

# Detection, Characterization, and Localization of GNSS RFI

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## **ABSTRACT**

Even low-power radio frequency interference (RFI) can deny the use of global navigation satellite systems (GNSS) over a large area. With the number of such occurrences increasing worldwide, GNSS RFI also threatens civil aviation.

During flight inspections however, it can be hard for an operator of flight inspection systems (FIS) to assess GNSS RFI correctly, even with specialized, but non-automated equipment. In addition, due to the non-deterministic behavior of different GNSS receivers, the consequences of RFI can be diverse. For analyzing GNSS RFI, the FIS operator needs automated support in three tasks (detection, characterization, and localization), without being distracted from the primary flight inspection mission.

In order to develop this capability, Aerodata teamed with Braunschweig University and equipment manufacturer IFEN to initiate the research project “DOGS”. Funded in the frame of Germany’s federal aviation research program “LuFo”, the goal is to prototype an airborne solution automating all three tasks, and testing this in flight.

Installed into a research aircraft, this receiver prototype will be flight tested with RFI being broadcast in the E6 band. This allows checking for the performance of the receiver and the effect of the RFI on Galileo E6 and Beidou B3 signals.

## **INTRODUCTION**

The use of global navigation satellite systems has become ubiquitous over the last years, not only in aviation, but also for users in various other domains. Under normal conditions, systems like the American Global Positioning System (GPS), the Russian Glonass, the European Galileo or the Chinese BeiDou allow users worldwide to determine their own position, velocity, and time (PVT) uniformly, accurately and immediately.

For this, all systems use constellations of multiple satellites, broadcasting signals on different carrier frequencies. Due to the limited amount of available power in the satellites and the huge distances between satellites and users, the signals are received at power levels so low, that they are usually underneath the ambient noise floor. The GNSS receivers thus have to de-spread the received signals in order to be able to use them for positioning.

This is why GNSS-based positioning can be jammed rather easily by simply over-powering the received signals. Even with low to modest output power levels, radio frequency interference can affect the availability of GNSS over a large area. The combination of the ubiquitous use in various domains and the simplicity of denying its use has led to various challenges in practice. More and more reports on incidents related to GNSS RFI worldwide show, that the assumption of a clean RF spectrum cannot be met under all conditions.

In general, sources of radio frequency interference can be divided into non-intentional and intentional occurrences. While most non-intentional occurrences of RFI can be characterized as jamming (i.e. resulting in a denial of service), intentional interference can be both jamming (with more sophisticated interferers) and spoofing (i.e. resulting in wrong outputs). Both types can have significant consequences for civil aviation [1].

Jamming usually affects the availability and continuity of GNSS. When not being able to meet the required navigation performance (RNP) using other means of navigation, the pilots will get an indication and will follow contingency procedures (e.g. to go around in GNSS based approach procedures). As there is a clear indication of the failure, jamming usually does not affect the integrity (i.e. the trust a pilot can put into the correctness of the outputs of his navigation systems).

Spoofing on the other hand could result in positioning errors exceeding the allowed limits, without giving the pilot an indication of this (misleading information). This breach of integrity can have catastrophic results, given that the output of the GNSS receiver is used in communication (station finding), navigation (RNP, PBN, TAWS, etc.) and surveillance (ADS-B). In instrument meteorological conditions (IMC) without any further indications, GNSS spoofing could lead to controlled flight into terrain (CFIT) or other possibly hazardous situations.

GNSS RFI has thus the potential to lead to unsafe conditions with a high criticality, threatening the safety of air traffic. For this reason, airborne users of GNSS have to be protected from interferences as far as possible. As mandated by the International Telecommunication Union (ITU), the RF spectrum needs to be managed and monitored around the world. All ITU member states are mandated to implement a spectrum management system, which includes a continuous spectrum monitoring and a central occurrence database [2]. Flight inspections can play a beneficial role in supporting the spectrum monitoring by providing measurements and observations to this database.

