Versatile and Configurable GNSS Interference Detection and Characterization Station

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BIOGRAPHY

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Daniel Meister received his MSc. degree in Computer Science from the Georg Simon Ohm University of Applied Sciences Nuremberg, Germany, in 2015. Upon graduation he joined the Fraunhofer Institute for Integrated Circuits IIS, where he is involved in signal processing for GNSS receiver including software and hardware development.

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Christian Otto received his B.A. degree in Computational Linguistics in 2002 and his M.A. degree in Linguistics in 2014 from the Friedrich-Alexander University of Erlangen-Nuremberg. Since 2001 he has been working in the context of Fraunhofer Institute for Integrated Circuits IIS in the field of Sensor Networks and GNSS receiver software development.

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ABSTRACT

In this paper, we present a versatile, configurable and customizable GNSS interference detection station. Up to three GNSS bands with a bandwidth of up to 80 MHz and a resolution of up to 8 bit can be continuously analyzed. If an interference is found, a user-customizable signal characterization is carried out to extract the interference signal's parameters. The batch of affected data is archived for possible off-line analysis, including tagging of its appearance time and duration. Finally, the extracted characteristic is used to compare it with previously characterized ones for possible recognition. This information can then be used to gain insights about the interference source as well as providing the means for its removal. The architecture of the system, including the detection and characterization algorithms, as well as the web-based interface, is presented. The paper concludes with a presentation and discussion of the interferences found within a several weeks long measurement campaign near the motorway and airport in Nuremberg, Germany, in early 2017.

INTRODUCTION

Autonomous global navigation satellite system (GNSS) systems, such as reference stations and time servers, can be severely affected by interferences. This is largely due to the fact that an autonomous system depends on human assistance as a fail-safe. If there is no human in the loop (i.e. the system is fully autonomous), there is a sufficient risk of system failure due to interferences. As a consequence interference monitoring is necessary, to warn the primary system and to prevent an interference from severely reducing the performance of the primary system.

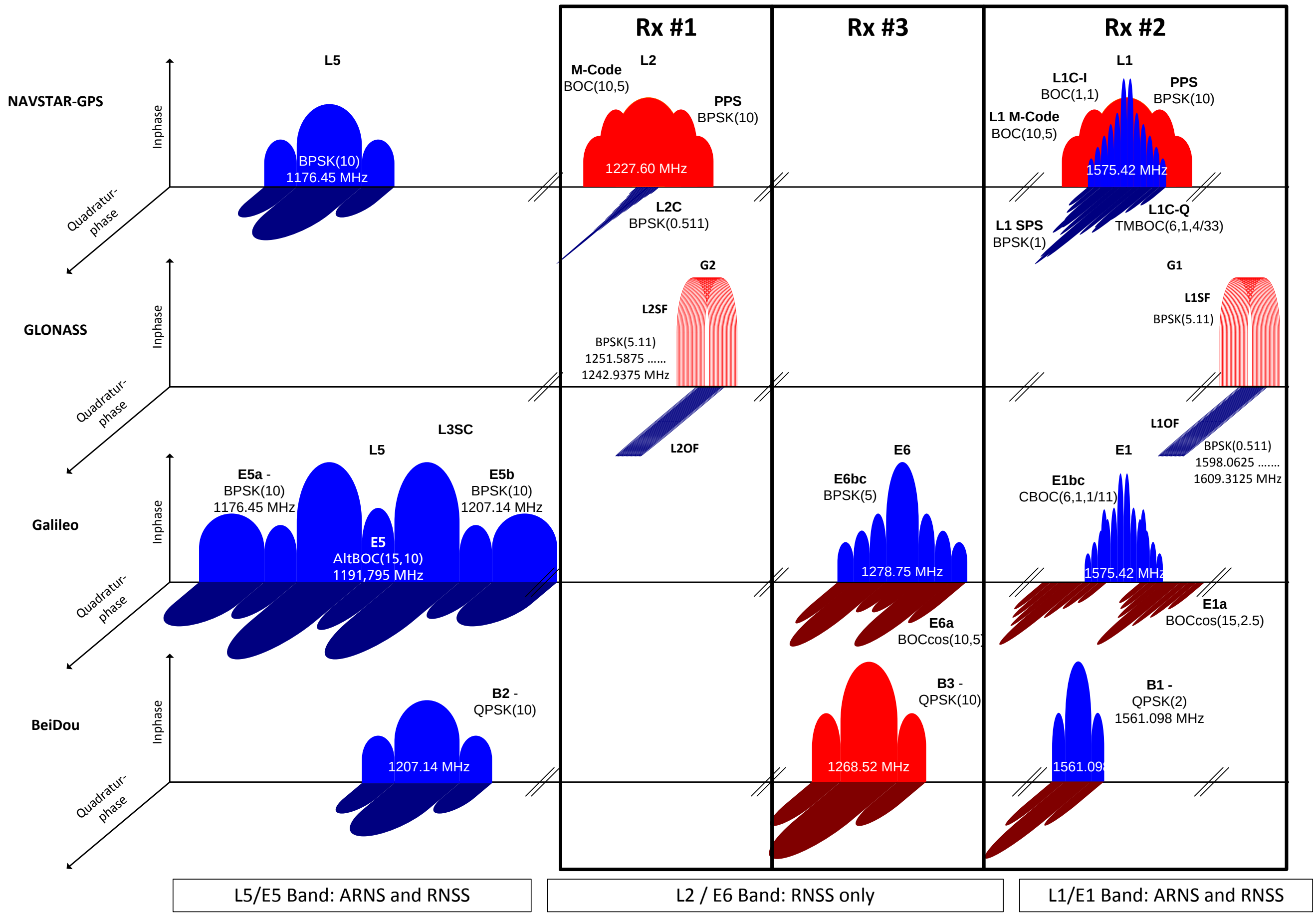


Figure 1. Overview of GNSS frequency bands and configurations supported in the current set-up

Further, when an interference is detected, it should be analyzed to determine the impact to the system, the intent of the interference signal should be assessed, and the signal should be classified. This process allows for awareness through monitoring, removal of unlawful transmitters, and localization of unintentional interference sources. By gaining this information from the electromagnetic (EM) spectral environment, more reliable system operation can be guaranteed.

GNSS signals have low received power (ca. -130 dBm received on earth). As a consequence, jammers (intentional interferences) require little transmit power to surmount the GNSS signals and to cause spatial and temporal unavailability of the services. GNSS jamming is categorized as a denial of service (DoS) attack, because the GNSS service is completely obstructed by the jammer. Privacy protection devices (PPDs) are commercially available jammers, even though the use thereof is prohibited. Unintentional interferences such as harmonics or intermodulation signals caused by poorly designed or faulty radio frequency (RF) equipment can also significantly interfere with GNSS signals. It is therefore clear that the threat of interferences – whether intentional or not – is a valid concern within the scope of GNSS design.

