A complete tutorial on NovAtel SPAN setup, processing, and analysis

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Glossary

- **ALIGN**: Commercial name given by NovAtel to a RTK solution between a moving base and rover that can output heading and pitch between the two or relative positioning.
- **AMSL**: Above Mean Sea Level, altitude referenced to the geoid.
- **AGC**: Automated Gain Control. An electronic device that receives the signal amplified by the antenna's LNA and refines the gain to a constant output for processing by the receiver.
- **ARP**: Antenna Reference Point. This is the point to which all antenna measurements are reduced if the receiver is using an antenna model. Otherwise, the output position is that of the antenna's radio-electrical phase center.
- **ASCII**: American Standard Code for Information Interchange, it's a character encoding standard used to represent text in computers and electronic devices.
- **CAD**: Computer Aided Design, software that helps users design and visualize objects before they are built or manufactured. It can be used for:
  2D drafting (e.g., architectural floor plans, circuit diagrams)
  3D modeling (e.g., mechanical parts, consumer products, vehicles)
  Simulation and analysis (e.g., stress testing, motion simulation)
  Rendering (creating photorealistic images of designs)
- **CPU**: Central Processing Unit, is the main processor of a computer—it acts as the brain that carries out instructions from programs by performing calculations, making decisions, and managing data.
- **DGNSS**: DGNSS: Differential GNSS, this term can be interpreted in two ways. Some use it to define any positioning technique based on differences, while others restrict it to code-only DGNSS.
- **DMI**: Distance Measurement Instrument, typically a wheel encoder or sometimes a ground radar that measures the ground velocity of a vehicle by means different than GNSS or IMU. It has a positive impact in SPAN performance in GNSS denied environments.
- **EGNOS**: European Geostationary Navigation Overlay Service, European SBAS clone of the US made WAAS.
- **EKF**: Extended Kalman Filter. It is an extension of the standard Kalman Filter, which is only optimal for linear systems. The EKF predicts the future state of a system and corrects that prediction using new measurements.
- **ETRS89**: European Terrestrial Reference System 1989, it's a geodetic coordinate system used as the standard geodetic datum for Europe. Based on the International Terrestrial Reference System (ITRS) but fixed to the stable part of the Eurasian tectonic plate. ETRS89 moves with the Eurasian plate, meaning coordinates remain stable relative to Europe. This avoids coordinate shifts due to tectonic motion that affect global datums like WGS84.
- **GIS**: Geographic Information System, is a computer-based system used to capture, store, manage, analyze, and visualize geographic data.
- **GNSS**: Global Navigation Satellite System. Name that describes the amalgamation of the available satellite navigation irrespective of the country of origin:
  - **GPS**: Global Positioning System. Operated by the US Department of Defense
  - **GLONASS**: Globalnaya Navigatsionnaya Sputnikovaya Sistema. Operated by the Russian government.
  - **Galileo**: Global system operated by the European Commission only civilian operated constellation available.
  - **BeiDou**: Global and regional system operated by China.

