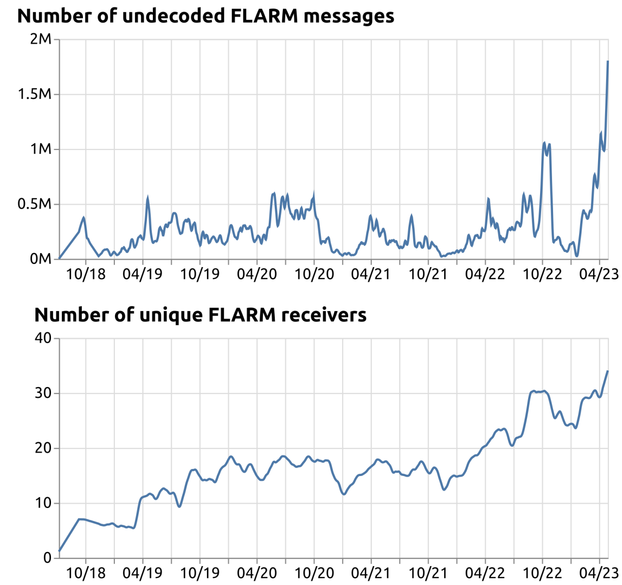

Fig. 5: Number of FLARM messages and unique receivers recorded in the OpenSky database since 2018.

practically all other aviation communication technologies, which lack cryptographic measures.

Since 2015, the FLARM protocol's encryption uses the Corrected Block Tiny Encryption Algorithm (XXTEA) [12], known for its simplicity and low computational requirements. The encrypted payload is 24 bytes long, preceded by a preamble, sync word, and address, with a checksum appended. However, the XXTEA algorithm remains vulnerable, as a chosen-plaintext attack was published in 2010. [13]

Additionally, the centrally-held encryption keys are not regularly rotated, posing urgent security risks. A reverse-engineering effort of the protocol, published in 2008, revealed the packet format and encryption keys, prompting FLARM to change the keys in 2015. However, these changes, too, were quickly reverse-engineered and leaked, repeating the pattern in 2017 with new keys. As a result, anyone can receive and send FLARM messages, compromising the system's security guarantees.

Thus, despite FLARM's encryption, the state of the art is no different in practice compared to ADS-B and other aviation protocols. The upside is that this enables research insights such as those presented in the present paper.

C. Evolution of FLARM Data in OpenSky

The FLARM messages have been stored in the OpenSky database, specifically in the table named `flarm_raw4`, since late 2018. It is important to note that the settings for FLARM receivers differ from ADS-B receivers. In the case of ADS-B, receivers are assigned an integer identifier associated with a registered OpenSky user. However, FLARM receivers are designed to utilize the existing software of the OGN Project.

Practically, the FLARM receiver is configured with the same name as the one used in the OGN project. Typically, this name is based on the ICAO identifier of the closest aerodrome in proximity. Initially, during the early days of FLARM storage by The OpenSky Network, most receivers were administered in Switzerland. Over time, the coverage has gradually improved, resulting in the deployment of 30 receivers, which by the year 2023 are sharing close to 2 million messages per day with the OpenSky Network (Figure 5). We can discern a clear seasonal effect as gliders and other light aircraft see more usage in warmer conditions.

Notably, in 2022, a significant number of German receivers were added to the network (Figure 6). Efforts are underway to convince local aeroclubs in other European countries such as France to share their FLARM data already feeding OGN with the OpenSky Network. Academics and enthusiasts demonstrating the potential use cases of such open data and how they could serve safety and performance concerns would be instrumental in facilitating this process.

Figure 7 illustrates the distribution of unique aircraft across different categories in relation to FLARM usage. Primarily, gliders (including tow planes) and paragliders constitute the majority (see the map on Figure 9), followed by General Aviation aircraft and helicopters. The surrounding environment highly influences this distribution. Figure 8 highlights the significant presence of glider activity in Germany, attributed to historical factors linked to the consequences of the Treaty of Versailles. On the other hand, the appeal of paragliding is understandably greater in the Swiss mountains compared to the Netherlands, which affects the respective activity levels in these regions.

In addition to manned aircraft, we have also collected a limited number of UAV trajectories. These data provide valuable insights for safety analyses concerning the integration of unmanned traffic beyond visual line of sight at very low altitudes [7], [8].