Moreover, the GNSS signal bands are fairly wide. A bandwidth of approximately 50 MHz is used for most GNSS bands, with the exception of nearly 92 MHz for the Galileo E5 AltBOC band, as shown in Fig. 1. As a result, the continuous, high dynamic monitoring of multiple GNSS bands is a challenging and expensive task.

Several academic and commercial interference monitoring systems (IMSs) have been developed. An IMS has been developed for the European Space Agency (ESA) [1], with the goal to protect the Ranging and Integrity Monitoring Stations (RIMSs). A commercial off-the-shelf (COTS) signal analyzer, which employs sophisticated detection algorithms, is used to monitor the frequency bands from 800 to 1800 MHz. Approximately 200 MSamples of data sampled, at a bandwidth of 28 MHz, can be stored and further analyzed. This is sufficient for Galileo OS and European Geostationary Navigation Overlay Service (EGNOS) signals, but not for monitoring the entire transmitted bandwidth. To overcome the challenge of wide-band signal monitoring, a new approach for an IMS has been described using a compressed sensing analog to information converter [2]. However, this has only been shown in theory. The commercially available *Spirent GSS200D* [3] is an IMS which provides continuous monitoring with analysis and characterization of only a single frequency band. A maximum bandwidth of approximately 16 MHz is achieved which is insufficient for the monitoring of wide-band GNSS signals and for the full transmission band, too.

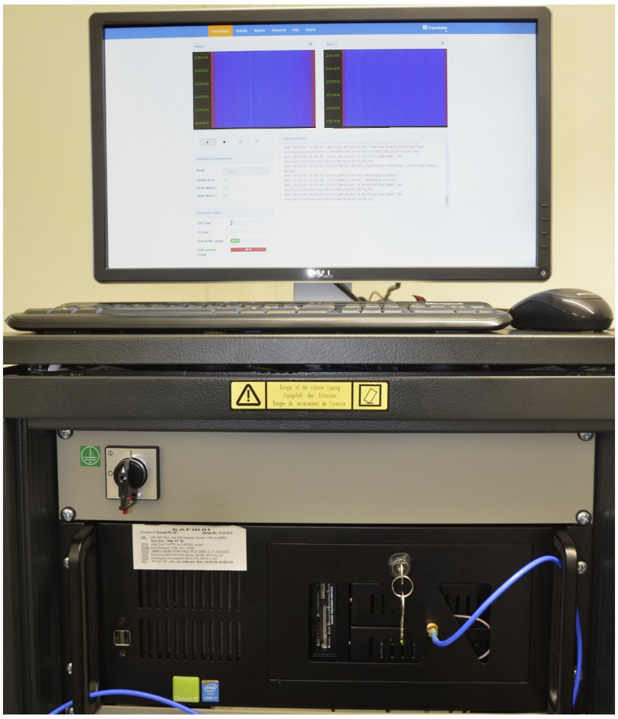


Figure 2. Photo of the actual system hardware

In this paper, we present a versatile, configurable and customizable GNSS interference detection station. The station is designed to operate in conjunction with other GNSS receivers and provides a web-based user interface for remote control and monitoring. Up to three GNSS bands with bandwidths of up to 80 MHz at 8 bit I/Q quantization and an overall data rate of 1.3 Gbit/s can simultaneously and continuously be monitored and analyzed. Therefore all GNSS signals and full transmission bandwidths are supported. In the case of an interference detection, the signal is characterized and the signal parameters are estimated accordingly. A batch of the recorded I/Q data (customizable, with a default value of 2 GByte) containing an interference signal is stored. This enables post-processing and an in-depth analysis of the interference by the user. The signal definitions and parameters are saved in a database so that they can be used for pattern recognition of the interferences. Insight can be gained from the database with regard to the interferences, which can ultimately result in the removal of an interference source.

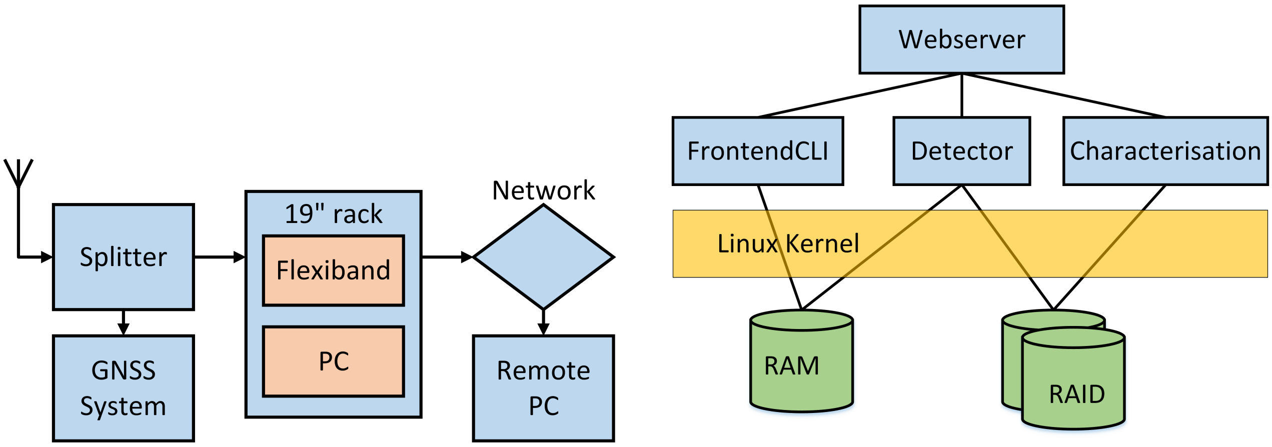
The system architecture as well as the characterization methods are presented. Some examples of real-life interferences recorded and characterized in a multi-week measurement campaign are shown. The campaign was done near a motorway and airport in Nuremberg, Germany in early 2017.

SYSTEM DESCRIPTION

The interference detection station combines the in-house developed Flexiband universal serial bus (USB) front-end [4], integrated into a 19-inch rack mounted personal computer (PC). Figure 2 shows a photo of the final system.

Dedicated interference detection and characterization software runs on the platform, and can be accessed through a web-based user interface. This station can be operated in parallel with other GNSS sensors sharing the same antenna. The station is situated at the Fraunhofer Institute in Nuremberg, Germany and uses a geodetic reference antenna (*NavXperience 3G+C Reference* on the roof of the Fraunhofer building, capable of receiving the complete L-Band). Figure 3(a) shows the system concept.