### **GNSS RFI ASSESSMENT IN FLIGHT INSPECTION**

For flight inspections and procedure validation, GNSS is required in two ways: for the primary positioning of the

aircraft (e.g. during GBAS approaches) and for the reference positioning (in order to compare the received measurements with the expected ones). This implies that, during typical flight inspection or procedure validation missions, the FIS operator should also be aware of any GNSS interference.

On the one hand, it is crucial that the flight inspection mission can be continued even in case of GNSS RFI [7]. With many reference systems being based on GNSS, the FIS operator needs to know if the aircraft is currently affected by GNSS RFI in order to select other means of positioning in time. It needs to be ensured that these alternative means of reference positioning can operate independently from GNSS. [7]

On the other hand, the presence of GNSS RFI can lead to hazardous conditions in the primary navigation for other aircraft, too. This is why it is crucial to detect GNSS RFI during flight inspection, to collect as many observations as possible, and to report this as part of the spectrum monitoring. In order to assess the threat of GNSS RFI effectively, three steps have to be carried out:

1. **Detection:** The first step is to detect the presence of GNSS radio frequency interference. Unless RFI is detected, no further action is required.
2. **Characterization:** When GNSS RFI is present, the characterization of this occurrence helps to judge its criticality. By classifying the occurrence, it is possible to distinguish between intentional and unintentional interference. Together with the received power level, the RFI's impact on primary GNSS receivers can be judged.
3. **Localization:** If deemed necessary, the localization of the source of GNSS RFI can be a crucial step to help the national regulator to keep the RF spectrum clean. Stationary sources of RFI can be located by combining multiple relative bearing measurements taken at different positions. In order to determine the interferer's position as precisely as possible, a specific trajectory must be flown to ensure that errors due to multipath effects are minimized.

Especially with the operator's focus on the primary mission of inspecting and calibrating a ground-based navigation aid, assessing the consequences of GNSS RFI puts a significant amount of additional workload on the FIS operator. This is especially true for non-automated equipment present in current flight inspection aircraft.

### **EXISTING EQUIPMENT ON FLIGHT INSPECTION AIRCRAFT**

Historically, two distinct systems have been in use in flight inspection aircraft for decades.

On the one hand, dedicated spectrum analyzers – ideally switchable between different antennas – are used to monitor the RF spectrum. Digital spectrum analyzers, allow monitoring the spectrum for interfering signals. As laboratory-type equipment, spectrum analyzers usually feature a very wide operating frequency range and a high dynamic range. Deeply integrated into an automatic flight inspection system (AFIS), connected via a programmable RF switch matrix to multiple antennas, and controllable via a graphical user interface, spectrum analyzers are a key component for detecting and characterizing radio frequency interference in different frequency bands.

On the other hand, direction-finding systems allow the localization of any stationary signal sources. Best direction finding performance is usually achieved when analyzing the phase differences between the distinct elements of an antenna array. This is why a high level of phase synchronization is required throughout the complete processing chain and over a wide range of environmental conditions. Similar to spectrum analyzers, modern direction finding systems are deeply integrated into the AFIS. They feature a graphical user interface and offer the flexibility to switch between various antenna arrays.

A typical equipment console incorporating a digital spectrum analyzer and a direction finding system is shown in Figure 1. Even though both devices can be operated locally, they are integrated seamlessly into the AFIS software for remote operation and can be used for detailed RFI assessments.



**Figure 1: Example for a Modern AFIS Installation with a Digital Spectrum Analyzer (top right) and a Direction Finder (bottom left).**

When it comes to assessing the (potential) impact on GNSS RFI, a FIS operator has to perform all three steps mentioned above manually. However, the primary focus of a FIS operator should be on the navigation aid under inspection.

Assessing the potential threat of GNSS interference in parallel requires a very high level of training and results in a significant additional workload.