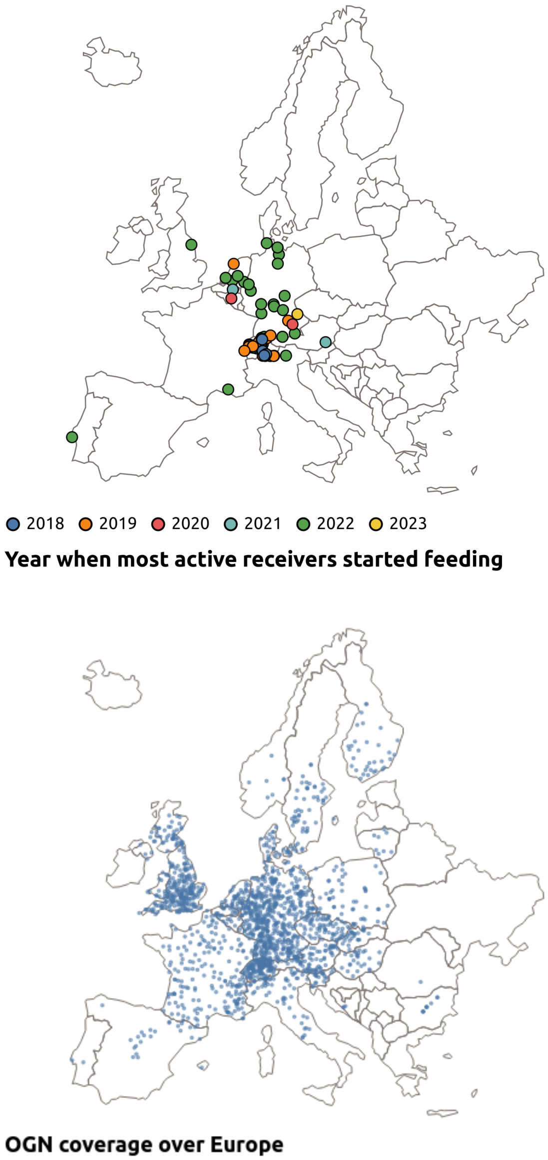

Fig. 6: Evolution of FLARM coverage in Europe since 2018 (top). Many new receivers started feeding after 2022. The OGN coverage is provided for comparison (bottom).

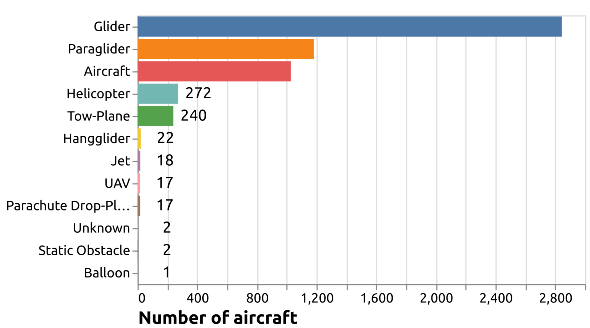

Fig. 7: Type category distribution since 2018. FLARM is mostly equipping glider aircraft, but only few General Aviation aircraft are also equipped.

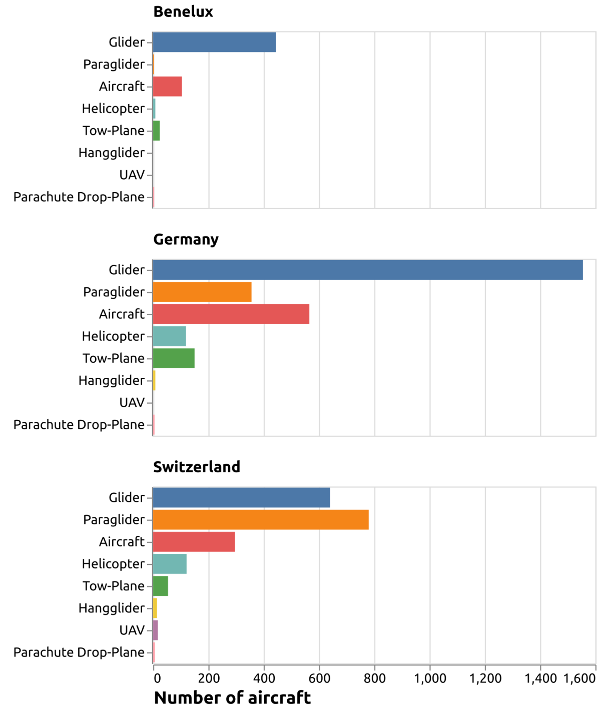

Fig. 8: Type category distribution differs according to country: Germany glider activity is very significant. Paragliders use FLARM a lot in Switzerland, but the activity is not that popular in the Netherlands.