The Flexiband RF data-grabber front-end has been developed for GNSS signal recording purposes. It supports up to three independent RF frequency bands in the L-band and S-band [5]. The typically used ceramic GNSS RF filters limit the analog reception bandwidth to approximately 54 MHz, sampled at a maximum rate of 81 MHz with 8 bit I/Q word-length. A field-programmable gate array (FPGA) is used for digital signal conditioning with filtering of the RF digitized signals including re-sampling and re-quantization. Moreover, the FPGA multiplexes the signal streams from multiple bands and inserts checksums, as well as counters for possible packet loss detection. The sampled data are multiplexed and transferred using USB 3.0 to a random access memory (RAM) disc of the PC, where the real-time interference detection is carried out. For the RAM disc, the overall data-rate limit is around 5 Gbit/s – equal to the maximum of USB 3.0. However, in the case of an interference present, the data shall be archived, through an overall data-rate of approximately 1.3 Gbit/s. This is determined to be the limit for the combined recorded data. The transfer rate includes all bands for the given bandwidths and word-lengths to guarantee a continuous transmission to redundant array of independent disks (RAID) storage.



(a) Block diagram of the system concept

(b) Block diagram of the system architecture and data-flow

Figure 3. System concept and architecture

An i7 quad-core processor with 32 gigabyte (GB) of RAM, 256 GB solid-state drive (SSD) and 2 terabyte (TB) RAID is used for the purpose of storing the detected events. This PC is running a Linux based operating system, with a Python based web-server and process handling. The characterization and analysis interface is implemented in Octave / Matlab. Thereby simplifying the process for users to implement their own detection and characterization algorithms.

The current project using the monitoring station has two configurations. These configurations support three reception frequency bands, as shown in Fig. 1 and are defined as follows:[1]

- **Configuration 1**:
  - Rx#2: L1/E1/G1 (1588.8 MHz center frequency, 38 MHz analog bandwidth, 40.5 MHz sample rate @ 8 bit I/Q) and
  - Rx#1: L2/L2c/G2 (1232.5 MHz center frequency, 38 MHz analog bandwidth, 40.5 MHz sample rate @ 8 bit I/Q)
- **Configuration 2**:
  - Rx#2: L1/E1/G1 (1574.9 MHz center frequency, 54 MHz analog bandwidth, 81 MHz sample rate @ 4 bit I/Q) and
  - Rx#3: E6 (1278.7 MHz center frequency, 54 MHz analog bandwidth, 81 MHz sample rate @ 4 bit I/Q).

Configuration 1 is intended for the most frequently used GPS and GLONASS dual-band systems whereas Configuration 2 is intended for the monitoring of the wide-band Galileo public regulated service (PRS) bands on E1 and E6. Both configurations add up to an overall data rate of 1296 Mbit/s, therefore allowing a continuous recording to SSD without any data losses.

The system is calibrated in terms of the RF gain at the location where it is deployed. A power threshold can be determined which is used for the detection of interferences. The performance of the detector is dependent on the receiver settings. The minimum signal that is acquirable for the current set-up is determined to be -115 dBm. The minimum detectable signal, with the current system set-up, is determined to be -108 dBm. The maximum non-saturated signal is dependent on the dynamic range of the system, which is set by the user. For the 8 bit set-up, this can be as high as -70 dBm. Note that the RF chain (e.g. antenna, low-noise amplifier (LNA), Flexiband filter bandwidths and amplifier gains), can be altered to change the performance for a given scenario.

Batches of 2 GB of the recorded data is temporarily saved on a RAM disk. A root mean square (RMS) power detector is used to detect possible interference. If an interference is detected, then the batch of data is saved to the RAID storage. The data is stored with a meta-data file describing the recording settings, according to the Institute of Navigation (ION) Metadata standard [6]. Further processing, such as characterization and analysis, will follow from the RAID storage. Figure 3(b) shows the system architecture.

The characterization processing stage analyses the stored data to classify which type of interference was detected. Depending on the type of interference, the appropriate parameters are estimated. This information as well as the time of detection is stored in a meta-data file together with the stored data.

[1]The bands can be altered for future projects due to the capabilities of the Flexiband front-end. The analog filters used before sampling can be changed to be closer to the sample rate, for example.

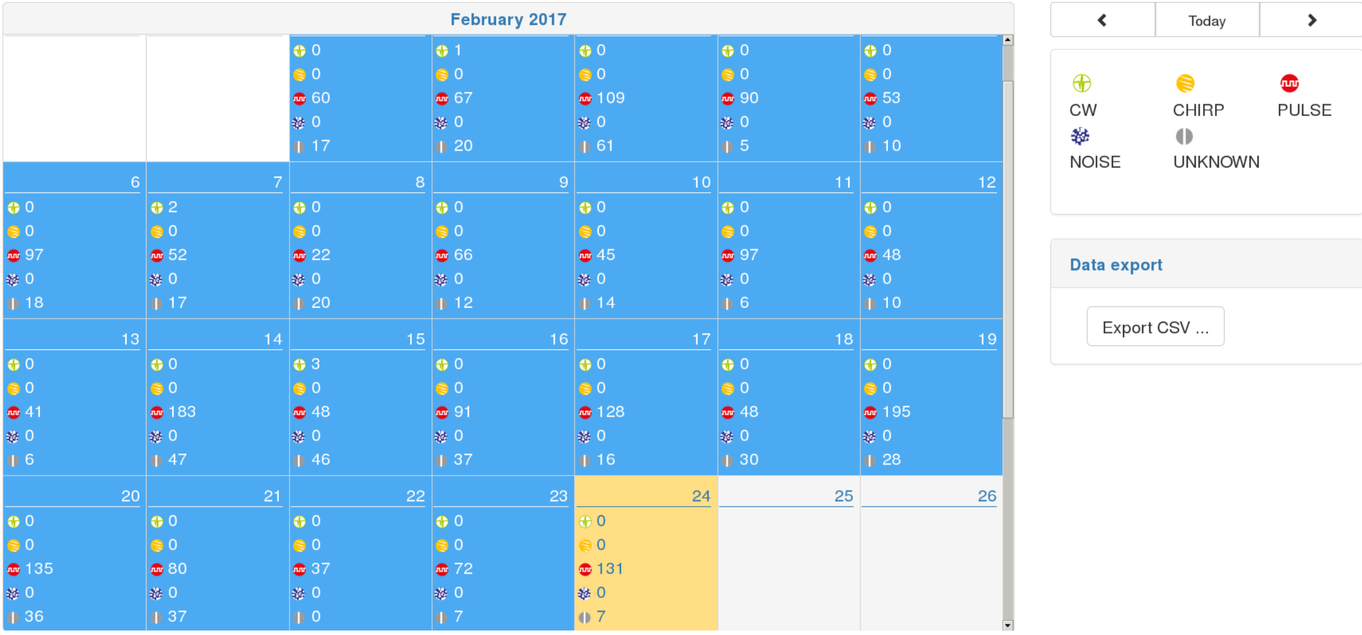


Figure 4. Calendar with events

The user interface to control the monitoring station is realized using a Python web-server. A web-browser can be used as a remote graphical user interface (GUI) for the system. A spectrogram (waterfall display) of both frequency bands are continuously updated with the most current analyzed data, to provide visual output to the user. The GUI provides system status information and displays the system event log.