This task can be specifically challenging also from a technical perspective. Especially the analysis of weak or fast-changing interference signals (e.g. chirping jammers) can be tedious with the given tools.

This challenge can only be mitigated by automating the assessment of GNSS RFI using specialized tools.

### **RESEARCH PROJECT DOGS**

This demand for an automated solution lead to the establishment of the research project “DOGS” (German: Detektion und Ortung von GNSS-Störungen aus einem Luftfahrzeug, English: Airborne Detection and Localization of GNSS Interference). Funded by the German Federal Ministry for Economic Affairs and Climate Action in the frame of the federal research programme “LuFo”, Aerodata AG teamed up with IFEN GmbH and the Technische Universität Braunschweig.

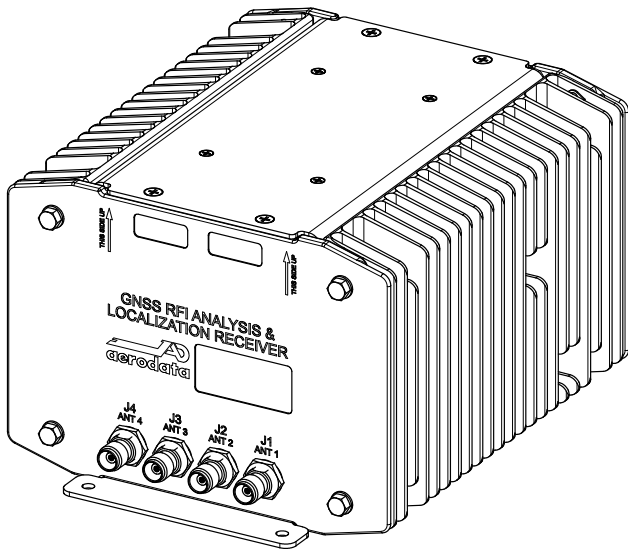
The overall goal of this joint research project is to develop a prototype system for automating the aforementioned tasks and to test it in a flight campaign. Each partner has its own distinctive focal areas:

- **Aerodata AG** from Braunschweig is a leading provider of special mission aircraft and systems. Aerodata acts as project lead, develops the prototype system and integrates all necessary components for the flight trials.
- **IFEN GmbH** is a manufacturer of GNSS signal generators and test receivers based in Poing. IFEN’s main responsibility is the development of the core functionality of the system, including the implementation of the hardware and the algorithms.
- The **Technische Universität Braunschweig** (TUBS) is an institute of technology in Braunschweig. Its Institute of Flight Guidance (IFF) supports the algorithm development and operates the research aircraft used for the validation campaign.

The DOGS project started in May 2022 and is planned to be completed by October 2024.

### **RFI Analyzer Prototype**

Within the research project DOGS, Aerodata developed the prototype of a GNSS RFI analyzer and localization receiver, called AD-GRAL-0100 (shown in Figure 2). This airborne receiver prototype was specifically developed by Aerodata AG to meet all constraints of the environment, and is based on specialized components provided by IFEN GmbH and.



**Figure 2: AD-GRAL-0100 Prototype**

This prototype is specifically tailored to analyze GNSS RFI in the E6 band, so between 1240 and 1300 MHz. This frequency band was chosen as a compromise between the feasibility of testing and the availability of GNSS signals. While the 1240 – 1300 MHz band contains the Galileo E6 and Beidou B3 signals, it does not contain any GNSS signals used operationally. In addition, this frequency band is (at least in Germany) allocated to other users, e.g. for amateur television. This is why interfering signals are rather common in this band.

Choosing E6 as the baseline frequency band allows performing real-world RFI tests, while still seeing the effects of the RFI on the GNSS signals. Aerodata obtained a short term transmission license of the German regulator (Bundesnetzagentur – BNetzA) for the duration of the test campaign.

The RFI analyzer prototype outputs raw I/Q measurements derived from its four phase-synchronized antenna inputs via a USB3 interface. The use of USB3 is required due to the high data rate of more than 200 MB per second.

