

# Characterization of Integrity Threats in Terrestrial Applications Using Real Signal Captures

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## BIOGRAPHY

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**Denis Naberezhnykh** received the BSc. degree in Physics from the Royal Holloway, University of London and is the Head of Low Carbon Vehicle and ITS technology at TRL. Denis has worked on numerous trials and test campaigns for the evaluation of GNSS-based vehicle OBUs, including Road Pricing OBUs.

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**Juan Pablo Boyero** is since 2012 working at the EC in the definition of the evolution of the Galileo and EGNOS missions,. Before he worked for nearly ten years in the private sector as Navigation Engineer, holding responsibilities within the Galileo System Performance area and acting both as System Prime as well as Technical Support to System Prime. He holds a MSC by the Escuela Técnica Superior de Ingenieros de Telecomunicación of the Universidad Politécnica de Madrid. Amongst the

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**Ignacio Fernandez** is currently responsible for the Galileo Commercial Service at the EC. Before, he was responsible of the receivers R&D activities at GSA and EC, time at which he launched the Integrity GNSS Receiver project. He has a MSC in Electronic Engineering by ICAI, Madrid, and a MBA by London Business School.

## ABSTRACT

The Integrity GNSS Receiver (IGNSSRX) is a European Commission funded project with three main objectives:

- a) The development of two platforms to capture and store GNSS radio frequency signal samples and a reference trajectory from representative low-, medium- and high-end sensors in terrestrial applications.
- b) An extensive data collection campaign aiming to characterize error sources, magnitudes and probabilities for two important GNSS terrestrial application areas: automotive and pedestrian users.
- c) The research and development of techniques and algorithms to mitigate the integrity threats in the two terrestrial environments studied using the collected data, thus allowing reliable terrestrial applications within these domains.

This paper presents the results for the first two objectives of the IGNSSRX project, providing the GNSS measurement error characterization results obtained from the analysis of the real data collected using the developed platforms during the acquisition campaign, together with a preliminary report on the developed techniques and algorithms.

### *Data Collection Platforms*

Two Data Acquisition and Storage Units (DASU) have been developed within the IGNSSRX project for the data collection campaign in the vehicular and pedestrian domains:

- Vehicular DASU:
  - RF Front-Ends: a high resolution FE and a three-antenna FE system working both in the GPS L1 and Galileo E1 bands and the GLONASS L1 band. The high-resolution FE allows the application of DSP techniques to detect the integrity threat and the three antenna array allows the use of the direction of arrival (DOA) information to identify non line-of-sight (NLOS) signals.
  - Record raw data from medium and low cost COTS sensors, such as IMUs and odometer, for PVT hybridisation with GNSS as well as to

provide a reference of the performance or representative medium and low cost solutions used in these applications

- Truth reference equipment using a high accuracy/high availability reference system based on high geodetic-grade GPS&GLONASS dual-frequency receiver, tactical-grade IMU and digital wheel probe, processed using a dedicated COTS post-processing software.
  - Common atomic clock (CSAC Caesium clock) synchronizing the platform with the truth reference equipment.
- Pedestrian DASU:
    - RF Front-Ends: a high resolution FE in the GPS L1 and GLONASS L1 bands.
    - Records GSM and Wi-Fi measurements to augment/hybridise with GNSS and mobile phone platform as a COTS reference
    - Truth reference equipment based on a GPS&GLONASS L1/L2 geodetic receiver plus route trace.
    - Common atomic clock (CSAC Caesium clock) synchronizing the platform with the truth reference equipment.

### *Data Collection Campaigns*

Using the two DASU an extensive data collection campaign has been carried out covering representative road and pedestrian user environments:

- Vehicular campaign: fourteen days of road data collection covering a motorway route with open sky (best case), and an urban route through typical city environments with canyons and tunnels.
- Pedestrian campaign: a number of different routes around city areas in three cities. Of these routes there are two "city centre" routes, where there is a mixture of closely spaced buildings, covered arcades and wider roads; two in "out of town" shopping centres with large car parks for initialisation and limited visibility in the remaining of the route; and a rural/suburban route around a park area.
- Interference campaign: the collected data is complemented by tests performed with a signal simulator to test the impact of interferences and spoofing.

### *Offline Analysis Unit (OAU)*

Based on the SRX software receiver [1] for processing the collected RF samples and by taking advantage of the accurate reference system and a common reference atomic clock integrated in the DASU platforms, the measurement errors (code, carrier phase and Doppler) can be accurately determined, and by using precise orbit, clock and ionosphere data from reliable sources (such as the IGS) it is possible to distinguish between local and non-local error contributions. DSP techniques applied to the collected RF samples allow identifying the nature of the local sources of error or interferences (e.g. by means

of spectral and temporal analysis of the signals, multi-antenna analysis, etc.).

### Characterization Results

Data analysis, aimed at identifying and characterising the integrity threats in terrestrial environments, has been performed. This analysis allows the construction of real-data scenarios which encapsulate the failure events encountered.

Considerable research has been already done in other projects analysing urban threats to GNSS positioning, but little emphasis has been put on measurement error characterisation, especially with regard to the integrity implications. This is quite possibly due to the complexity and variety of error sources in urban environments, and the great difficulty associated with the discrimination of the actual error sources in the individual measurements.

The sophisticated vehicular and pedestrian Data Acquisition and Storage Unit (DASU) platforms and the Offline Analysis Unit (OAU) enable the detailed study and characterisation of threats at both signal and measurement levels. Special attention is paid to those threats known to be major causes of positioning error in harsh environments, such as NLOS tracking, multipath, spoofing and interference.

Summarizing, this paper presents the platforms developed to collect real measurements along with the tools used for their analysis and provides the characterization of the integrity threats affecting GNSS terrestrial applications.

## INTRODUCTION

Personal navigation is becoming cheap and ubiquitous and as a result the GNSS market is exploding with new applications. Having extended to the mass market and being the population concentrated in the cities most of these applications take place in harsh environments. Also some applications involve liabilities (e.g. road tolling) and the key enabler to liability-critical applications is integrity, which should be achieved while maintaining the low-cost of the positioning equipment. Therefore, evolving the land user applications will require highly reliable and low cost navigation solutions.

Liability critical applications are non-safety-of-life applications which still require some level of integrity (with a relaxed integrity risk and a relaxed time-to-alarm if they are compared with aeronautical integrity). Local effects are the primary cause of signal degradation in cities so these applications require a robust and reliable positioning solution capable of delivering high integrity in urban conditions, with restricted sky visibility and with high levels of multipath and NLOS.

Integrity GNSS Receivers (IGNSSRX) is an EC project aiming to research on algorithms to mitigate the integrity

faults in terrestrial environments. With that purpose, IGNSSRX has the following three main objectives:

- Develop a platform able to monitor and store GNSS radio frequency signal samples and a reference trajectory.
- Perform an extensive real data collection campaign.
- Research and develop algorithms to mitigate the integrity faults in terrestrial environments.

