ROBOSAT Deliverable

D2.1 Requirement and design parameters for sensor setup and I/Q data grabber

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Abstract

This deliverables gives details about the acquired I/Q data grabber, its components and hardware specifications, its software and user interfaces as well as the encountered challenges so far in building the setup

Keywords: *I/Q data grabber; Global Navigation Satellite Systems (GNSS)*

1. Introduction

An I/Q data grabber is a tool used in wireless communication and navigation systems to capture the in-phase (I) and quadrature (Q) components of a received signal. These components represent the full complex baseband version of the signal, preserving both amplitude and phase information. By grabbing raw I/Q samples, engineers can analyze the signal exactly as the receiver sees it—before demodulation—enabling detailed inspection of modulation formats, interference, channel effects, and receiver performance.

The primary purpose of an I/Q data grabber is to support diagnostics, debugging, and. in our case, the algorithm developments, as I/Q data is the data richest in the features one can get from the wireless channels. With access to raw complex samples, one can improve the positioning algorithms at different receiver stages, starting from acquisition to tracking and navigation data. It also enables better characterization of interference (e.g., spoofing and jamming) as the Radio Frequency Fingerprints (RFF) or impairments are unfiltered in the raw I/Q data. This makes this I/Q grabber essential for our research as well as for collecting data to be provided in open-access to the research community. The main advantage of our I/Q data grabber would stay in the fact that it will enable reproducible experiments and offline analysis. Instead of relying solely on real-time processing, we can store captured I/Q data under various scenarios and run complex algorithms repeatedly, compare different receiver architectures, or test new algorithms and techniques under identical signal conditions. This capability greatly accelerates development and provides a controlled environment for evaluating system behavior under a wide range of scenarios.

The main challenge with I/Q raw data is the need of large storage space, as the data can be rather huge. For example, only one minute of GNSS I/Q data collected at 50 Mbps sampling rate and with a moderate 8-bit I+Q resolution in the Analogue to Digital Converter (ADC) would require close to 3 GB of storage. If one would like to collect such data in 10 different scenarios, the needed storage space would easily increase to 30 GB. We will address the storage spaces and our solutions in the ROBOSAT project in our Deliverable D4.1.

2. I/Q data grabber description

2.1. Overview

The I/Q data grabber used in this project is the MGSE©-REC (Mobile Recording Unit), manufactured by TeleOrbit GmbH in Nuremberg, Germany, with technology licensed from the Fraunhofer Institute for Integrated Circuits (Fraunhofer IIS). The device is a modular RF front-end designed to digitize and record raw GNSS signals across multiple frequency bands simultaneously. It captures the in-phase (I) and quadrature (Q) components of the incoming RF signals, producing raw I/Q data that can subsequently be processed by software-defined GNSS receivers for signal analysis, positioning, and interference studies.

The unit is available in several configurations: single-channel (SC), dual-channel (DC), and triple-channel (TC) variants, as well as rack mount versions for laboratory use. The model employed in our work is the single-channel version (MGSE©-REC-SC), licensed for use at Tampere University, which includes three FPGA configurations covering the L1/E1 frequency band. This enables the capture of signals from GPS and Galileo constellations at this frequency.

2.2. Hardware Specifications

The MGSE©-REC is a compact unit measuring 188 × 125 × 50 mm, making it highly portable and suitable for both static and mobile measurement campaigns. It is powered directly

Figure 1. I/Q Logger

through a single USB 3.0 connection at 5V / 900 mA, meaning it does not require an external power supply when connected to a laptop or a PC with a USB 3.0 port. The maximum RF input power is 0 dBm, and the device operates within a temperature range of 0°C to 55°C with a relative humidity tolerance of up to 95%. The key specifications are summarized in Table 1.