### **Integration into Research Aircraft**

For the test campaign, the research aircraft “D-ILAB” will be used. This Cessna F406 (as shown in Figure 3) is a twin-turboprop aircraft without a pressurized cabin.

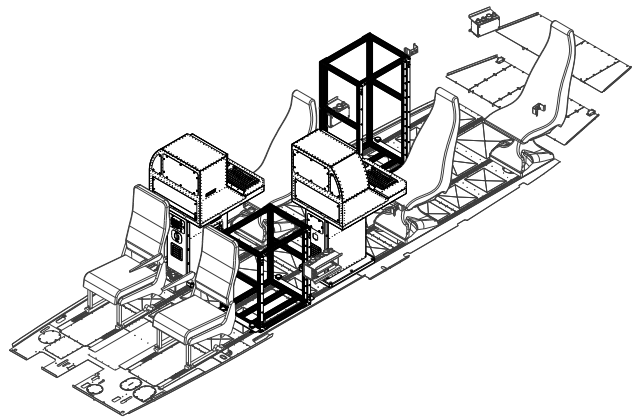
This research aircraft is operated by the Institute of Flight Guidance of the University of Braunschweig and was modified intensively by the holder of the type certificate (French company ASI Aviation) to incorporate multiple mission system provisions for different types of academic and scientific research.



**Figure 3: Research Aircraft D-ILAB**

Next to specific sensors, this scientific modification includes e.g. a nose boom with measurement equipment, a power supply for mission equipment, two operator consoles, two 19” racks for mission equipment, and fuselage opening provisions (which are approved for certain maximum weights and frontal areas).

The aircraft cabin including these mission equipment provisions is shown in Figure 4.

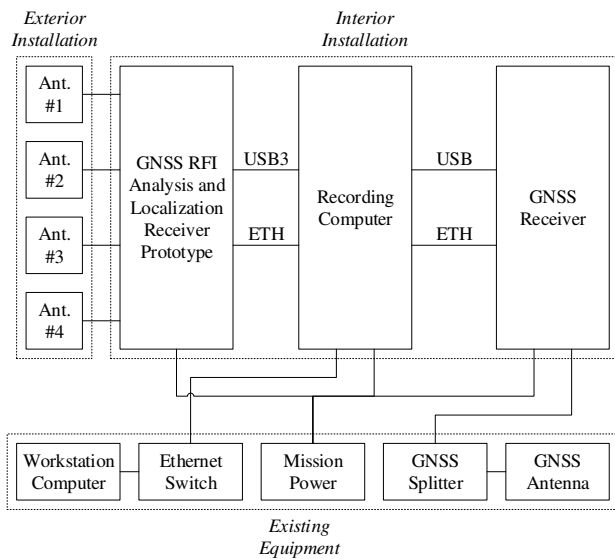


**Figure 4: Mission Equipment Provisions within the Cabin of the Research Aircraft**

The aircraft (including all scientific modifications and provisions) is certified as a “regular” CS-23 airplane in the normal category, including supplemented manuals for the pilots and for maintenance. In contrast to experimental or research aircraft, it can be operated very flexibly and internationally, but requires that all modifications are covered by a change approval according to EASA rules.

In order to perform the research flights, a modification project was initiated aiming at eventually obtaining a supplemental type certificate (STC). This modification installs additional equipment in the aircraft’s approved provisions. As shown in the block diagram in Figure 5, the modification of this aircraft incorporates four components

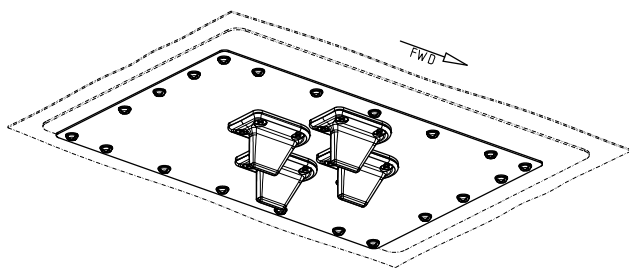
and is divided into an exterior installation (the antenna array) and an interior installation (including the RFI receiver prototype, a GNSS receiver, and the recording computer).