In order to accomplish the objectives the IGNSSRX project is divided in the following phases:

- Platform Development
- Extensive Real Life Data Collection
- Analysis and Characterization
- Integrity Research
- Prototype

This paper presents the results obtained in the first three phases.

## DATA COLLECTION PLATFORMS

A key aspect to provide an integrity service in terrestrial environments is to understand and characterise the user environment, mainly in terms of signal multipath and interference. With this purpose in mind a significant effort in the project has been devoted to the development of an Environment Monitoring, Storage and Analysis Unit (EMSAU), used to sample data from different environments, analyze the results and validate the integrity algorithms. In order to do that, the developed EMSAU is able to acquire and store digital samples of the radio frequency environment using RF Front-Ends (FEs), provide an accurate reference trajectory, and replay and analyse the data offline able to characterise multipath and interference events.

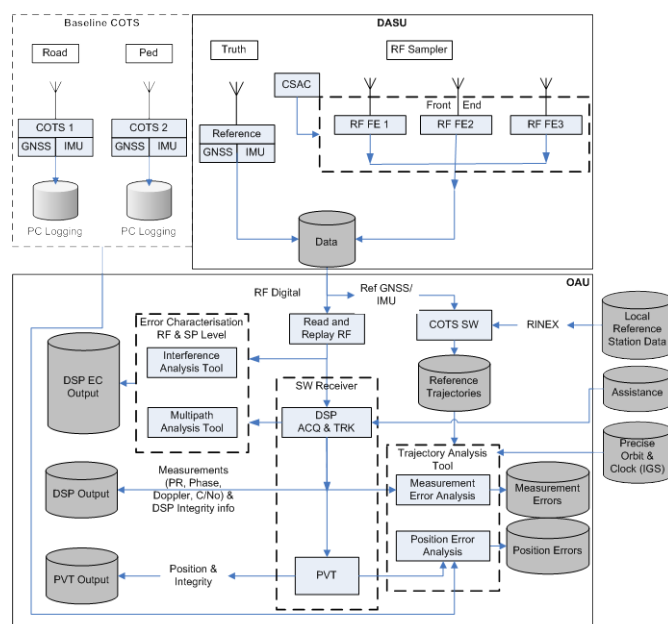


Figure 1- EMSAU Overview

The EMSAU platform is composed of two main elements, as described in Figure 1:

- Data Acquisition and Storage Unit, in charge of collecting the data
- Offline Analysis Unit, in charge of analyzing the collected data.

This section will describe the Data Acquisition and Storage Unit (DASU) developed in the project, while the Offline Analysis Unit (OAU) is described in the Offline Analysis SW section after describing the collection campaigns carried out.

Regarding the land user applications, two different types of users have been identified according to the platform they use, vehicular and pedestrian. As a consequence, two different types of DASU platforms have been developed:

- Vehicular DASU
- Pedestrian DASU

### Vehicular DASU

Figure 2, Figure 3 and Figure 4 provide a description of the platform architecture, elements and assembly on the car used for the vehicle data collection.

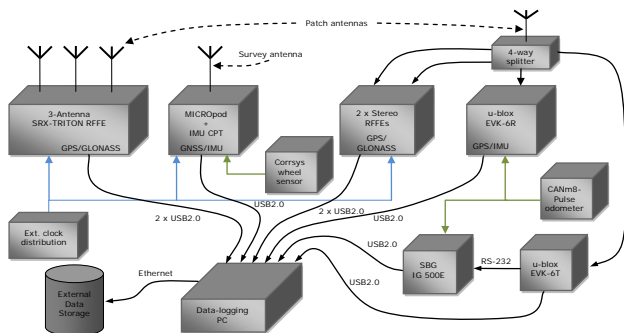


Figure 2- Vehicular DASU Architecture



Figure 3- Vehicular DASU Elements



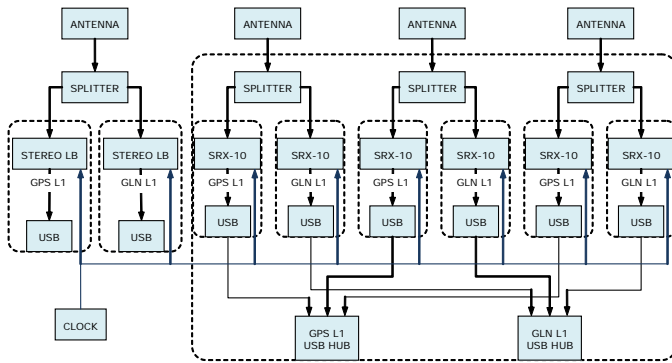
Figure 4- Vehicular DASU Assembly

The vehicular platform has been developed with the following elements:

- The truth reference trajectory and attitude is provided by a NOVATEL GPS&GLONASS L1/L2 with SPAN-CPT and wheel sensor:
  - Novatel Micropod OEMV-3+MPPC / CPT-IMU / GPS-702-GG antenna
  - Corrsys-Datron WPT1000 Incremental Wheel Pulse Transducer (DMI) for test car
- A common atomic clock is used to synchronize all the elements:
  - Symmetricom SA.45s CSAC
- Two types of RF Front-Ends are used to collect RF samples in the GPS L1 band (also containing Galileo E1 signals) and in the GLONASS L1 band:
  - High resolution (8-bits) GPS&GLO RF FE: *STEREO* [2]
  - Three-Antenna GPS&GLO low resolution (1-bit) RF FE: *SRX-TRITON* [3]

The Front-Ends architecture and their configuration are described in Figure 5 and Table 1.

- RFFE Antennas: 4 x Tallysman TW2400 patch antenna mounted on roof antenna rack
- Low and Medium cost INS:
  - u-blox EVK-6R (Low cost)
  - SBG IG500E (Medium cost)
- Raw GPS Measurements (u-blox): u-blox 6T
- CANm8 - PULSEx4 Vehicle CAN bus speed signal to frequency converter.
- Data Logging computer:
  - Commell LV-67K mini ITX industrial motherboard system 2 x 1TB HDD memory
- Data Storage unit where the data is allocated after each collection day:
  - 24TB RAID 6 NAS (QNAP TS-879U-RP 32TB 2u Rack NAS)
- Umbilical user interface:
  - Cabin user interface for initialisation and logging status (umbilical)
  - LED combinations for unit states and potential sources of error