The user can configure the detection and characterization and other system settings through the GUI. A calendar displays detected interference events, as shown in Fig. 4[2]. The characterization information of an event is obtainable from the calendar, and the possible means to download the data is provided. The detected interference database, similar to what is used by the calendar, can be downloaded including the assignment of characterized interferences.

INTERFERENCE CHARACTERIZATION

Interference characterization is required to comprehend what type of interferences are possible, as well as which mitigation techniques should be implemented to protect a system. GNSS interferences are traditionally classified into two main categories

- unintended interferences (e.g. signals for other applications, their harmonics or intermodulation products), or
- intentional interferences (e.g. low cost jammers such as PPDs).

This is considered as a limiting definition, as the signal forms used for jammers are evolving. As a consequence, traditional GNSS interference classification algorithms focus on these type of interferences. Jammer types that are popularly used are [7]:

- band limited noise,
- CW tone,
- frequency modulated continuous wave (FMCW) (i.e. chirp-signals),
- pulsed signals, and
- wide-band noise or matched GNSS signal spectrum

As some GNSS bands coexist with other systems, non-intentional interferences are highly likely and can be expected.

In this system, interferences are classified in two dimensions, as shown in Fig. 5. The intersection of the definitions shows an example spectrogram of such an interference. Time is on the x-axis and frequency is on the y-axis of each of these intersections, and the yellow shows the detected values of the spectrogram. Refer to this diagram for discussion in subsequent sections.

[2]In the calendar only a continuous wave (CW) chirp interference is regarded as a “chirp”, a pulsed chirp will be flagged as a pulsed interference.

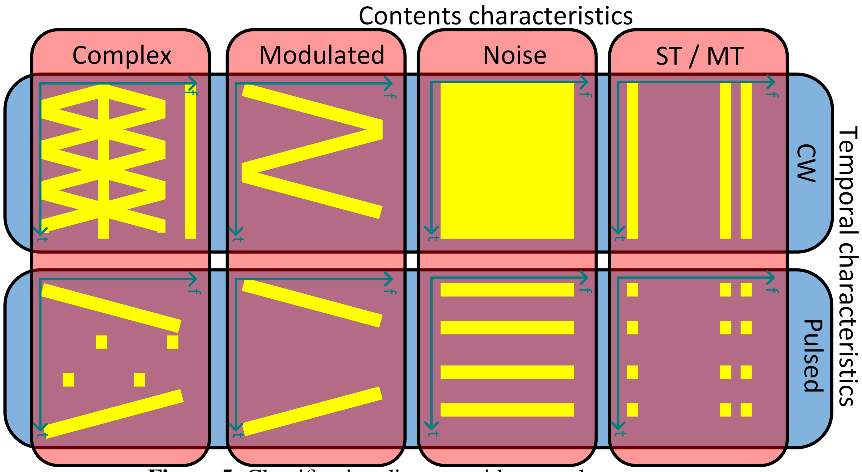


Figure 5. Classification diagram with example spectrograms

First, the interferences are classified according to their temporal characteristics. A signal is either a CW or a pulsed signal. Thereby, the transmission mode of different interferences are separated.

The second dimension contains the contents of the signals. The contents determine the type of interference. A number of different content types exists, these are briefly described in the following:

Tone A single tone (ST) signal transmits a single sinusoidal signal with a fixed frequency, and a multi tone (MT) signal is composed of multiple static sinusoidal signals. These signals are traditionally CW, but some examples of pulsed tone signals have been observed.

Noise A noise signal transmits over a band of frequencies, which is either limited to certain GNSS signals (i.e. band limited noise signals), or transmits over all observable frequencies of the receiver (i.e. broad band noise signal). Generally, a larger band of the spectrum is jammed resulting in high spectral density, which results in classification difficulties as the average spectral power is low. Spectrum matched jammers are also classified under this category as a larger band is being jammed.

Modulated A modulated signal is a sinusoidal signal which changes its properties (frequency or amplitude) over time. Typically these signals are FMCW (chirp) signals and popularly used by PPDs, [8]. However, there are many cases were pulsed chirps are observed.

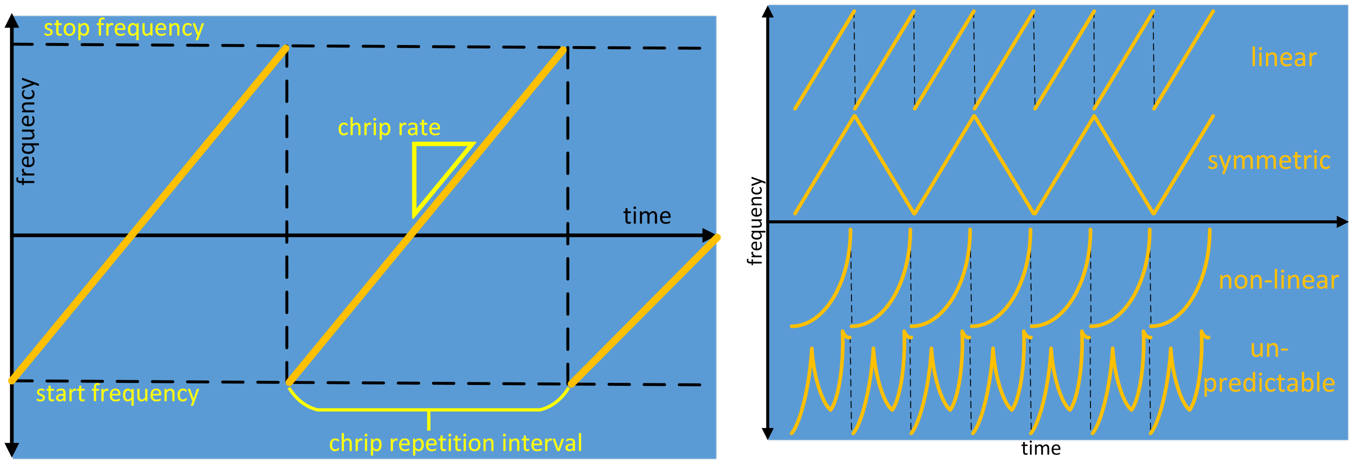
Complex A complex signal is a combination of the aforementioned signals. These cannot be characterized as a single signal, but only as a compound signal. Often when multiple simultaneous interferences are observed, they are perceived as a complex signal by the receiver.