**Figure 5: Block Diagram of the Modification**

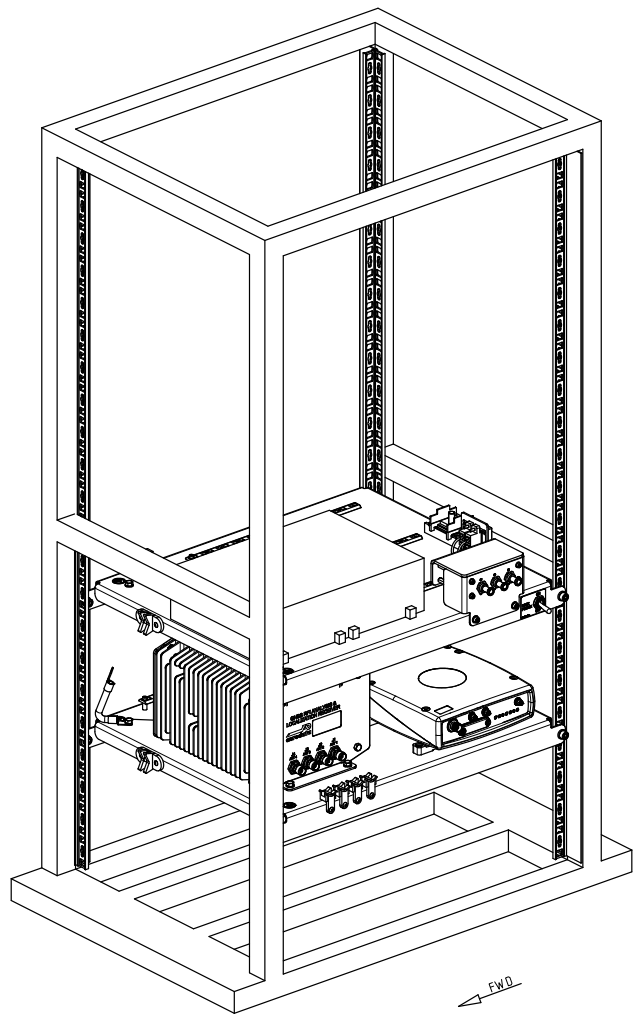
All newly installed components use the existing and approved 28 V DC mission power. Both the pilot in the cockpit and the operator in the cabin can switch off the system completely.

Four L-Band antennas are mounted in a circular pattern on one of the approved opening provisions on the bottom of the fuselage. This antenna array is very similar to the L-band antenna arrays of direction finding systems and allows to perform the localization of RFI. As shown in Figure 6, the antennas are mounted on a cover plate on one of the approved fuselage opening provisions.



**Figure 6: Installation of Antenna Array**

The rack installation incorporates the RFI receiver prototype, the GNSS receiver, the recording computer, as well as the interconnection and power cables. All components are mounted on two shelves, which are installed within the right hand mission equipment rack. The planned installation is shown in Figure 7. All components are powered from the aircraft's 28 VDC mission power supply and are protected with distinct circuit breakers.



**Figure 7: Rack Installation (RF Receiver Prototype: bottom shelf left. GNSS Receiver: bottom shelf right. Recording Computer: top shelf left)**

The AD-GRAL-0100 RFI receiver prototype (as shown in Figure 2) is connected to the four L-band antennas via phase-matched cables. It interfaces with the aircraft's suppression line for protecting itself from strong transmissions in neighboring frequencies.