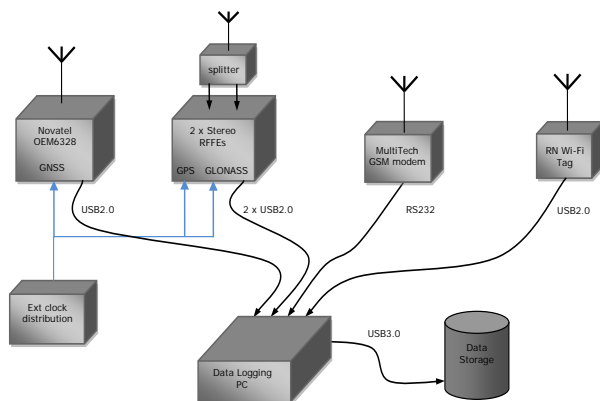
**Figure 5- Vehicular DASU RF Front-Ends Architecture**

RFFE Configuration for Vehicular DASU	
STEREO 1 LB chain (high resolution GPS L1 sampling)	<ul style="list-style-type: none"> <li>• IF bandwidth: 4 MHz</li> <li>• ADC quantization: 8 bits</li> <li>• ADC sampling rate: 10.28 Ms/s I</li> <li>• Data throughput: 10.28 MB/s</li> </ul>
STEREO 2 LB chain (high resolution GLONASS L1 sampling)	<ul style="list-style-type: none"> <li>• IF bandwidth: 10 MHz</li> <li>• ADC quantization: 8 bits</li> <li>• ADC sampling rate: 21.576 Ms/s I</li> <li>• Data throughput: 21.576 MB/s</li> </ul>
SRX-10 Three-antenna RFFE (DOA studies)	<ul style="list-style-type: none"> <li>GPS L1 chains</li> <li>• IF bandwidth: 4.2 MHz</li> <li>• ADC quantization: 1 bit</li> <li>• ADC sampling rate: [10] Ms/s I</li> <li>• Data throughput: 3.75 MB/s</li> <li>GLONASS L1 chains</li> <li>• IF bandwidth: 9.6 MHz</li> <li>• ADC quantization: 1 bit</li> <li>• ADC sampling rate: [20] Ms/s I</li> <li>• Data throughput: 7.5 MB/s</li> </ul>

**Table 1- Vehicular DASU RF Front-Ends Configuration**

### Pedestrian DASU

Figure 6 and Figure 7 provide a description of the platform architecture, elements and assembly in the pedestrian rucksack.



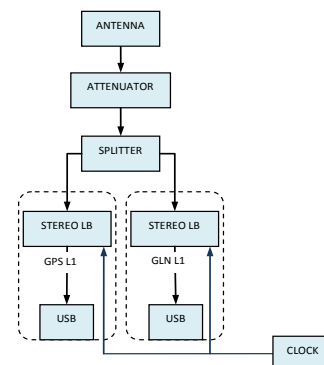
**Figure 6- Pedestrian DASU Architecture**



**Figure 7- Pedestrian DASU Elements and Assembly**

The pedestrian platform has been developed with the following elements:

- The truth reference trajectory and attitude is provided by a NOVATEL GPS&GLONASS L1/L2:
    - Novatel OEM628-D2S-00G-0T0
    - GPS-702-GG antenna (hidden within the rucksack)
  - A common atomic clock is used to synchronize all the elements:
    - Symmetricom SA.45s CSAC
  - RF Front-End used to collect RF samples in the GPS L1 band (also containing Galileo E1 signals) and in the GLONASS L1 band:
    - High resolution (8-bits) GPS&GLO RF FE: *STEREO* [2]
- The Front-Ends architecture and their configuration are described in Figure 5 and Table 1.
- RFFE Antennas: Tallysman TW2400 patch antenna mounted within the rucksack
  - Wi-Fi Modem: Roving networks RN-171
  - GSM Modem: Multitech MTSMC-G2-ED, Orange PAYG SIM
  - Data Logging computer:
    - Commell LV-67K mini ITX industrial motherboard system 2x512GB SSD memory
  - Data Storage unit where the data is allocated after each collection day:
    - 6TB RAID 5 (Qnap TS-412 8TB NAS)
  - Umbilical user interface:
    - User interface for initialisation and logging status (umbilical)
    - LED combinations for unit states and potential sources of error



**Figure 8- Pedestrian DASU RF Front-Ends Architecture**



RFFE Configuration for Pedestrian DASU	
STEREO 1 LB chain (high resolution GPS L1 sampling)	<ul style="list-style-type: none"> <li>• IF bandwidth: 4 MHz</li> <li>• ADC quantization: 8 bits</li> <li>• ADC sampling rate: 10.28 Ms/s I</li> <li>• Data throughput: 10.28 MB/s</li> </ul>
STEREO 2 LB chain (high resolution GLONASS L1 sampling)	<ul style="list-style-type: none"> <li>• IF bandwidth: 10 MHz</li> <li>• ADC quantization: 8 bits</li> <li>• ADC sampling rate: 21.576 Ms/s I</li> <li>• Data throughput: 21.576 MB/s</li> </ul>

**Table 2- Pedestrian DASU RF Front-Ends Configuration**

### Encountered Problems

A wide range of problems had to be solved during the design, development, integration and validation of the DASUs due to their high complexity and the great amount of generated data (vehicular: 43.1MB/s and pedestrian 31.8MB/s). Apart from taking special care in the design to ensure that all the data throughput could be stored and having to cope with important delays in the procurement of some of the elements and also with some malfunctioning HW, one of the critical steps was the validation of the platform. Three were the main problems encountered, thoroughly analysed and successfully solved:

- The wheel sensor, which besides feeding the truth reference was initially also feeding the SBG, generated a rate of pulses too high for the SBG but only when the car was travelling at high speeds, this was not detected at design level due to a problem in the documentation of the interfaces. Finally, the SBG was connected to the car odometer using a CANM8-PULSE.
- Although the CSAC clock and almost all the elements were protected from the external power source (vehicle battery) with a converter/regulator, the clock distribution unit was not completely protected, which provoked C/N0 drops when processing the samples recorded by one of the FEs. Once the cause was found out, an additional DC-DC converter was used to protect all the elements.
- In the initial assembly of the pedestrian platform, the PC motherboard generated some interference that affected the FE. After testing different configurations, the problem was solved with the final assembly.

## DATA COLLECTION CAMPAIGNS

Several thorough data collection campaigns have been carried out using the DASU platforms. The purpose is to allow a better understanding of the terrestrial environment threats or feared events for satellite radionavigation in terrestrial environments.