Temporal classifications

The temporal classification is considered as the first classification stage, as this allows for the baseline of the transmission mode. The classification is executed directly on a spectrogram (also known as a waterfall-map). In the case of CW detection, the duration of the signal is estimated, followed by the characterization of the signal content.

In the case of a pulsed signal, the pulses are analyzed. The association of pulses is the first challenge within classification. The first step is to measure each pulse width and to associate pulses with similar widths as belonging to the same transmitter. Therefore, the possibility exists that multiple interferences can be analyzed simultaneously. Next, the pulses of the same family are correlated with each other to ensure that they exhibit similar content (note that at this stage, the content is not classified, as the correlation has no *a priori* information). This allows for the possibility to separate pulses with the same pulse width but with different contents as different signals. Once the pulses are separated their pulse repetition interval (PRI) is estimated. The duty cycle can be calculated as the ration of the pulse width to the PRI.

Once the temporal characteristics have been classified and estimated, all pulses classified as being from the same interference are then stitched together (i.e. constructing a CW signal) to create a condensed spectrogram which is used for further analysis of the contents.



(a) Chirp parameter diagram

(b) Chirp type diagram

Figure 6. Chirp parameters and types

Contents characterization

The classification of the contents should be done separately for each case.

Tone: ST and MT are easily characterized through the use of Fourier analysis, as the signals are stationary in frequency and exhibit extremely low spectral density. This makes the interference simple to detect, characterize and to estimate the center frequency.

If a MT is observed, the number of peaks in the spectrum should be estimated. Inter-modulation products caused by the down-mixing stage of a receiver and between the tones may cause false peaks. These should also be detected and removed. Usually, a MT has equal gain for each sinusoid, which means that even in the presence of a fading channel, the differences between the signals should not be too severe. On the contrary, the inter-modulation products tend to have relative large differences.

Noise: A noise signal is present over a larger bandwidth of the receiver. Therefore, the start and stop frequencies can be estimated. If the full band of the signal is interfered with, then the bandwidth of the interference cannot be estimated as it is spread over the entire band.

If a communication signal is observed in the navigational bands, it will be considered as a noise signal due to the broader bandwidth when compared to ST or MT signals. Therefore it is often advised to do further analysis on noise signals to understand their intent and source.

Modulated signals are typically classified as a chirp signals. Generally a chirp signal has the following properties, as further analyzed in [9] and visualized in Fig. 6(a):

- **start and stop frequency [Hz]**: measurable with Fourier analysis,
- **chirp repetition interval [s]**: measurable with temporal repetition through Fourier analysis,
- **chirp rate [Hz/s]**: measured as the average change of frequency over time, and
- **chirp type**.

The chirp type can be used to classify the type of transmitter. Note that for certain types, the properties listed above may not yield meaningful outputs. Among (but not limited to) possible chirp types are:

- **linear**: A chirp with a linear change of frequency in a single direction. This type resembles a saw-tooth wave on a spectrogram.
- **symmetrical**: A chirp with a linear change of frequency in both directions. This type resembles a triangular wave on a spectrogram.
- **non-linear**: A chirp with a non-linear change of frequency. This is often the case with cheaper jammers having high tolerances on the transmitted waves. The chirp rate of such a signal is measured as the average change of frequency, and is often poorly estimated.

- **unpredictable**: A frequency modulated signal which is unpredictable in nature. These signals are often classified as noise signals.

Figure 6(b) shows the difference between these chirps on a spectrogram.

Chirp signals have many forms and parameters to be estimated, and they are widely used by interferences. Therefore, this class of interference is a significant challenge and popularly discussed in literature [8], [9].

Complex: If a signal is too complex to be classified, it is flagged as "unknown" and requires an operator to determine the classification. For current systems, this is sufficient as most interferences are simple, or the number of interference incidents are relatively low, resulting in a low probability of multiple simultaneous interferences. However, in the future this issue should be addressed as interference incidents are increasing and interferes are becoming more complex.

MEASUREMENT RESULTS

The system was used for a measurement campaign in January and February 2017. The described station was mostly run with configuration 1 (L1/E1/G1 and L2/G2 bands with 38 MHz bandwidth each) at the Fraunhofer IIS laboratory in Nuremberg, Germany. The used roof antenna is located about 1.5 km from a busy motorway. The premises is also situated in close proximity (about 3 km) to an operational commercial airport (International Air Transport Association (IATA) station code NUE). The station uses a geodetic reference antenna (*NavXperience 3G+C* with approximately 30 dB gain) on the roof of the Fraunhofer building.[3]

General observations

Over the course of the measurement campaign, 3121 interference events were observed in L2/G2 band and only 14 incidents (less than 1 % of interferences) in the L1/E1/G1 band. This was expected, since the L1/E1/G1 band is within the well protected Aeronautical Radio Navigation Services (ARNS) and Radio Navigation Satellite Services (RNSS) band whereas the L2/G2 is only within the RNSS protected band, sharing it with many other services, especially military transmission, radars and aeronautical systems (e.g. origin from the airport located nearby).

An event is defined as the presence of an interference in a 13 s batch of the 2 GByte of raw data. Similar interferences are merged together if they occur in subsequent batches of data. Despite this additional precaution, the majority of events are the same reoccurring interferences. A low diversity of interferences is therefore observed. Many chirp like events (especially "pulsed chirps"), as well as tone interferences have been detected and characterized. An overview about the amount and type of interference found per measurement day is depicted in Fig. 7[4].

Figure 8 shows the number of occurrences for different times in the week[5]. In this graph, it can be seen that the interferences are fairly constant for the day in the week. The most interferences occur during the daytime, with the peak over noon; however, there are a large number of interferences measured between 23:00 and 1:00 at night as well.