Parameter	Value
Dimensions (L × W × H)	188 × 125 × 50 mm
Power Supply	5V / 900 mA via USB 3.0
Maximum RF Input Power	0 dBm
Operating Temperature	0°C to 55°C
Relative Humidity	0 – 95%
Storage Temperature	-55°C to +125°C
Data Interface	USB 3.0 Type B
Maximum Sampling Frequency	81 MHz (all bands)

Table 1. MGSE©-REC general specifications

2.3. Connectors and Interfaces

The front-end is equipped with several connectors and indicators. On the main panel, there is one SMA antenna connector, a USB 3.0 Type B port for both data transfer and power supply, and SMB connectors for a 10 MHz reference clock input and output. An optional parallel data output (Honda E68-LFD) and an SMB synchronization connector are also available for advanced configurations.

The device features two LED indicators: a "power" LED that confirms the front-end has been fully initialized and is ready for operation (fast blinking indicates an error), and a "run" LED that illuminates when the USB data transfer is active. A physical switch allows the user to toggle between the internal and an external 10 MHz reference clock. Two additional LEDs indicate whether the active antenna DC supply is enabled ("DC ant") and whether an over-current or short-circuit condition has been detected on the antenna line ("O-C"). The active antenna support provides up to 70 mA at 4.5 VDC.

Label	Connector Type	Description
Antenna	SMA	Antenna input
10 MHz In	SMB	Input for an external reference clock signal
10 MHz Out	SMB	Sinusoidal output of the internal 10 MHz reference clock
USB	USB 3.0 Type B	Data interface to the PC and power supply
Sync	SMB	Optional connector for synchronisation of two or more front-ends

Table 2. MGSE©-REC connector overview.

2.4. Supported Frequency Band

In the single-channel configuration licensed at Tampere University, the MGSE©-REC covers the L1/E1 GNSS frequency band with three available FPGA configurations. The digitized output is a complex (I/Q) signal with a digital intermediate frequency (IF) below 10 MHz and a non-flipped IF spectrum orientation. The sampling rate can go up to 81 MHz, which provides sufficient bandwidth to capture the full signal spectrum. An open-sky view is required for reliable GNSS signal reception.

Band	Centre Freq. [MHz]	Digital IF	RF BW [MHz]	Signal Type
L1/E1	1575.42	< 10 MHz	Up to 60	Complex (I/Q)

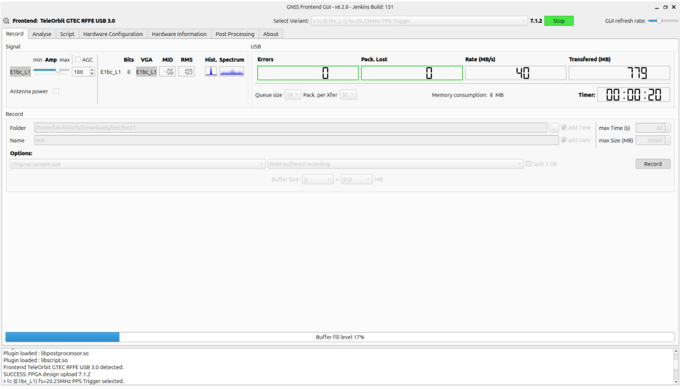
Table 3. Frequency band configuration of the MGSE©-REC-SC at Tampere University.

2.5. Software and User Interface

The MGSE©-REC is operated through a dedicated software application called FrontendGUI, provided on a USB flash drive included with the device. The software runs on Linux (tested with Ubuntu 20.04 LTS 64-bit) and requires approximately 30 MB of disk space, at least 1 GB of RAM, and a 2.8 GHz CPU.

The FrontendGUI provides a tabbed interface with several functional areas. The Record Tab is the primary tab used for capturing data, providing controls for adjusting the variable gain amplifier (VGA), enabling or disabling the active antenna power, specifying the output directory and filename, and setting the recording duration or maximum file size. Three output formats are available during recording: "Original sample size", which stores all channel data multiplexed into a single .usb file together with an embedded transfer protocol; "1 Byte/sample (TC)", which extracts the channel into a separate .bin file and applies a symmetrization operation (performing x2+1 on each sample); and "1 Byte/sample (TCA)", which performs the same extraction but without symmetrization. Three recording modes are also selectable: direct recording writes data immediately to disk but is sensitive to storage write-speed limitations; RAM-buffered recording, which is the recommended mode, buffers the incoming data stream in RAM before flushing to disk, compensating for temporary write-speed drops;

and round-robin recording, which runs continuously and overwrites the oldest stored data when the available storage is full, with data always split into 2 GB portions.