Two types of GNSS vulnerabilities are considered to impact on terrestrial applications:

- Poor satellite reception:

- Dense urban environments often called “urban canyons” – created by a combination of tall buildings on both sides of the road and narrow roads (partial signal obscuration, multipath and NLOS)
- Reflective buildings (multipath and NLOS)
- Dense forestation – tall trees on both sides and over the top of the road (partial signal obscuration)
- Tunnels – (signal obscuration)
- Interference experienced by GNSS receivers that can affect integrity of positioning. It can be classified into three categories:
  - Unintentional
  - Intentional (Jamming)
  - Intentional (Spoofing)

Hence, the performed data collection has covered different environments representative for each user type:

- Vehicle Data Collection: motorway and urban
- Pedestrian Data Collection: sub-urban, urban and indoor

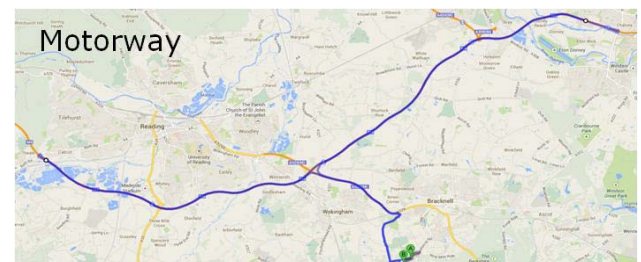
However, the probability of capturing interference signals in real environments is low, even in selected areas. Furthermore, even if interference events are detected, it will be hard to ensure that they are characterised correctly on their own, as the actual type of interference would be unknown. Therefore, a complementary data collection has been carried out:

- Interference Data Collection, described below.

### Vehicle Data Collection

The vehicle data collection was performed repeating two different routes, motorway and urban, between April and July of 2014:

- *Motorway*: the route starts from TRL’s office and goes along M4 as shown in Figure 9, is 92km in length and takes 64 minutes in free flow traffic.
- *Urban*: consists on a city drive in London from Hammersmith towards Tower Bridge and returning back to Hammersmith as shown in Figure 10. It contains urban canyons and a 300 meter tunnel. The route is 24km in length and it is a 59 minute drive in free flow conditions. However during the testing, average route cycle time was approximately 2 hours 30 minutes due to start-stop traffic.



**Figure 9- Vehicle Data Collection: London Motorway route**



Figure 10- Vehicle Data Collection: London Urban route

Table 3 summarizes the total amount of data collected in each type of environment. The data was collected alternating different antenna separations:  $\lambda/2$ ,  $\lambda$  and  $2\lambda$ .

Route	Hours
Urban	79:41
Motorway	32:19
<b>Grand Total</b>	<b>112h</b>

Table 3- Road: Amount of Data Collected

### Pedestrian Data Collection

The pedestrian collection campaign was carried out in Nottingham, Leeds and Madrid between the dates of 18 June and 24 July 2014 and covering a range of sub-urban, urban and indoor (shopping centres) scenarios. The amount of collected data in each environment is detailed in Table 4.

Route	Number of Loops	Recorded Time
NG1 – Nottingham City Centre	31.75	10.67 hours
LS1 – Leeds City Centre	32	18.99 hours
NG2 – Nottingham sub-urban	10.25	3.72 hours
NG8 – Nottingham sub-urban	4	4.80 hours
Alcalá de Henares (Madrid) - indoor	27.5	13.77 hours

Table 4- Pedestrian: Amount of Data Collected

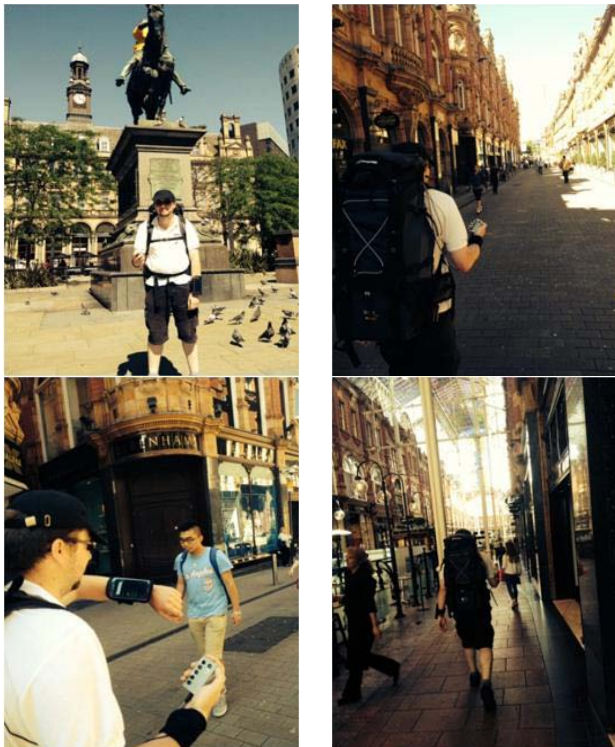


Figure 11- Pedestrian Data Collection: Leeds

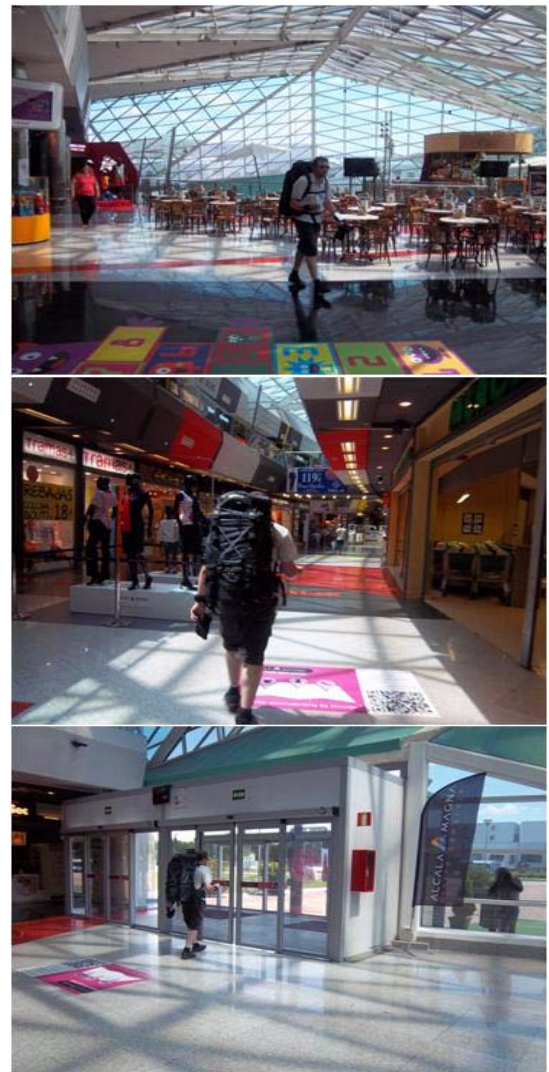


Figure 12- Pedestrian Data Collection: Alcalá de Henares (Madrid)

In the Alcalá Magna shopping centre additional indoor navigation data was collected using WIPODE, a Wi-Fi based indoor navigation solution consisting on a mobile application that provides indoor positioning using the Wi-Fi signals received from the routers placed along the shopping centre (see [4] for further details):



Figure 13- Pedestrian Data Collection: Indoor Navigation with WIPODE

### Interference Data Collection

The interference collection campaign was carried out at the EC Joint Research Centre (JRC) in Ispra (Italy) during July 2014. Two different interference scenarios were tested:

- Jamming
- Spoofing



### Jamming

The jamming scenarios were tested using the STEREO 8-bit RF FE [2] covering those interferences consisting on non-navigation-like signals with the potential of disrupting or degrading the performance of GNSS receivers, comprising both unintentional and the intentional interferences. Table 5 provides an outline of the jamming scenarios configured and tested at the JRC and Figure 14 shows the jamming tests set-up.