Similar interferences can be associated together to simplify the analysis of the interferences. For example, a pulsed interferer with a pulse width of 31 μs and a PRI of 3.2 ms (i.e. duty cycle of approximately 1 %) was observed 219 times during the measurement campaign. These pulses contained a linear chirp with a bandwidth 1.26 MHz and a chirp rate of 66.4 MHz/ms.

This data analysis can be used to create a profile for the given environment, which can aid in the understanding of the environment and provide the means to mitigate site-specific interferences.

Even though a large number of interference occurrences have been observed, a longer measurement campaign will be required to be able to make decisive conclusions for the given area and system settings.

In the following, some exemplary interferences detected in the current measurement campaign are analyzed and discussed:

Pulsed chirps

Figure 9(a) shows the spectrogram of a wide-band chirp (L2 band with center frequency 1.2325 GHz and 38 MHz analog bandwidth). The intensity of the spectrogram is the power spectral density in dB/Hz. The chirp is a symmetric pulsed chirp (i.e. with each pulse the chirp moves in the opposite direction), with a PRI of 0.5 ms and a pulse width of 20 μs. This is a non-traditional interference for GNSS.

Figure 9(c) shows the spectrogram of a narrow-band chirp detected in the same band. This interference is a non-linear pulsed chirp, and moves in the same direction each time. The chirp is classified as non-linear due to the flattening of the edges.

[3] The geodetic antenna attenuates all signals under an elevation of 15 ° (i.e. ground based signals like the interferences to be monitored / detected) by approximately 20 dB.

[4] Results for only Configuration 1 are shown in the figure. The "gaps" in the dates are caused when the system was set to Configuration 2.

[5] This represents the data over the mentioned measurement campaign.