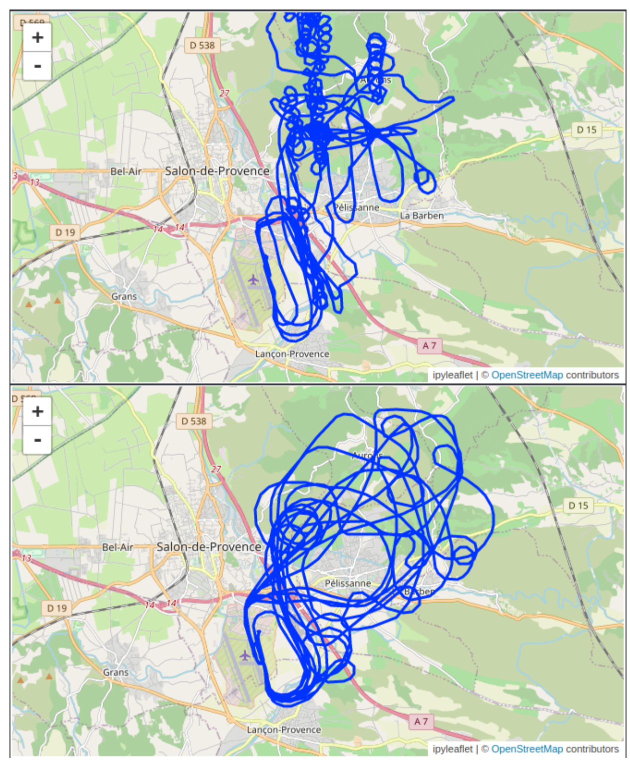

Fig. 9: FLARM data reflects very different patterns according to the type of aircraft: gliders (top) try to sail for as long as possible by making the most of the local aerology; tow-planes (bottom) make many rotations and land very shortly after the glider they tow detaches.

IV. Exploratory Analysis

We now take a first exploratory look at the detection of thermals and the analysis of GPS quality information using OpenSky's FLARM data.

A. Detection of thermals

Gliders do not have engines to provide thrust and enough lift to gain altitude. They use tow planes or winches in order to take-off, but they must find other tricks after they detach. A talented pilot can stay in the air for many hours as he harnesses the local aerology. Pilots can take advantage of *thermals*, of *ridge lift*, where the glider takes advantage of wind blowing against a slope or ridge to generate upward lift, and of *wave lift*, which occurs when strong winds encounter mountains or other obstacles, creating oscillating waves of air that the glider can ride to gain altitude.

Thermals are vertical columns of rising hot air that occur when the Earth surface if heated, subsequently warming the layer of air above it. As this portion of air becomes warmer than its surrounding environment, it becomes less dense and ascends in a column. Thermals are commonly observed beneath cumulus clouds, but they can also be founds in clear air. Birds and dust devils are a common indicator to locate thermals around. When a pilot locates a thermal area, the glider can manoeuvre in a circular path within it, taking advantage of the upward-moving air to ascend.

In this study, we look into the possibility of using glider altitude changes and circling patterns in their trajectories to detect potential thermals. The detection algorithm can be defined as follows.

Let's denote a trajectory as $\mathcal{F}$, where $\mathcal{F}$ is the set of all data points sequenced by time. Each data point consists of a set of flight states, including vertical rate (VS) and heading change ($\Delta\psi$), at each time t.