Type of Jamming Interference	Tested Interference Parameters	Representative Threat
CW (sinusoid Non-Pulsed)	Two frequencies and six different $I/N_0$ for each frequency.	Spurious or harmonic interferences
CW (sinusoid Pulsed)	One frequency, six pairs of PRF and PW values, and two different $I/N_0$ values for each pair.	Radio-navigation radars
Chirp (Non-Pulsed)	One frequency, six pairs of BW and SP values, and nine different $I/N_0$ values for each pair.	Intentional sweep jammers
Chirp (Pulsed)	One frequency, one duty cycle, five different BW, and two different $I/N_0$ values for each BW.	Space-borne or surveillance radars.
Wideband (In-band)	One frequency, one BW and nine different $I/N_0$ values.	Wireless comm. Systems
Wideband (Out-of-band)	One frequency, one BW and nine different $I/N_0$ values.	Wireless comm. systems

Table 5- Interferences: Jamming Tests

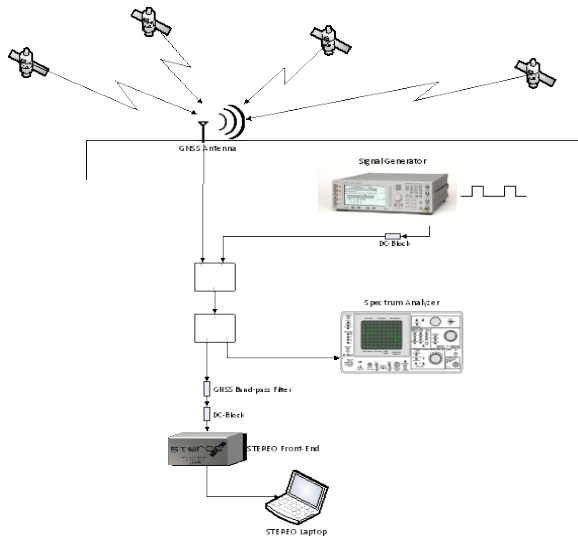


Figure 14- Interferences: Jamming tests set-up

### Spoofing

The aim of the spoofing data collection was to provide data to test a spoofing detection algorithm based on the direction of arrival of the spoofing signals, which would all come from the same direction. Thus, in order to simulate spoofing at the JRC EMSL anechoic chamber, the GNSS signals received by an antenna placed on the roof were re-broadcast inside the anechoic chamber using a single transmitter, which in some tests was static and in motion in others (see Figure 15 and Table 6). The GNSS signals were sampled using the SRX-TRITON Three-

Antenna FE ([3]) placed within the anechoic chamber and configured with an antenna separation of  $\lambda/2$ . Coming from the same source within the anechoic chamber, all the re-broadcast signals arrive to the FE antennas from the same direction (same DOA angle).

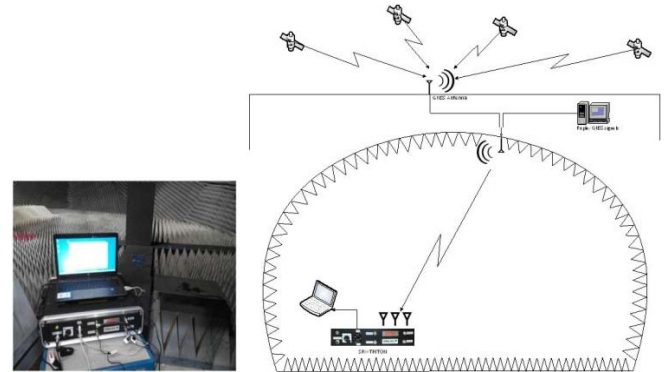


Figure 15- Interferences: Spoofing tests set-up

Retransmitted Signals	Transmitter position	Duration
Real GPS&GLONASS signals	Static transmitter (around 70° of elevation)	1h 20min
Real GPS&GLONASS signals	Moving transmitter (elevation starting at 70°, then 90° and ending at 20°)	20 min
Playback of GPS&Galileo IOV signals already recorded on the 16th of May 2014 (21:10:00)	Static (around 70° of elevation)	20 min

Table 6- Interferences: Spoofing Tests

Also, in order to improve the completeness of the data set collected within the project a scenario with GPS and Galileo IOV signals already recorded on the 16th of May 2014 was played back within the anechoic chamber and recorded with the three antenna single frequency FE (SRX-TRITON [3]).

### OFFLINE ANALYSIS SW

The data analysis is performed using the Offline Analysis Unit (OAU), which forms part of the EMSAU (see Figure 1). The OAU is formed by the following elements:

- Truth Solution Generation
- Error Characterisation at signal-processing level
  - Interference Analysis Tool (IAT)
  - Multipath Analysis Tool (MAT)
  - JINGO pre-correlation Interference Analysis Tool
- OAU SW Receiver (SRX10 [1])
- Trajectory Analysis Tool (TAT)
  - Measurement Error Analysis Tool
  - Position Error Analysis Tool
- TAT and SRX10 MMI

For a correct analysis it is very important to have an accurate reconstructed trajectory to be used as the truth reference. The reconstruction of the true trajectories is



based on NOVATEL post-processing tools. The followed approach has been different for each platform:

- Vehicle:
  - Waypoint Inertial Explorer
  - Multi-pass, forward and reverse, dual frequency GPS/GLN carrier phase processing with 100Hz IMU data and high resolution wheel probe data.
  - Base stations bound trial area
- Pedestrian:
  - Sub-urban: truth obtained by processing the OEM628 receiver outputs.
  - Urban and Indoor:
    - More challenging environments.
    - Incomplete coverage from the OEM628 receiver due to high obscuration
    - Truth derived based on interpolation between GNSS positions and Google Earth representation of route taken.
    - Height derived from OEM628 data in good coverage and Google Earth.

The collected RF samples are processed with the SRX10 GPS&GLONASS Software Receiver [1] providing measurements and PVT estimations.

The measurement and position errors are computed with the Trajectory Analysis Tools (TAT). The pseudorange and Doppler measurement errors are obtained taking into account that:

- The actual geometry range is obtained from reference trajectories and the reference satellite positions
- The ionosphere present in the measurements (single-frequency) is corrected using IONEX data
- The clock can be corrected as the RF samples are taken using an stable CSAC atomic clock

The TAT allows performing a statistical analysis of the errors for each satellite, constellation, time period, zone, etc. and taking into account elevation and C/N0. Thus, problematic periods with relevant discrepancies at the measurement/PVT level are identified and analyzed in detail with the Error Characterisation tools at RF and SP level.