The installed GNSS receiver is a Septentrio AsteRx-U. Connected to a GNSS antenna on top of the fuselage (via a splitter), it provides raw multi-constellation / multi-frequency GNSS observables with a high update rate. The receiver incorporates multiple proprietary interference mitigation filters, which are disabled to obtain comparable results to primary GNSS receivers (which do not necessarily include such filters).

The GNSS receiver is also capable of outputting baseband measurements for its supported frequency bands. Using a Fourier transform, these baseband I/Q samples can be converted from the time domain into the frequency domain.

By plotting and monitoring the resulting power levels over the frequency range, the presence of GNSS RFI can be seen clearly for each frequency band.

In order to record and analyze all measurements, an industrial-grade commercial-off-the-shelf (COTS) computer system is installed into the rack. This computer is connected to the RFI analyzer and the GNSS receiver via USB and Ethernet cables.

The output data of all components is recorded on this computer's fast solid-state disks (SSD). Recording all data allows to post-process the data for algorithm development and to playback the recorded interference signals using a GNSS signal generator. However, due to the high data rate of more than 200 MB/s, the recording computer is not capable of analyzing each received sample individually in real time.

Instead, it was decided to limit the function of the newly installed computer system to recording only. This way, this computer does not require to be connected to a display and input devices, but can operate headless without any interaction.

In order to preview the performance in real time during the flights, the recording software forwards low-frequency snapshot data via an Ethernet connection to the a mission computer already available. This mission computer can be operated via the display and input devices of the mission operator console, and runs a software with a graphical user interface to visualize the low-rate data snapshots. The software is capable of plotting different measurements, including:

- Magnitude and phase over frequency for the four input channels of the RFI analyzer
- Relative bearing estimation, based on the phase differences between the input channels
- Magnitude over frequency for the baseband samples of the GNSS receiver
- Carrier-to-Noise densities ( $C/N_0$ ) over time for the different frequency bands supported by the GNSS receiver

This way, the performance of the receiver can be assessed already in flight during the trials. This does not only allow to check the correct operation of the receiver, but also to change the transmissions on the ground, depending on the observed behavior.

### **Broadcast of E6 Interference**

The E6 frequency band (1240 ... 1300 MHz) used for the trials was selected as a compromise. On the one hand, this frequency band is not used operationally in civil aviation, but

is utilized extensively for other applications (including e.g. amateur television in Germany). On the other hand, this band contains civilian GNSS signals (Galileo E6-BC and Beidou B3-I), which can be processed by commercial GNSS receivers.

This allows broadcasting radio frequency interference without interfering with any civilian user, while still being able to evaluate the impact on real GNSS signals.

In order to be allowed to broadcast interfering signals in this band, the German telecommunication regulator (BNetzA) granted a short-term transmission approval for transmitting at Braunschweig airport with a maximum output level of 30 dBm in the E6 band. This allows transmitting radio frequency interference signals, which are comparable to typical interfering signals (like from personal privacy devices (PPDs) or defective equipment).

Of course, not interfering with the safe operation of air traffic is of dominant importance. This is ensured on the one hand by continuously monitoring the L1 and L5 reception on the ground, with a GNSS receiver/antenna located in the vicinity of the interferer. On the other hand, the Deutsche Flugsicherung GmbH (DFS, the German air navigation service provider) will issue Notices to Air Missions (NOTAMs) for Braunschweig airport in order to raise the awareness for all operators. In case of any performance degradation of the operationally used GNSS signals, the transmission will be switched off immediately.

In order to test different RFI signals, a set of observed jamming characteristics was compiled from literature [3][4][6]. Even though most of the documented RFI occurrences are analyzed within the L1 (and L2) bands, the broadcast signals in the E6 band (i.e. Galileo E6-BC and Beidou B3-I) are similar to (advanced) GNSS signals on other frequencies. Thus, it is expected to obtain similar results compared to e.g. L1 interference.

The E6 interference signals are implemented on a Rohde & Schwarz SMBV100A vector signal generator. This signal generator is capable of outputting these predefined scenarios with power levels of up to 25 dBm. This allows connecting the output of this signal generator directly to an omnidirectional rooftop dipole antenna, without the need for additional amplification.