We split the trajectory into one-minute chunks. For a given chunk F_c, where i is the index of the chunk, the vertical rates and heading changes are represented as follows:

$$VS_c = \{VS_{c,1}, VS_{c,2}, ..., VS_{c,n}\} \tag{1}$$
$$H_c = \{\Delta\psi_{c,1}, \Delta\psi_{c,2}, ..., \Delta\psi_{c,n}\} \tag{2}$$

The maximum vertical rate and the median heading change within the chunk F_c are calculated:

$$VS_{\text{max, c}} = \max(V_c) \tag{3}$$
$$\Delta\psi_{\text{med},c} = \text{median}(\Delta\psi_c) \tag{4}$$

We can then detect the circling and climbing using a conditional function $f(F_i)$, defined as follows:

$$f(F_i) = \begin{cases} \text{True} & \text{if } V_{\text{max}_i} > 2\,\text{m/s} \quad \& \quad \Delta\psi_{\text{med}_i} > 5^\circ \\ \text{False} & \text{otherwise} \end{cases} \tag{5}$$

Where indicating the chunk is in a circling and climbing if the maximum vertical rate in the chunk exceeds 2 m/s and the median heading change exceeds 5 degrees. Finally, we determine the existence of thermal when a glider is circling and climbing for longer than 2 minutes. Figure 10 shows an example of this detection process.

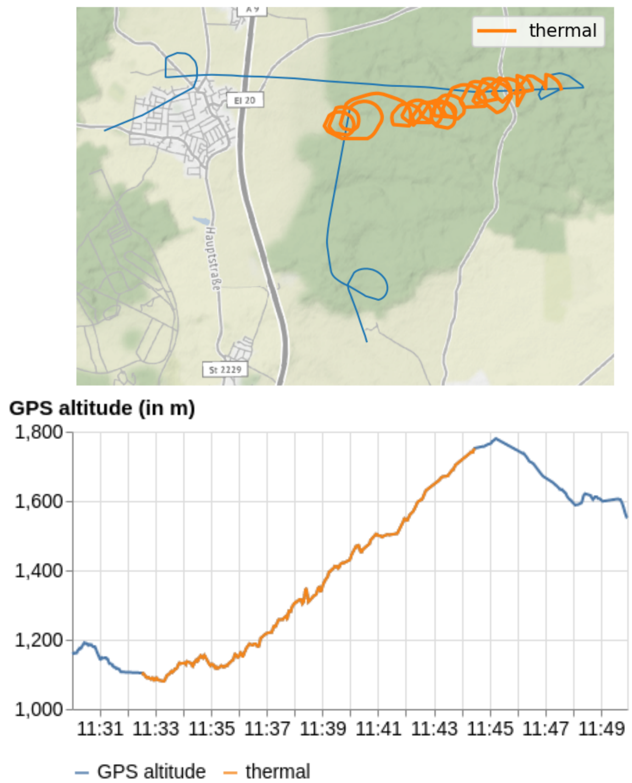

Fig. 10: Automatic thermal detection for gliders

The detection process can be applied to all the flights at a certain time to determine the locations of thermal, and we can also study the movement of thermal by comparing results obtained at different time steps. Figure 11 shows an example of thermal locations and movements in Southern Germany.

B. GPS quality information

Table I mentions the existence of 12 bits to encode the quality of the GPS position in the binary representation of FLARM messages. In spite of lacking public details about the encoded information, we perform in this section a first analysis of the general quality of GPS signals by FLARM receivers.

The 12 bits of information can be split into two integer values between 0 and 63 that we named here `quality_1` and `quality_2`. As both values are highly correlated, we assume that they could represent the vertical and lateral uncertainty in the signal, with higher values when the signal degrades, e.g. when the transceiver comes indoor or closer to buildings (Fig. 12)

ADS-B messages also encode similar information with uncertainty (`NUCp` indicator in version 0) and accuracy indicators (`NACp` indicator in more recent versions). `NUCp` encodes 10 values, from 0 (containment radius on horizontal position error

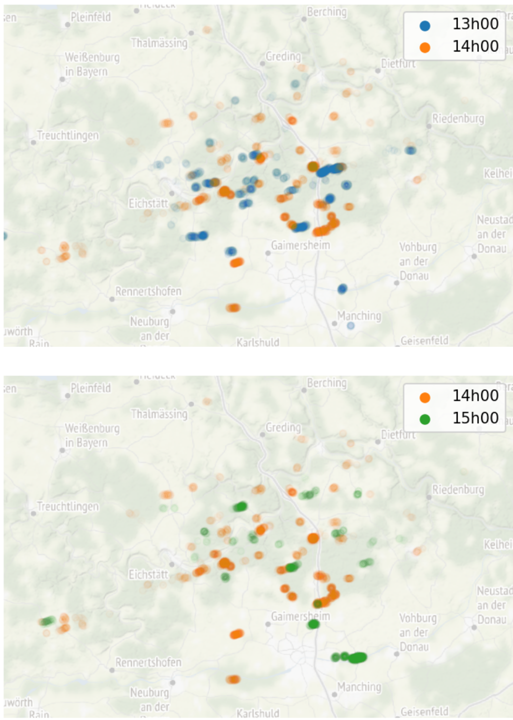

Fig. 11: Examples of detected thermal hotspots movements in Southern Germany, on July 4th, 2020.