    - **QZSS**: Regional system operated by Japan providing coverage to Japan
    - **NavIC**: Regional system operated by India providing coverage to India
- **GRIT**: GNSS Resilience and Integrity Technology. Commercial name given by NovAtel to a suite of firmware aimed at enhancing the performance, security, and integrity of GNSS.
- **GUI**: Graphic User Interface, is a visual way for users to interact with computers and software using icons, buttons, menus, and windows, rather than typing commands in a text-based interface (like a command line).
- **ICGC**: Institut Cartogràfic i Geològic de Catalunya, Geodesic authority in Catalunya
- **IMU**: Inertial Measurement Unit, is an electronic device that measures and reports a body's specific force, angular rate, using a combination of:
  Accelerometers – to measure linear acceleration in 3 perpendicular axes.
  Gyroscopes – to measure angular velocity rotation in 3 perpendicular axes.
- **ITRF2020**: International Terrestrial Reference Frame 2020, latest realization (version) of the International Terrestrial Reference Frame (ITRF), a very precise, global reference frame maintained by the International Earth Rotation and Reference Systems Service (IERS).
- **KML**: Keyhole Markup Language, it's a file format used to display geographic data in Earth browsers like Google Earth and Google Maps.
- **LiDAR**: Light Detection and Ranging, it's a remote sensing technology that uses laser light to measure distances to objects and create detailed, accurate 3D maps of the environment.
- **LNA**: An electronic device that amplifies the very weak signal from a GNSS antenna, adding minimal noise, to ensure it can be reliably processed by a GNSS receiver.
- **MEDEA**: is a GNSS receiver developed at Rokubun that couples a u-blox ZED-F9P receiver with an IMU Analog Devices ADIS 16500 which in this test was being used by Vladimir Suvorkin to obtain data for his doctoral thesis.
- **NMEA**: National Marine Electronics Association, in the context of boating and marine electronics, it typically refers to the communication standards used by marine devices to exchange data. There are two main standards NMEA 0183 and NMEA 2000
- **NovAtel**: Canadian tech company dedicated to satellite navigation owned by Hexagon, a Swedish multinational conglomerate.
- **NTRIP**: Networked Transport of RTCM via Internet Protocol. A software layer that allows the transmission of RTCM data over the Internet.
- **OEM**: Original Equipment Manufacturer, an OEM is a company that produces parts or products that are then used or sold by another company under that company's brand name.
- **PCB**: Printed Circuit Board, is a flat board that holds and connects electronic components using conductive pathways, or traces, etched from copper sheets.
- **PCO**: Phase Center Offsets, are corrections applied to account for the fact that a GNSS antenna's electrical phase center (the point where satellite signals are effectively received) does not coincide exactly with the antenna's physical reference point.
- **PCV**: Phase Center Variations, refers to the variation in the location of a GNSS antenna's phase center depending on the direction (elevation and azimuth) of the incoming satellite signals.
- **QGIS**: Geographic Information System software by the name of Quantum GIS
- **RBV**: Rotations Body to Vehicle, refer to the rotational offset required to transform data from the IMU (Inertial Measurement Unit) Body Frame to the Vehicle Frame
- **RINEX**: Receiver Independent Exchange. File type designed to store GNSS raw data derived from a widespread open standard that allows to share raw data between different brands.

- **RTCM**: Radio Technical Commission for Maritime Services, an organization that manages radio standards affecting maritime traffic. RTCM Special Committee 104 developed DGNSS standard RTCM 10403.3, enabling the transmission of raw base station GNSS data to GNSS rovers for either code-only DGNSS or RTK.
- **RTK**: Real Time Kinematics positioning technique by which the raw data from a base station is used to compute a centimeter level precise vector to a rover receiver that is being fed the raw data from the base station.
- **SBAS**: Satellite Based Augmentation System, generic name for a regional augmentation system born to provide service to aviation users. Started by the United States Wide Area Augmentation System (WAAS) which, in its receiver implementation, is described in the RTCA DO-229F standard: Minimum Operational Performance Standards for Global Positioning System / Wide Area Augmentation System Airborne Equipment.
- **SPAN**: Synchronized Position Attitude Navigation. Commercial name given by NovAtel at the fusion of GNSS and IMU data to provide robust navigation in challenging environments, output Position Velocity Attitude Time and raw data at high data rates.
- **SPGIC**: Servei de Posicionament Geodèsic Integrat de Catalunya, is the backbone geodetic service of Catalonia, delivering high-precision, real-time positioning
- **TCP**: Transmission Control Protocol, it’s one of the main protocols in the Internet Protocol (IP) Suite and is used to establish reliable, ordered, and error-checked communication between devices over a network.
- **UPC**: Universitat Politècnica de Catalunya, Polytechnical University of Catalunya.
- **USB**: Universal Serial Bus, is a standardized technology used to connect, communicate, and supply power between computers and peripheral devices, such as keyboards, mice, flash drives, external hard drives, cameras, printers, and smartphones.
- **VRS**: Virtual Reference Station, is a GNSS correction method that creates a virtual base station near your rover (e.g., GNSS receiver). Instead of using a single physical base station, VRS uses data from multiple reference stations in a region to simulate a base station right near your location. This improves accuracy and consistency.
- **WGS84**: Geodetic datum in which the GPS ephemeris is broadcast.