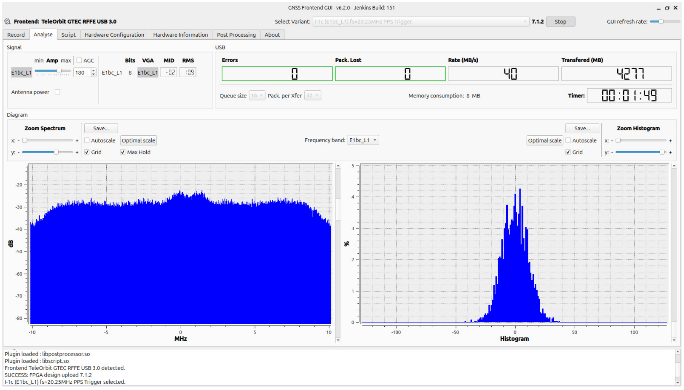


Frontend: TeleOrbit GTEC RFFE USB 3.0
Select Variant: I-1c (E1bc_L1) fs=20.25MHz PPS Trigger 7.1.2
E1bc_L1 180 | E1bc_L1 8 E1bc_L1 -06 109
Antenna power ☐
Errors: 0
Pack. Lost: 0
Rate (MB/s): 40
Transfered (MB): 779
Queue size 16 Pack. per Xfer 32
Memory consumption: 8 MB
Timer: 00:00:20
Folder /home/lab-tc407b/Downloads/test/test1 ☑ add Time max Time (s) 60
Name test ☑ add Date max Size (MB) 20000
Original sample size RAM buffered recording ☐ Split 2 GB
Buffer Size: 3 x 512 MB
Buffer fill level 17%

```
Plugin loaded : libpostprocessor.so
Plugin loaded : libscript.so
Frontend TeleOrbit GTEC RFFE USB 3.0 detected.
SUCCESS: FPGA design upload 7.1.2
I-1c (E1bc_L1) fs=20.25MHz PPS Trigger selected.
```

Figure 2. Record tab in FrontendGUI

The Analyze Tab displays detailed real-time spectrum and histogram plots of the received signal for the active frequency band. The spectrum is computed using a Fast Fourier Transform (FFT) and supports zoom controls, automatic scaling, and a maximum-hold mode that retains the peak value at each frequency bin. This tab allows the user to visually inspect signal quality and verify that the VGA or AGC settings are producing an appropriate signal level prior to initiating a recording session, without logging any data to disk.



Frontend: TeleOrbit GTEC RFFE USB 3.0
Select Variant: I-1c (E1bc_L1) fs=20.25MHz PPS Trigger 7.1.2
E1bc_L1 180 | E1bc_L1 8 E1bc_L1 -02 109
Antenna power ☐
Errors: 0
Pack. Lost: 0
Rate (MB/s): 40
Transfered (MB): 4277
Queue size 16 Pack. per Xfer 32
Memory consumption: 8 MB
Timer: 00:01:49
Frequency band: E1bc_L1
☐ Autoscale ☑ Grid ☑ Max Hold | ☐ Autoscale ☑ Grid

```
Plugin loaded : libpostprocessor.so
Plugin loaded : libscript.so
Frontend TeleOrbit GTEC RFFE USB 3.0 detected.
SUCCESS: FPGA design upload 7.1.2
I-1c (E1bc_L1) fs=20.25MHz PPS Trigger selected.
```