greater than 10 nautical miles) to 9 (containment radius shorter than 3 meters). Fig. 13 tries to find a correlation between the two indicators for aircraft equipped with both FLARM and ADS-B transceivers.

We envisioned using GPS quality information to study GNSS interferences at low altitude, similarly to what we previously did in [14], but limitations can already be anticipated. Even though the granularity of the FLARM indicators (two intervals of 64 values) is finer than the `NUCp` indicators (10 values), positional information with ADS-B seem to be of better quality than FLARM, which is a cheap portable device usually placed inside the cabin, hence more subject to all kind of masking effects.

V. Discussion

A. *Anomalies in FLARM data*

FLARM messages carry information about the aircraft type, as discussed in Section III, within their payload. This feature is primarily designed to accommodate the versatility of FLARM devices, which can be easily transferred from one aircraft, such as a glider, to a paraglider for instance. During our analysis of the data trajectories, we discovered a few interesting instances. We observed FLARM emitters that remained operational for several weeks within private residences situated in proximity to a receiver hosted at the same location (Figure 14). Furthermore, we encountered cases where FLARM emitters were active inside moving vehicles, specifically within cars travelling between different locations.

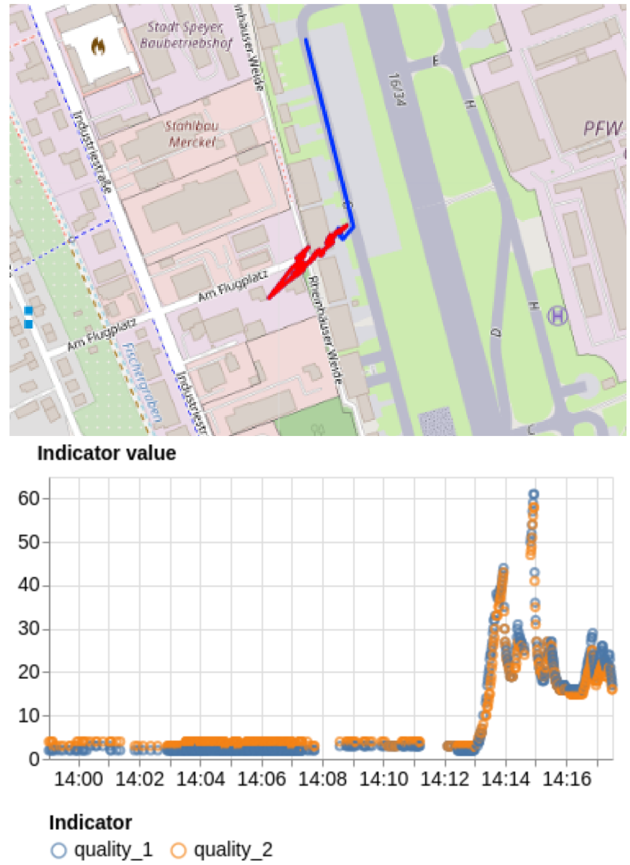

Fig. 12: This trajectory segment sees its GPS quality indicators degrade when the aircraft comes close to a hangar. The ground trajectory also becomes erratic.

The decoded trajectories followed regional routes published on OpenStreetMap (Figure 15).

B. *Future Developments*

In its new U-Space regulation, the European Union Aviation Safety Agency (EASA) provides more clarity on e-Conspicuity systems such as FLARM and ADS-B, emphasizing the need for manned aircraft in U-space airspace to be electronically conspicuous to U-space service providers. Similar to the Federal Aviation Administration's RemoteID and DroneID regulations in the United States, a new system called Automatic Dependent Surveillance – Light (ADS-L) is planned and guidance material and acceptable means of compliance have been published at the end of 2022.