The fault characterization in the signal processing domain comprises:

- Multipath Characterization - Multipath Analysis Tool (MAT)
  - Analysis of C/N0
  - Analysis of the Code Discriminator Output (DLL)
  - Analysis of the Correlation Peak:
    - Slope Asymmetry Metric (SAM)
  - Analysis of the Code NCO Output
    - NCO and Truth Ranges Difference (NTRD)
  - Multi-Antenna Analysis
- Interference Characterization - Interference Analysis Tool (IAT)
  - Statistical Analysis (Stationary Characterization)
    - Histogram

- Kurtosis
- Autocorrelation function (ACF)
- Time-Frequency Analysis TFA (Non-Stationary Characterization)
  - Spectrogram
  - Wigner-Ville distribution (WV)
- Cyclic Autocorrelation Function CACF (Cyclostationary Characterization)
- Multi-Antenna Analysis

## CHARACTERIZATION RESULTS

A first characterization is provided in this section, it will be completed by the end of the project, together with the research in integrity algorithms.

### Measurement and Position Error Characterization:

The pseudorange and Doppler errors along with the position errors have been characterized using the Trajectory Analysis Tools (TAT). These tools allow several types of analysis. The following figures show an example of some of them.

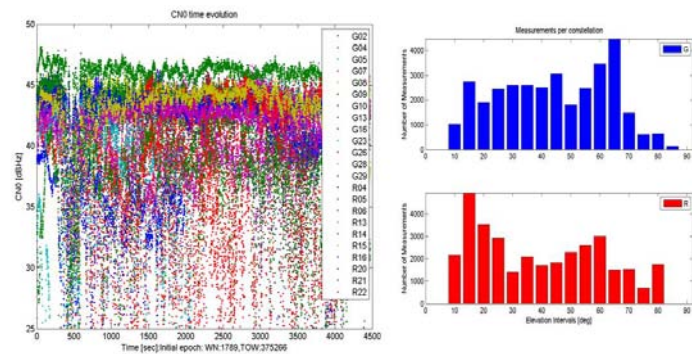


Figure 16- TAT: C/N0 and Elevation - Motorway

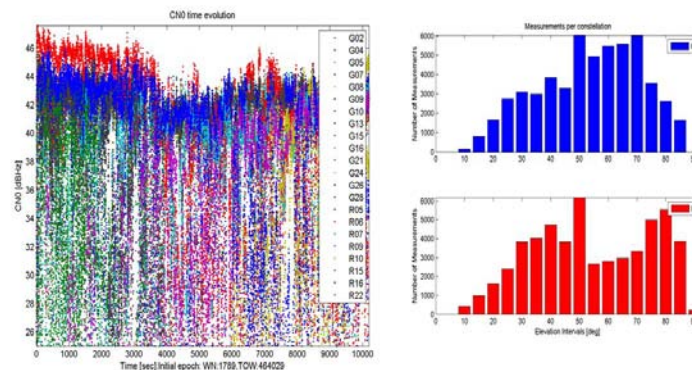


Figure 17- TAT: C/N0 and Elevation - Urban

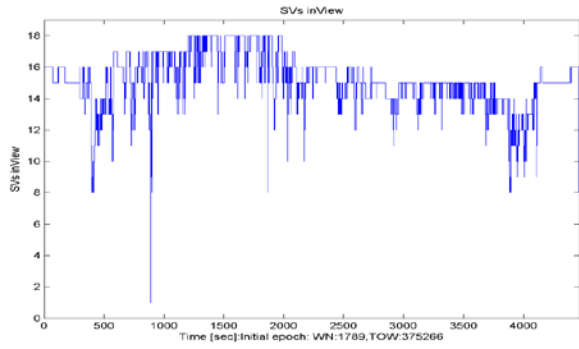


Figure 18- TAT: SVs in view - Motorway

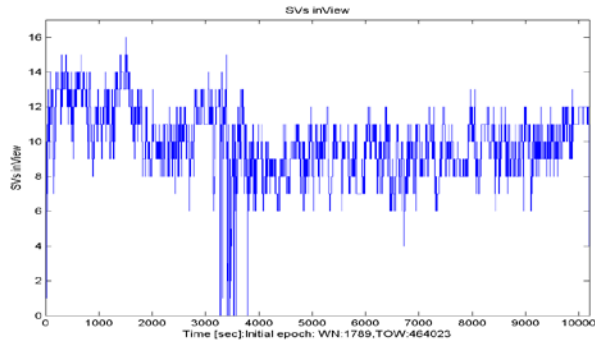


Figure 19- TAT: SVs in view - Urban

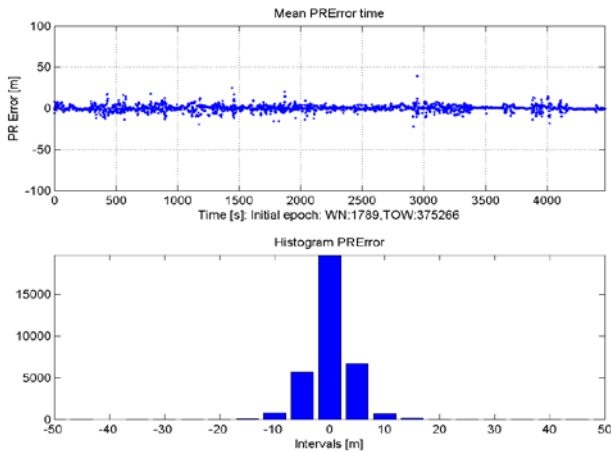


Figure 20- TAT: Pseudorange Error - Motorway

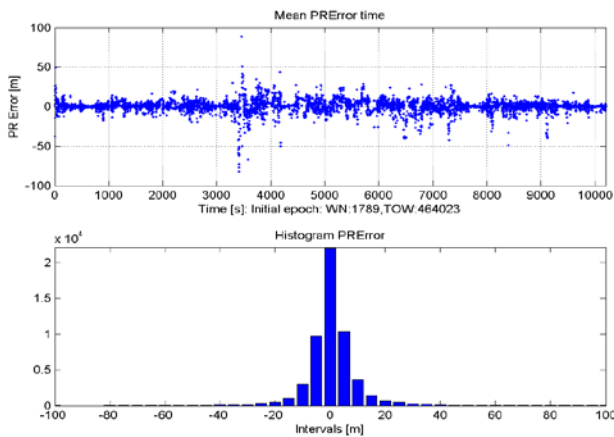


Figure 21- TAT: Pseudorange Error - Urban

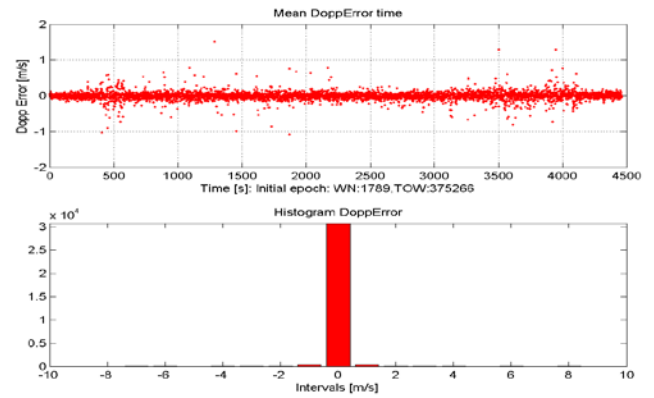


Figure 22- TAT: Doppler Error - Motorway

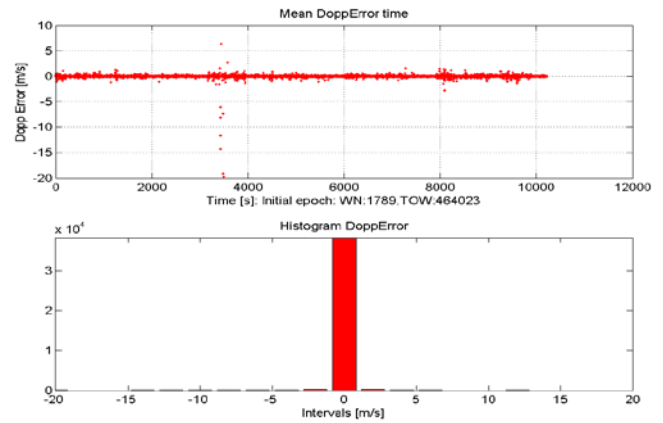


Figure 23- TAT: Doppler Error - Urban

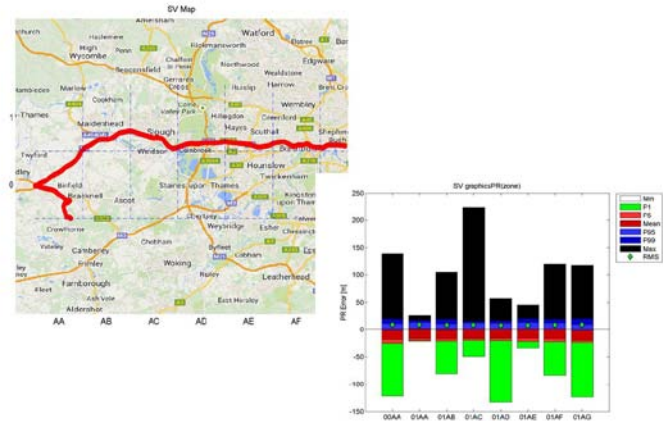


Figure 24- TAT: Pseudorange Error – Statistics per Zone

The fadings appearing at the beginning of Figure 16 are caused by the tree canopy, very dense in that part of the road and the decrease of number of satellites in view of Figure 18 is caused by a bridge. Figure 17 shows that low elevation satellites are less in view in the urban scenario, where also C/N0 experienced some fadings due to tunnels and buildings. The effect of the tunnel can also be seen in the number of satellites in view provided by Figure 19.