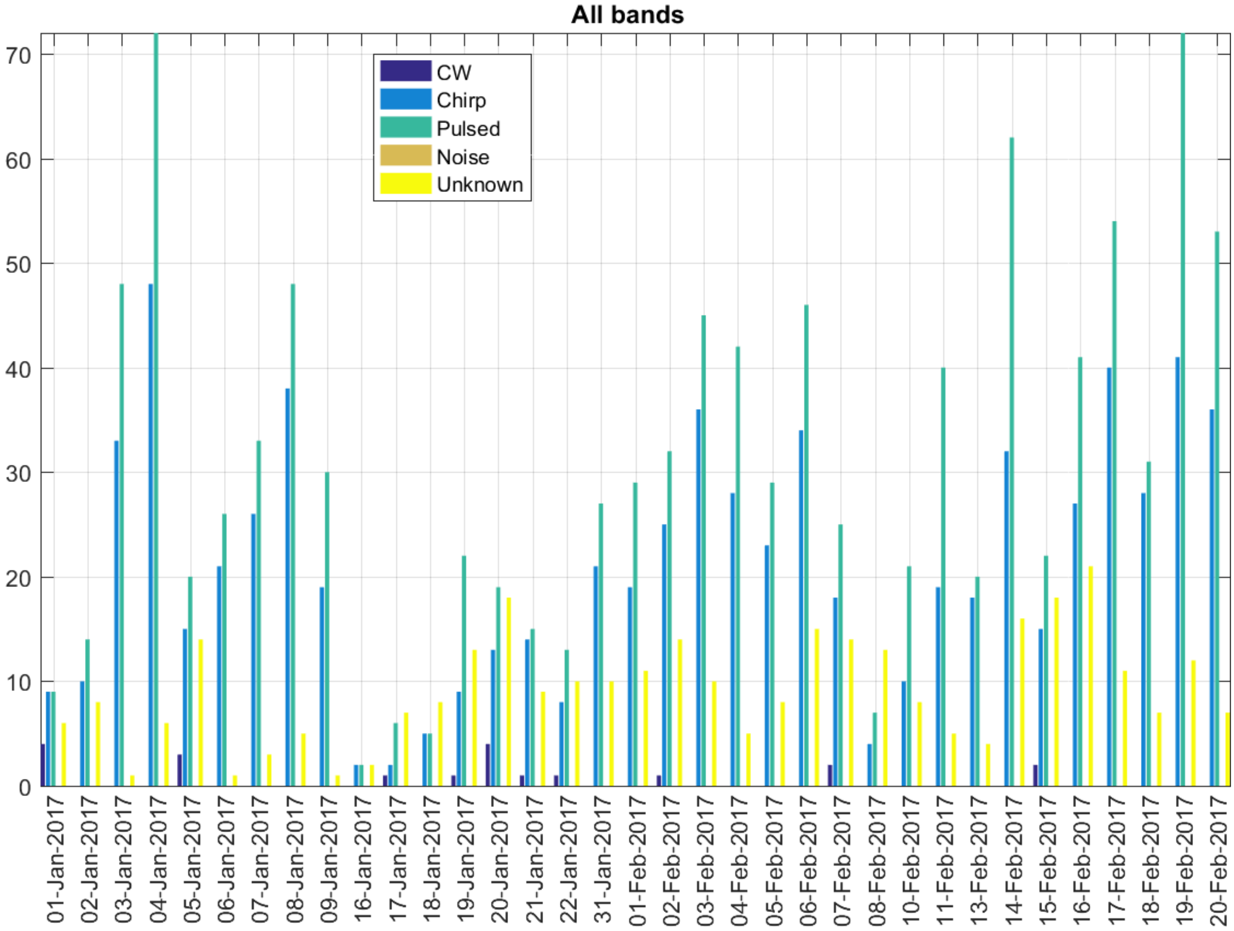


Figure 7. Found and characterized interferences within the measurement campaign

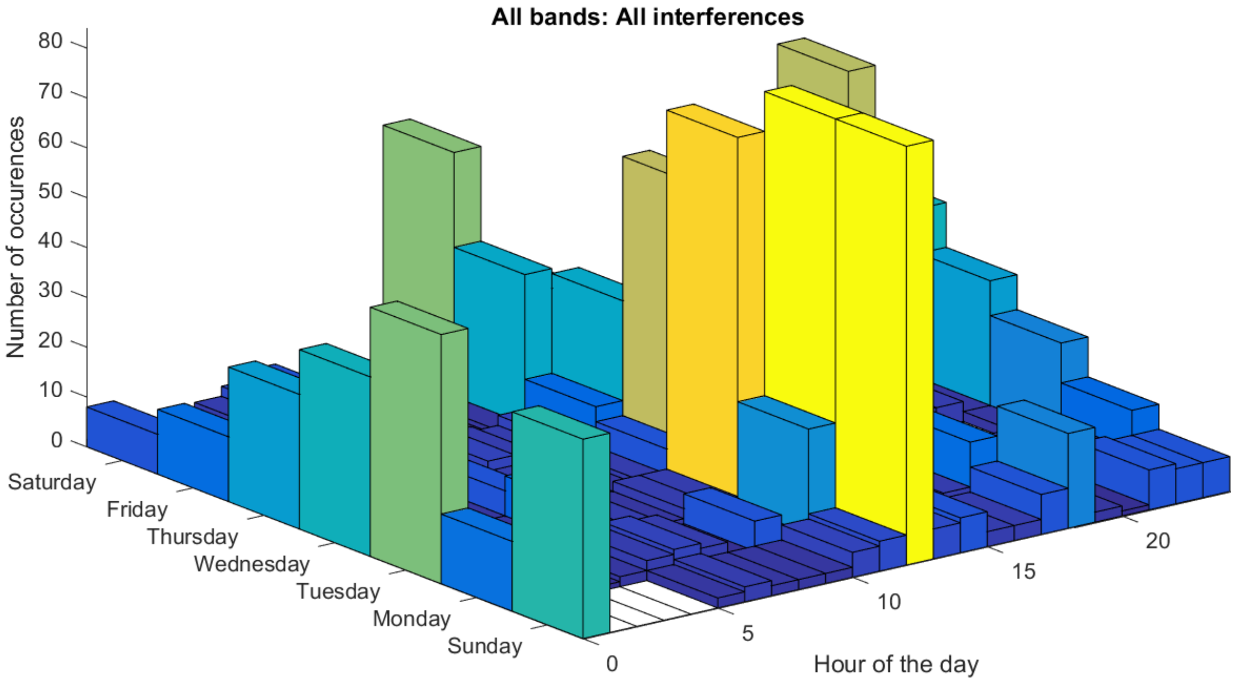
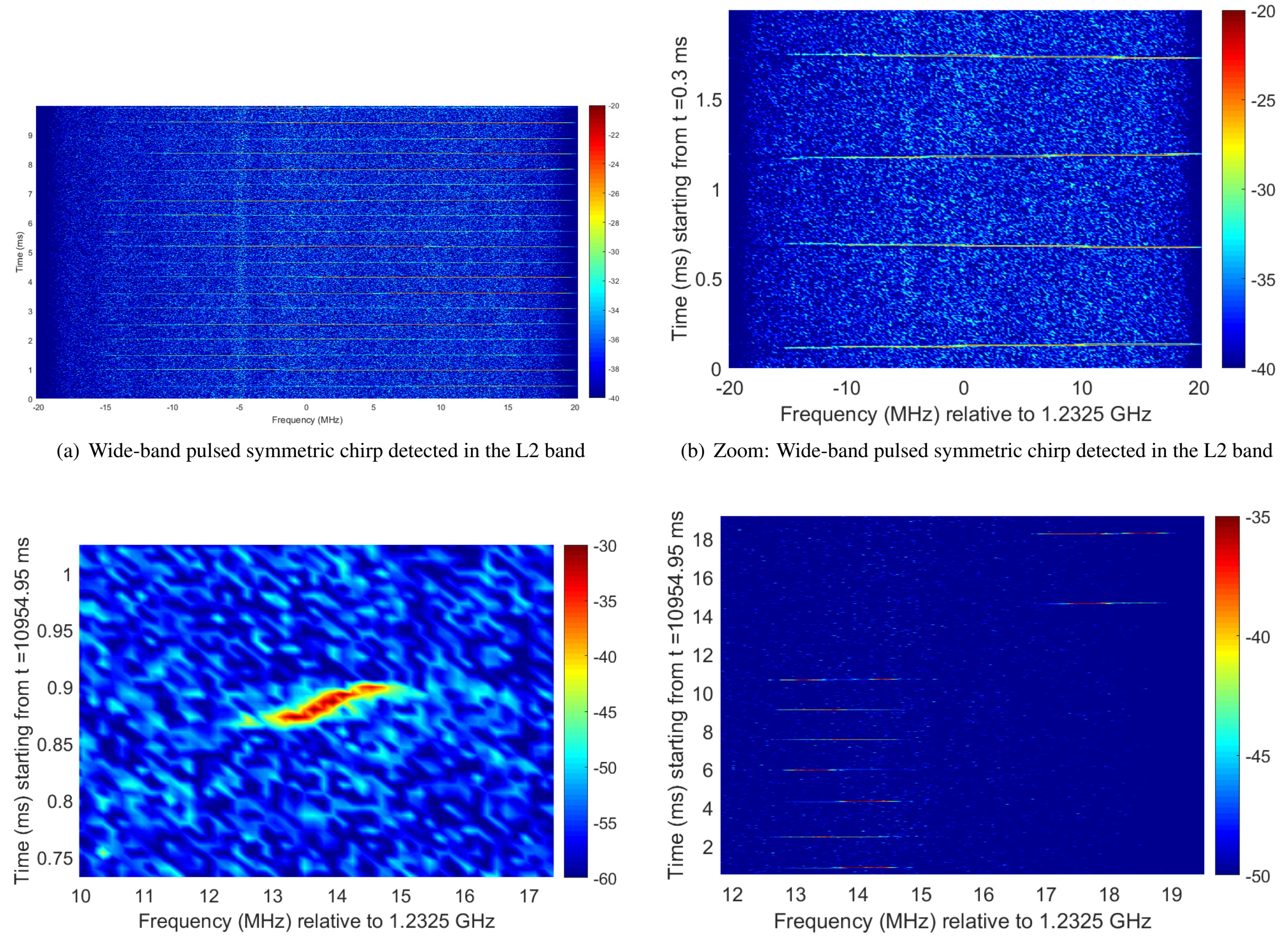


Figure 8. 2-D histogram for the number of occurrences for a given weekday and hour in all frequency bands



(a) Wide-band pulsed symmetric chirp detected in the L2 band

(b) Zoom: Wide-band pulsed symmetric chirp detected in the L2 band

(c) Narrow-band pulsed non-linear chirp detected in the L2 band

(d) Narrow-band pulsed non-linear chirp with irregular pulse structure detected in the L2 band

Figure 9. Wide- and narrow-band chirp examples

Figure 9(d) shows the same chirp on a larger scale. As seen here, the PRI changes as well as the center frequency of the pulsed interference. The initial PRI is 1.6 ms, then changes to 3.6 ms. The initial center frequency is 13.77 MHz, relative to the local oscillator (LO), then changes to 18 MHz. Both chirps have the same shape and a bandwidth of approximately 2.2 MHz. This indicates the occurrence of a dynamic interference. Such types of interferences are difficult to mitigate due to the changing nature of the pulses. These types of interferences are also difficult to classify, as they have varying parameters and appear to be two distinct interferences.