For FLARM users, the most relevant decision is ED 2022/024/R, [15] which delves into electronic conspicuity. Four means of being conspicuous are introduced: a) certified ADS-B on 1090 MHz, b) certified ADS-B on 978 MHz, c) ADS-L 4 SRD-860 (similar to FLARM), and d) mobile telecommunication networks such as 4G and 5G, which is planned to be codified in "ADS-L 4 MOBILE" by EASA later this year. While ADS-L is not expected to replace FLARM, it has potential as a surveillance system but lacks certain features necessary for air-to-air interaction and collision avoidance.

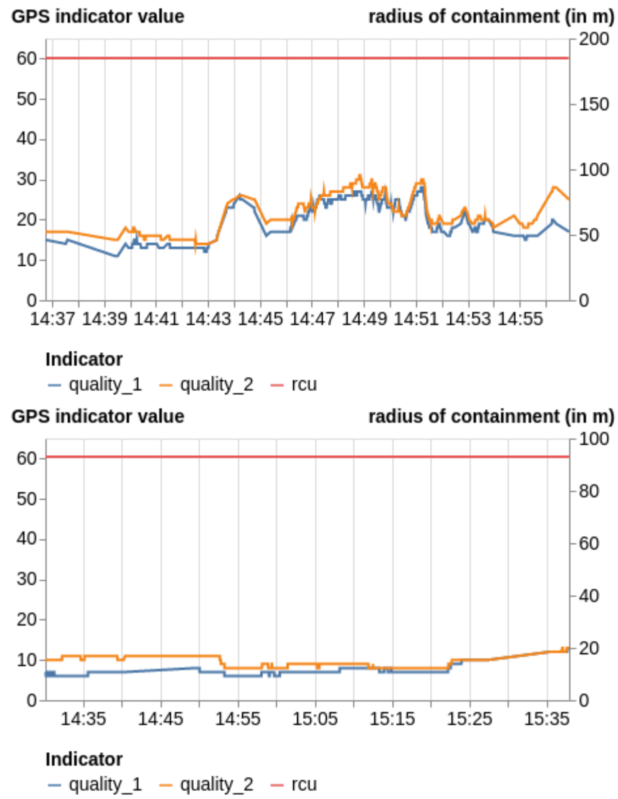

Fig. 13: Comparison of FLARM GPS indicators and information from the ADS-B uncertainty indicator NUCp

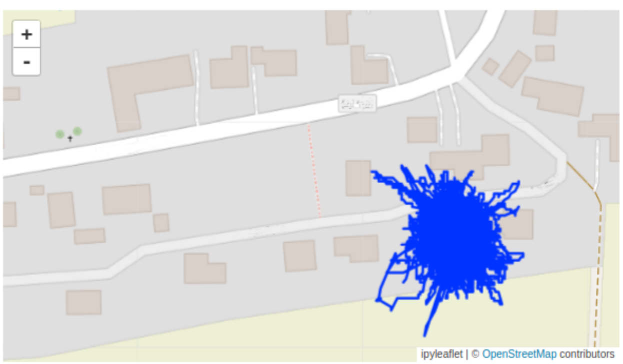

Fig. 14: FLARM transceiver continuously transmitting for several weeks at a private property in Southern Germany

FLARM will likely remain compatible, the company has plans to incorporate ADS-L via software updates. [16] The OpenSky Network will watch these developments closely and plans to integrate ADS-L in the future to collect additional movement data in U-space that is not available currently.

VI. Conclusion

This paper presents the FLARM data collected by the OpenSky Network and highlights its potential for future research in the aviation field. FLARM is widely utilized in smaller aircraft, and we have demonstrated the new possibilities offered by this data for analyzing the behavior of these light aircraft.

Fig. 15: FLARM transceiver mapped to a paraglider left on while travelling by car from a local camping area near Füssen, Germany

FLARM data provides valuable insights into the activities of general aviation planes, gliders, helicopters, gyrocopters, paragliders, ultralights, and drones. It can be effectively employed to study the behavior of these aircraft types at low altitudes and enhance situational awareness.

By utilizing a subset of the OpenSky's FLARM data, algorithms can be developed to identify areas with favorable thermal conditions for gliders by analyzing their climbing segments. Additionally, we have conducted an initial analysis of the GPS signal quality based on supplementary information transmitted in FLARM messages. This opens up the possibility of future GNSS signal monitoring.