Figure 3. Analyze tab in FrontendGUI

The Post-Processing Tab provides a built-in conversion tool for recorded .usb files. Since the raw .usb format preserves the full USB transfer protocol structure, including the 2-byte preamble, 4-byte packet counter, and 4-byte suffix per 1024-byte packet, post-processing is required to extract usable I/Q sample data. The tab allows the user to select an input .usb file, analyze it for packet losses (which are displayed graphically as vertical red lines along the file timeline), and convert it into one of three output formats: protocol removal only, which strips the transfer protocol without separating the channel data into a single output file; "1 Byte/sample (TC)", which additionally separates the channel data into individual per-band .bin files and applies symmetrization; or "1 Byte/sample (TCA)", which performs the same separation without symmetrization. The resulting .bin files are organized in an interleaved I/Q format and can be directly read into MATLAB or other signal processing environments, including software-defined GNSS receivers such as the FGI receiver used in this project.

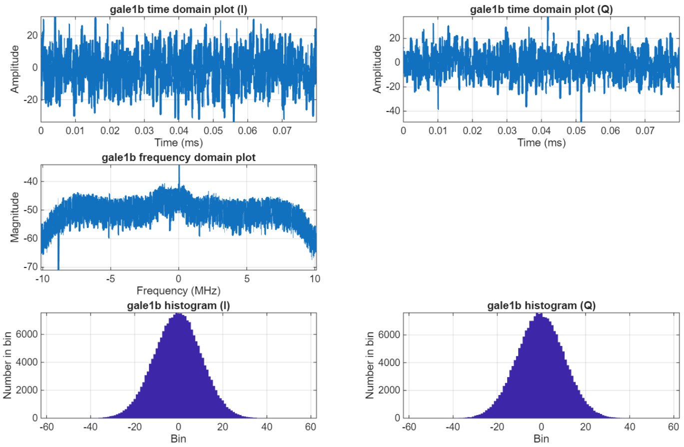


Figure 4. Sample Data processed in MATLAB

2.6. Data Format and USB Transfer

The MGSE©-REC streams digitised samples to the host PC via USB 3.0 in packets of 1024 bytes. Each packet includes a 10-byte overhead consisting of a 2-byte preamble (0x55 0xAA), a 4-byte incrementing counter for detecting lost packets, and a 4-byte suffix (0xDEAD 0xBEEF). This leaves up to 1014 bytes of actual I/Q sample data per packet. The raw recorded file uses the .usb extension and preserves this packet structure. For further processing, the front-end software converts these files into .bin format by stripping the transfer protocol. High-speed storage (SSD or RAID) is recommended by the manufacturer to sustain the required data rates.

2.7. Gain Control

The MGSE©-REC channel has an independently adjustable variable gain amplifier (VGA). The gain can be controlled manually through a slider in the GUI (valid range: 70 to 200, with each step corresponding to approximately 0.5 dB, yielding a total gain variation of roughly 70 dB), or automatically using the built-in Automatic Gain Control (AGC) feature. For a typical active antenna with 20 dB of gain, a VGA setting of around 170 is suggested as a starting point.

2.8. Antenna Description

The antenna used in conjunction with the MGSE©-REC-SC for signal capture in this project is the navXperience 3G+C mobile (order number: navX-007), manufactured by navXperience GmbH, Berlin, Germany. It is an active, multi-constellation GNSS antenna designed for dynamic and mobile measurement applications, making it well suited for the data collection campaigns carried out in this work.

The 3G+C mobile supports reception of all signals from all four major satellite navigation systems, GPS, Galileo, GLONASS, and BeiDou, as well as L-band correction data services, operating across two frequency bands: 1150–1300 MHz and 1525–1610 MHz. The active gain of 29 dB makes it suitable for cable lengths of up to 10 m. The antenna employs Right-Hand Circular Polarization (RHCP) with an integrated Low Noise Amplifier (LNA) having a noise figure of less than 2 dB. A notable characteristic of the 3G+C series is its ability to track GNSS satellites down to 0° elevation, where most comparable antennas lose signal lock at around 7°, improving

Figure 5. Mobile antenna

the number of visible satellites and the overall signal-to-noise ratio.

The antenna draws less than 50 mA at 3.3–20 V, making it fully compatible with the 4.5 VDC, 70 mA active antenna supply of the MGSE©-REC front-end. The housing is laser-welded and rated to IP69K and MIL-STD 810g, with an operating temperature range of −45°C to +85°C. Key specifications are summarized in Table 4.