### **Flight Campaign**

The test campaign is scheduled for taking place in late summer 2024 around Braunschweig airport (EDVE) in Germany. The planned flight campaign includes different trajectories along with the transmission of differently characterized broadcast signals.

The primary purpose of this campaign is the collection of measurement data for later post-processing. The power

levels and characteristics of the interference as well as the aircraft's trajectory will be varied through the campaign. This not only allows testing the overall sensitivity of the system, but also verifying its direction finding capability.

**FUTURE DEVELOPMENTS**

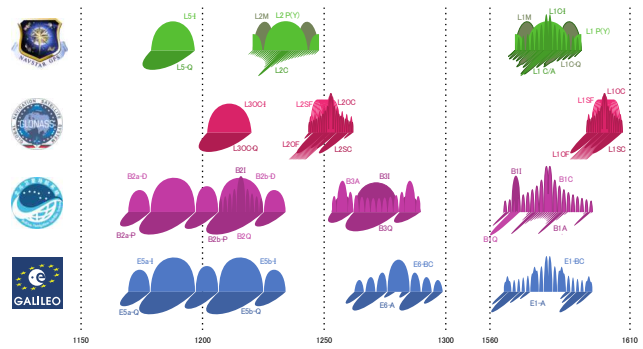
The data recorded during the flight campaign will be used to develop and refine algorithms for detecting, characterizing and locating GNSS interferers. With the time-synchronized recording of all data streams, a precise post-processing is possible. By replaying the collected I/Q samples using a signal generator, it is even possible to perform hardware-in-the-loop (HIL) tests with different types of GNSS receivers in order to characterize their behavior.

Once successfully demonstrated and validated in the frame of the research project, Aerodata AG and IFEN GmbH plan to refine the RFI analyzer, targeting on advancing its technology readiness level (TRL) from a prototype level (TRL 6) to a product level (TRL 8). This also includes the possibility to implement the developed algorithms directly on the hardware's integrated field programmable gate arrays (FPGA).

The resulting family of products is planned to include multiple variants with different functionalities. In contrast to the prototype receiver, the future products are planned to perform the detection, characterization and localization tasks internally. The product variants are primarily (but not exclusively) intended to be installed on flight inspection aircraft.

Aerodata plans to offer variants capable of analyzing one or two frequency bands simultaneously. Customers will be able to choose one or two 50 MHz wide frequency bands (L1: 1550 - 1600 MHz, E6: 1250 - 1300 MHz, L2: 1200 - 1250 MHz, L5: 1150 - 1200 MHz). As shown in Figure 8, these bands cover most current and future GNSS signals.

In addition, the products will be available in variants with or without continuous raw I/Q data output. As this option requires very high data bandwidths via USB3 connections as well as a powerful recording system, it is foreseen to be mainly of interest for academic and research organizations. The big advantage of recording raw I/Q data output is the possibility to re-generate these signals in a laboratory using IFEN's GNSS signal generators. This allows assessing the impact of recorded RFI signals on different GNSS receivers in a controlled laboratory environment.



**Figure 8: Supported GNSS Bands and Corresponding Signals (based on [8])**

**CONCLUSIONS**

In close collaboration with its partners in the frame of the research project “DOGS”, Aerodata has developed a prototype for analyzing GNSS RFI. This airborne receiver is capable of detecting, characterizing and locating GNSS radio frequency interference. It will be tested in a flight campaign using a test aircraft installation in late summer 2024. If the required performance level is met for these tests, Aerodata plans to develop commercial products, which can be installed on various types of aircraft, especially in the flight inspection domain.

By having automated means of detecting, characterizing and locating GNSS RFI, the situational awareness of a FIS operator regarding the GNSS spectrum is significantly increased.

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**Figure 9: Project Logo and Funding Acknowledgement**

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