In conclusion, the OpenSky Network's FLARM data is a valuable resource for aviation researchers. It provides unique insights into the behavior of light aircraft and offers opportunities for various research studies. We encourage researchers to utilize this dataset to contribute to the improvement of air traffic management, safety enhancement, and environmental concerns. Furthermore, we urge more crowd-sourced contributors to join and expand the coverage of the current FLARM feeds.

References

[1] The European Commission, "Commission regulation No 1207/2011 of 22 November 2011 laying down requirements for the performance and the interoperability of surveillance for the single European sky," 2011.

[2] ——, "Implementing Regulation (EU) No. 1028/2014 amending Implementing Regulation (EU) No 1207/2011," pp. 8–9, 2014.

[3] ——, "Implementing Regulation (EU) No. 2020/587 amending Implementing Regulation (EU) No 1206/2011 laying down requirements on aircraft identification for surveillance for the single European sky and Implementing Regulation (EU) No 1207/2011 laying down requirements for the performance and the interoperability of surveillance for the single European sky," 2020.

[4] M. Schafer, X. Olive, M. Strohmeier, M. Smith, I. Martinovic, and V. Lenders, "OpenSky Report 2019: Analysing TCAS in the Real World using Big Data," in *Proceedings of the 38th IEEE/AIAA Digital Avionics Systems Conference (DASC)*, San Diego, CA, Sep. 2019.

[5] M. Schäfer, M. Strohmeier, V. Lenders, I. Martinovic, and M. Wilhelm, "Bringing up OpenSky: A large-scale ADS-B sensor network for research," in *Proceedings of the 13th International Symposium on Information Processing in Sensor Networks*, 2014, pp. 83–94.

[6] B. Wang, G. Tresoldi, M. Strohmeier, and V. Lenders, "On the security of the FLARM collision warning system," in *Proceedings of the 2022 ACM Asia Conference on Computer and Communications Security*, May 2022.

[7] X. Olive and P. Le Blaye, "A Quantitative Approach to Air Traffic Safety at Very Low Levels," in *Proceedings of the 10th OpenSky Symposium*. Delft, The Netherlands: MDPI, Nov. 2022. [Online]. Available: https://www.mdpi.com/2673-4591/28/1/1

[8] X. Olive, P. Le Blaye, L. Sedov, and T. Krauth, "Quantitative air risk assessment for a drone inspection mission along fast-train lines," in *Proceedings of the 15th USA/Europe Air Traffic Management Research and Development Seminar*, Savannah, GA, Jun. 2023.

[9] X. Olive, A. Tanner, M. Strohmeier, M. Schäfer, M. Feridun, A. Tart, I. Martinovic, and V. Lenders, "OpenSky Report 2020: Analysing in-flight emergencies using big data," in *2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*. IEEE, 2020, pp. 1–10.

[10] J. Sun, X. Olive, M. Strohmeier, M. Schäfer, I. Martinovic, and V. Lenders, "Opensky report 2021: Insights on ads-b mandate and fleet deployment in times of crisis," in *2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC)*. IEEE, 2021, pp. 1–10.

[11] J. Sun, L. Basora, X. Olive, M. Strohmeier, M. Schäfer, I. Martinovic, and V. Lenders, "OpenSky Report 2022: Evaluating aviation emissions using crowdsourced open flight data," in *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*. IEEE, 2022, pp. 1–8.

[12] R. M. Needham and D. J. Wheeler, "TEA extensions," Cambridge University, Tech. Rep., 1997.

[13] E. Yarrkov, "Cryptanalysis of xxtea," *IACR Cryptol. ePrint Arch.*, vol. 2010, p. 254, 2010.

[14] B. Figuet, M. Waltert, M. Felux, and X. Olive, "GNSS Jamming and Its Effect on Air Traffic in Eastern Europe," in *Proceedings of the 10th OpenSky Symposium*. Delft, The Netherlands: MDPI, Dec. 2022. [Online]. Available: https://www.mdpi.com/2673-4591/28/1/12

[15] EASA, "ED Decision 2022/024/R: Technical Specification for ADS-L transmissions using SRD-860 frequency band (ADS-L 4 SRD-860)," December 2022.

[16] F. T. Ltd., "EASA introduces ADS-L in new U-Space regulation, further defines e-Conspicuity," 2023. [Online]. Available: https://www.flarm.com/easa-publishes-u-space-regulation-futher-defines-e-conspicuity/