Introduction

This tutorial outlines the complete workflow for correctly setting up and configuring a NovAtel SPAN system, from start to finish. It consolidates information scattered across multiple NovAtel documents into a single, continuous, resource and provides commentary on preferred procedures.

While I'm no longer affiliated with NovAtel, I spent seven years in a NovAtel technical support / application engineering role, assisting customers with NovAtel SPAN systems like the one described here.
You might be wondering why such a document was written. During those seven years, I conducted many system demonstrations for customers across various markets. However, in none of those demonstrations did I have the opportunity to install a SPAN system following all the steps required for a truly, end-to-end procedure. The reasons were numerous, but mostly, demos were time-constrained, forcing us to perform 'good enough' installations.
This text is a journey towards an 'as good as it gets' installation from beginning to end. If for any reason I must deviate from the ideal path, I will explain why and provide suggestions on how to proceed in your specific situation.

It's also important to note that NovAtel is not sponsoring this document. All the equipment portrayed in this document has been purchased by their respective owners, we never received any donations. While I enjoy working with high-end GNSS receivers, the only reason I had the opportunity to write this text is because I was fortunate enough to find a used PwrPak7D-E1 (PW7720E1-FDD-RYN-TBE-P1) at a significantly discounted price—an offer I couldn't refuse.

For me, it has been a very interesting journey to step into the role of the customer and experience things from their perspective.

Hardware

In this section the different components required to set up a fully working SPAN system will be reviewed, used hardware components will be discussed and reasoning behind their selection will be presented.

● GNSS receiver and IMU in an enclosure

Within the SPAN product line, the PwrPak7D-E1 with the Epson G320N IMU represents an entry-level hardware configuration in terms of IMU performance, offering the lowest specifications and cost within the SPAN product line. However, despite its ranking, it still performs very well.