Parameter	**Value**
Active Gain	29 dB
Passive Gain	3.8 dBic
Polarisation	RHCP
LNA Noise Figure	< 2 dB
VSWR (max)	1.5:1
XPD	> 15 dB
10 dB Beamwidth	160° to 180°
Supply Voltage	3.3–20 V
Current Draw	< 50 mA
Operating Temperature	−45°C to +85°C
Connector	TNC
Dimensions	Ø 172 mm × 72 mm
Weight	380 g
Protection Rating	IP69K, MIL-STD 810g

Table 4. NavXperience 3G+C mobile antenna specifications.

2.9. Antenna challenges

The initial tests with the navXperience antenna showed that the current antenna is malfunctioning; we are now in the process of replacing or repairing it, based on the provider inputs.

3. Other sensors on-board of the robot

Designing a capable perception payload is fundamental to the success of mobile robotics systems. In addition to the I/Q grabber, the goal of the robot is to collect comprehensive data on the environment that can be used later to for analysis. It is key to select the appropriate perception sensors while considering time synchronization, sensor calibration, latency, communication, thermal compensation, and hardware design decisions. To this end, we have conducted a comprehensive study [1] of sensors that can be integrated onto our walking quadrupedal robot, ANYmal. We additionally integrated the selected sensors into a flexible sensor suite that can be mounted on the robot and, in the future, also extended, taking into consideration all the precision-critical aspects previously mentioned.

The main sensors in our sensor suite include:

- **Two LiDARs:** for dense 3D reconstruction of the environment.
- **HDR Cameras:** for RGB images of the environment that can be used for semantics, and to enable the use of standard AI tools that rely on machine vision. Multiple cameras offer a comprehensive coverage of the surroundings, in high resolution and with good dynamic contrast.
- **Multiple Inertial Measurement Units (IMUs):** for accurate, high-frequency motion estimation. Especially for walking robots, high-precision state estimation is difficult due to the non-constant motion and the impacts that happen during walking, which can be hard to accurately estimate. We selected a range of different quality/price IMUs, to provide an exhaustive set of options. IMUs, are especially important in bridging the temporal gaps between other sensors, and are an essential building block of many multi-modal sensor suites.
- **Standard RTK-GNSS Unit:** to provide ground truth global positioning to aid in mapping and alignment of various data sources. We include this sensor despite the future integration of the IQ grabber to also provide a standard commercial solution that can also work as a baseline for evaluating the quality of the GNSS fix.
- **Leica Total Station:** is a high-precision surveying tool that we use to obtain ground-truth motion estimation. While the frame of the Total Station is not GNSS aligned, it still provides the most accurate possible ground truth shape of the robot's trajectory. For this, the Total station tracks a prism that is mounted on top of the robot, providing sub-millimeter accuracy.

A visualization of the sensor suite is shown in Figure 6. This sensor suite was then used to collect the dataset detailed in [2], which is discussed in more detail in D5.1. This data works as an initial testing platform for the algorithms developed in ROBOSAT, and helps us iterate over the design and improve future data-collection efforts.

4. Long-term Autonomy

We have upgraded the robot's legs from series elastic actuators to direct-drive motors from Maxon, doubling the maximum torque (from 80 Nm to 140 Nm) and increasing the effective payload (from 15kg to 80kg) and efficiency by a significantly larger margin. We have also done initial system identification using methods developed in our lab for this [3]. This facilitates sim-to-real transfer of Reinforcement Learning (RL)-based controllers, and enables rapid deployment and prototyping. We have made the robot stand and verified the electrical and mechanical capabilities of the new legs. Additionally, we have verified in air that the joints move and the internal state estimator correctly reads and smoothly commands the motors. We are currently training an initial blind locomotion policy to test the robot's basic functionality on flat or slightly uneven terrain. If this proves successful, we can directly transfer to training perceptive policies that can handle rough terrains much better [4]. Afterwards, we will test and deploy the robot in outdoor conditions to evaluate the increased autonomy and range.