Figure 10(a) shows the spectrogram of a paired narrow-band chirp (Rx#3 reception band for E6 band with center frequency 1.2787 GHz and 54 MHz analog bandwidth). The interference consists of two chirps with the same chirp rate and bandwidth, but operating at different center frequencies. The first center frequency is 15.9 MHz relative to the LO, and the second is 0.95 MHz. Both chirps have the same form and a bandwidth of approximately 1.1 MHz.

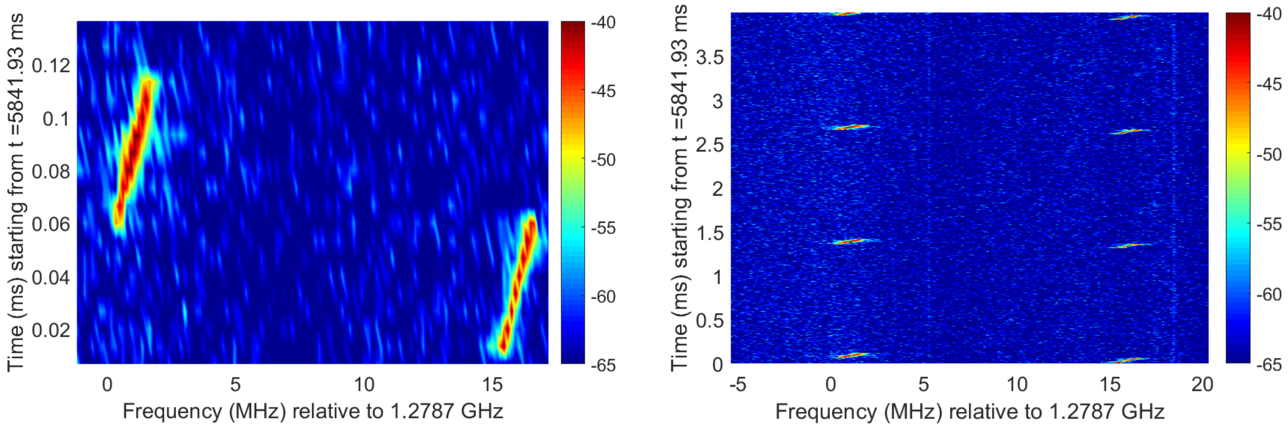
Figure 10(b) shows the same interference, but note that the two chirps have the same PRI and pulse width, which indicates that these signals are indeed from the same source.

Single Tones

Figure 10(c) shows the spectrogram of a ST (Rx#3 reception band for E6 band with center frequency 1.2787 GHz and 54 MHz analog bandwidth). This tone was visible for the full 13 s batch of data recorded.

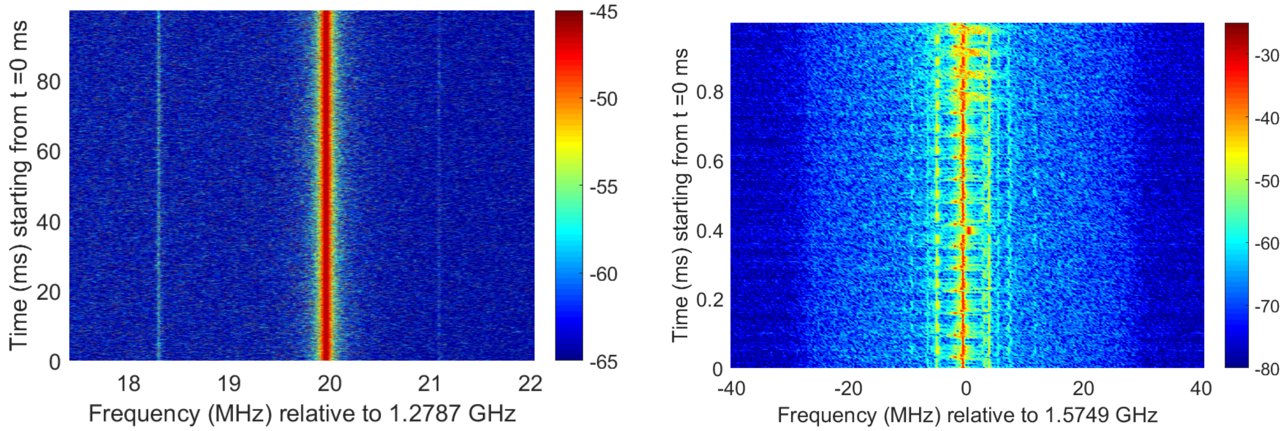
Unknown

Figure 10(d) shows the spectrogram of a unknown interference (Rx#2 reception band for E1 band with center frequency 1.5749 GHz and 54 MHz analog bandwidth). In this case, the interference is a CW, and some periodic elements are visible which may indicate that it is an interference. In the analysis of the data, it is shown that the received signals are so strong that it pushes the receiver into saturation. This indicates that saturation has a profound impact on interference classification methods and limits receiver performance.



(a) Paired pulsed chirp interference detected in the E6 band

(b) Paired pulsed chirp interference, detected on the E6 band



(c) Single tone continuous wave interference, detected on E6 band

(d) Unknown continuous wave interference, detected on E1 band

Figure 10. Pulsed chirps and continuous wave interferences examples

CONCLUSION

A GNSS interference detection station which monitors continuously and automatically across the entire GNSS signal bands has been presented. The station operates with broad bandwidths (up to 80 MHz) and a dynamic of up to 8 bit I/Q. The recorded raw data can also be saved on hard disk for off-line post-processing and analysis. A major feature of the station is that the architecture allows the user to implement their own detection and characterization algorithms.

The characterization methodology and algorithms were presented. The main aim was to show that interferes are increasingly more complex and difficult to analyze. Accordingly, the classification methodology should be adapted to progress with the development of interferences.

Some detected events in Nuremberg, Germany were presented and discussed. This presents the operational capabilities of the system, as well as the occurrence of non-traditional interferences.

The results obtained in the first weeks of a measurement campaign using this system were presented. It was noted that the L2 and E6 frequency bands suffer from many, most-likely non-intentional, interferences that cannot be assigned to a specific event.

For further research, we propose to evaluate the long term statistics, using a GNSS antenna turned towards the motorway in Nuremberg, Germany. This will result in more insights towards potential interference events. Determining the sources of the interferences, with focus on the local spectrum allocation, is proposed as future analysis of the station. Moreover, the actual impact of the interference on the GNSS performance should be assessed, e.g. using the spectral separation coefficient (SSC) and calculating the effective C/N0 as a function of the interference detected.

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