The TAT tools also allow analysing the time evolution of the errors and provide histograms, see Figure 20, Figure 21, Figure 22 and Figure 23. Looking at these graphics it can be seen that the pseudorange and Doppler errors follow Gaussian-like distributions with heavier tails. The typical values of the equivalent sigma of the central part of the pseudorange and Doppler distributions (containing 68% of the samples) are 4-6 m and 0.1 m/s respectively in motorway scenarios and 6-7 m and 0.14 m/s respectively in urban ones, but with much heavier tails in urban than in motorway. The heavier tails are caused by the local effects, like multipath and NLOS (see an example of NLOS in Figure 25).

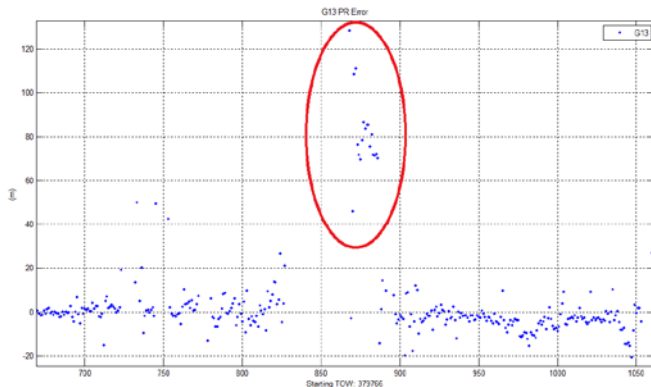


Figure 25- TAT: SV Pseudorange Error (NLOS example) - Urban

The detection of problematic periods is done using a sliding window of configurable width that is moved along the errors (pseudorange, Doppler and position), computing the mean, RMS, percentile 95 and maximum values of the errors within the window and comparing them against the configured thresholds (see an example in Figure 26).

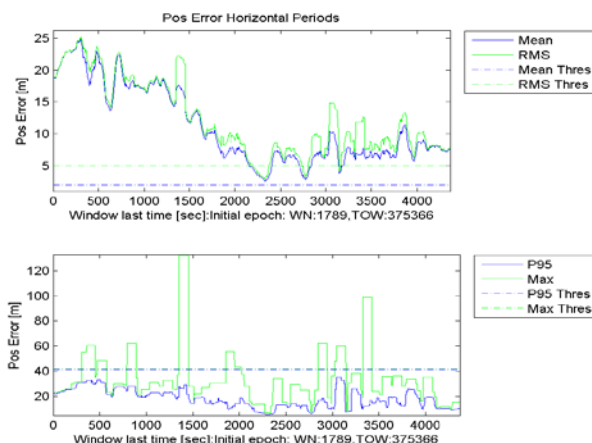


Figure 26- TAT: Problematic Period Identification

#### Multipath Characterization:

There is no single technique able to deal with the different multipath situations in GNSS. A set of complementary techniques is needed to cope with the wide range of multipath situations: C/N0, DLL, SAM and NTRD.

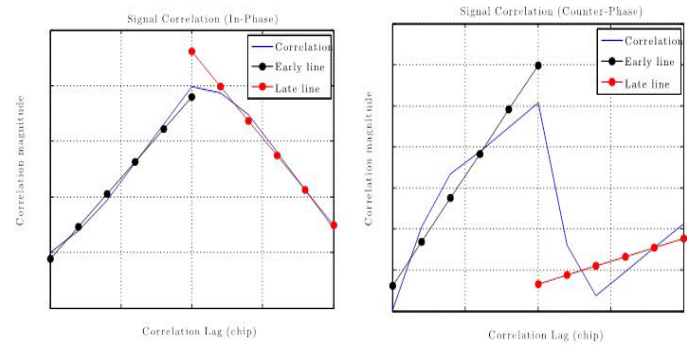


Figure 27- MAT: Slope Asymmetry Metric (SAM)

Table 7 provides the multipath analysis classification depending on the multipath delay relevance:

	Metric	Issue
Low Delay	C/N0	It needs C/N0 estimation under nominal conditions (i.e. without multipath).
High Delay	DLL	It presents spikes in the presence of multipath instead of presenting a magnitude change.
	SAM	It can take a value of 0 even with the presence of multipath.
	NTRD	It needs to know the truth pseudoranges.
	C/N0	It needs C/N0 estimation under nominal conditions (i.e. without multipath).