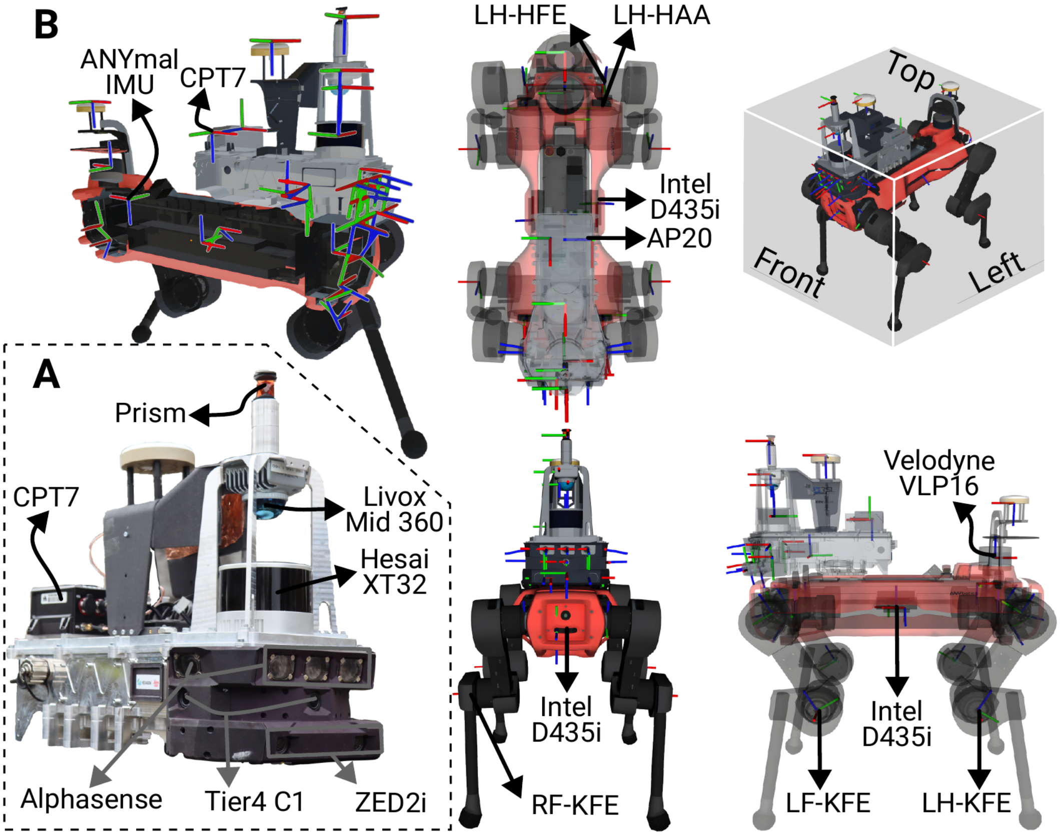


Figure 6. Sensor placement visualization of the entire sensor suite. A) Shows the spatial relationships of the sensors on the ANYmal payload, and B) shows the sensors of the ANYmal base platform components. Each colored axis represents a sensor or joint frame. For brevity, repeated sensors are not shown (e.g., 6× Intel RealSense D435i depth cameras).

5. Conclusions

The initial acquisition and set-up with I/Q grabber have been completed, according to the plan, but there are some challenges to overcome regarding the GNSS antenna currently used with the I/Q grabber; the solutions are currently discussed with the company from where the antenna was acquired. As a Plan B, we have an older GNSS mobile antenna available in the lab and initial tests with it showed that it can be also used, if needed. In terms of the robotic set-up, additional sensors (except the I/Q grabber) have already been integrated in the ANYMal robot and the robot's legs have been updated for long-term autonomy. The next steps will be to conduct in-lab and field measurements with the developped set-ups, first individually, at TAU and ETH premises, respectively, and later on, in a joint manner, at Consortium level.

■ References

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