Table 7- MAT Multipath Classification

The characterization analysis will be completed using the MAT tools with the problematic periods identified by the TAT tools.

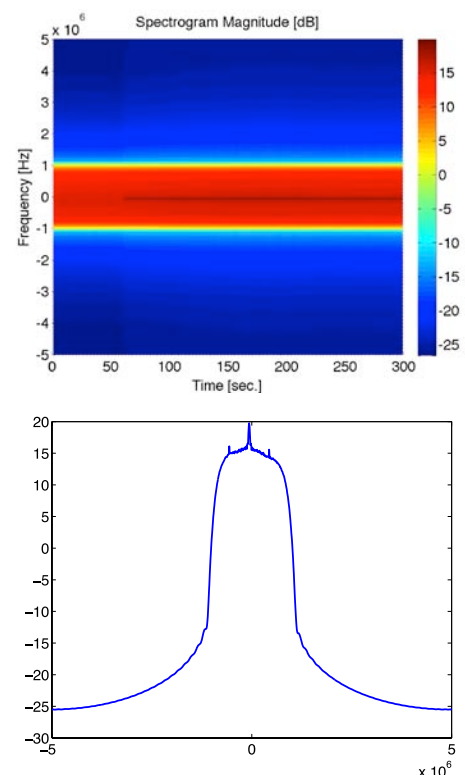
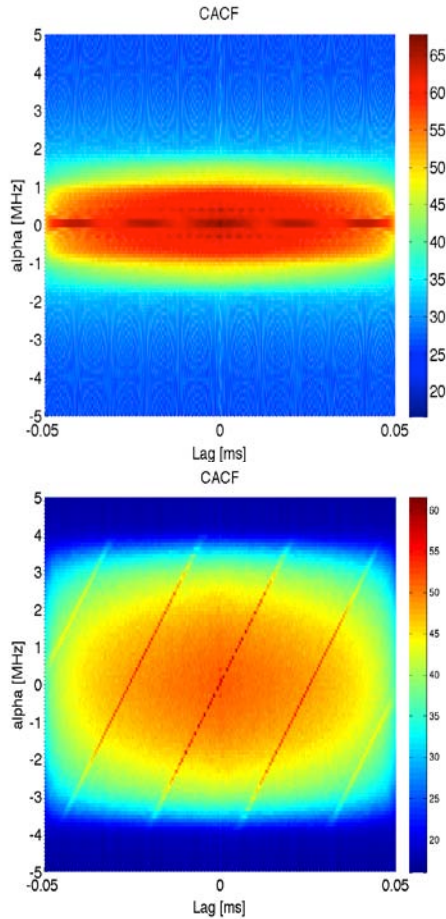


Figure 28- IAT: TFA spectrum with a pulsed wave interference

- Frequency variation: CACF (simplicity with respect to WV.)

#### Interference Characterization:

The data collected in the interference campaign was analyzed with using the IAT interference detection and characterization techniques already described in the previous section. Figure 28 and Figure 29 provide an example of the IAT generated outputs when running different techniques.



**Figure 29- IAT: CACF with a constant wave interference (left) and with a chirp interference (right)**

As a conclusion, depending on the interference type these are the techniques able to detect the presence of interference and, in some cases, also provide information about its type:

- Constant Wave (CW): Detected by all techniques.
  - No information: Statistical Analysis (Low computational burden).
  - Information: TFA/CACF.
- Pulsed Wave: Detected by all techniques.
  - Information: ACF enough (simpler than TFA/CACF)
- Wide-Band: It needs to apply TFA or Cyclostationary analysis (CA).
  - Spectrogram (selected due to its simplicity).
- Frequency variable: It is needs to apply TFA or CACF.
  - Instantaneous frequency: Wigner-Ville (WV).

Table 8 summarizes the obtained results showing the capability of the different IAT techniques to detect the type of interference:

		IAT Analysis					
		Kurt.	Hist.	ACF	Spect.	PWVD	CACF
Type of interference	Continuous Wave	+	+	+	+	+	+
	Pulsed Wave	+	+	+	+	+	+
	Wide-Band	—	—	—	+	—	+
	Freq. Varying	—	—	—	+	+	+

**Table 8- IAT Interference Type Detection Capability**

The Multi-Antenna techniques need to be tested with the collected data and will be completed by the end of the project, together with the research in integrity algorithms.

## CONCLUSIONS AND FUTURE WORK

The two developed IGNSRX data acquisition platforms (Vehicular and Pedestrian DASUs) allow the collection of a wide range of RF samples, sensor measurements and GNSS observables along with the corresponding truth reference trajectory, which allow developing, testing and validating road and pedestrian integrity applications. Also, a summary of the main difficulties encountered during the development of the platforms has been provided.

Several extensive data collection campaigns have been carried out covering different environments:

- Vehicle Data Collection:
  - Motorway and
  - Urban
- Pedestrian Data Collection:
  - Sub-urban,
  - Urban and
  - Indoor
- Interference Data Collection:
  - Jamming and
  - Spoofing

The data collection campaigns successfully fulfilled the expectations, thus, a high amount of data has been collected. This, along with the availability of the truth reference trajectory, will allow validating integrity algorithms with confidence levels up to  $1 \cdot 10^{-4}$  or  $1 \cdot 10^{-5}$ . Once the project is finished, the intention is to make the collected data available for further research.

The tools developed for processing and analysing the collected RF samples and data (OAU) allow to compute the GNSS measurement errors and to perform a statistical



analysis along with a characterization of the threats at signal, measurement and position levels. A first characterization is provided.

Next phase of the project will complete the fault characterization and focus on the research in integrity algorithms at signal, measurement and position levels, including techniques to detect signal impairments, hybrid integrity algorithms, PPP and, using the multi-antenna to estimate the DOA, NLOS identification and spoofing detection algorithms.

## REFERENCES

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[2] STEREO Dual Front-End:

<http://www.nsl.eu.com/primo.html>

[3] SRX-TRITON Multi-Antenna Front-End:

<http://www.gmv.com/en/space/products/srx-10/Front-end/>

[4] WIPODE Wi-Fi based indoor navigation:

<http://www.gmv.com/en/space/products/wipode/>