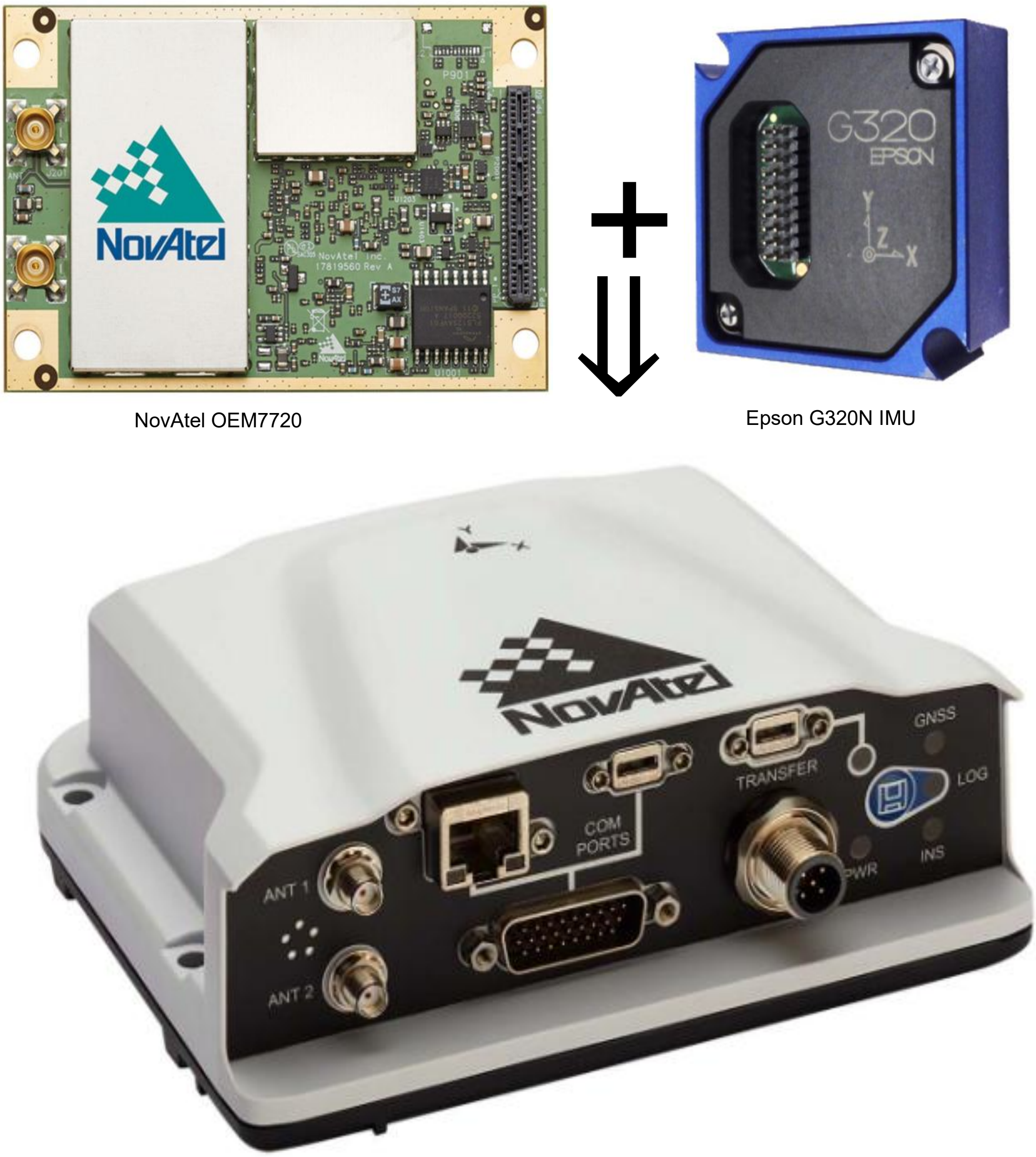

Figure 1. NovAtel PwrPak7D-E1 enclosure components

It's worth noting that while the IMU may have humble specifications compared to the rest of the NovAtel product line, the GNSS receiver, tasked with processing the real time solution, is a best-in-class OEM7720.
The meaning of the OEM7720 **FDD-RYN-TBE-P1** receiver firmware model within the PwrPak7D-E1 enclosure [1] is as follows:

F All GNSS constellations in view are supported (GPS+Galileo+GLONASS+BeiDou)

D Supported GNSS frequencies: L1 and L2

D Supported dual antenna inputs: Yes

R Real Time Kinematic rover capable: Yes

Y ALIGN heading and relative positioning capable: Yes

N Reserved

T Maximum GNSS only data output rate: 20Hz (SPAN synchronous output is 125 Hz)

B Output of raw GNSS observables in both NovAtel and RTCM formats.

E GRIT Interference Mitigation and Spoofing Detection

P1 SPAN Enabled, Profiles/Heave enabled, Entry level IMU

This firmware model provides all that is required to operate with an ideal set of GNSS constellations and signals, fostering a reliable real-time Position, Velocity, Attitude, and Time output in sustained deep urban canyon environments, as will be the case in our urban SPAN recording.

The performance of this humble SPAN system as specified by NovAtel is as follows [2] :

Outage duration	Positioning mode	Position accuracy (m) RMS		Velocity accuracy (m/s) RMS		Attitude accuracy (degrees) RMS	
		Horizontal	Vertical	Horizontal	Vertical	Roll/Pitch	Heading
0 s	RTK	0.02	0.03	0.020	0.010	0.020	0.090
	Single Point	1.00	0.60				
10 s	RTK	0.27	0.13	0.070	0.020	0.040	0.130
	Single Point	1.25	0.70				
60 s	RTK	15.00	1.63	0.720	0.065	0.095	0.210
	Single point	16.00	2.20				

	RTK with Land Profile and DMI	3.50	0.80	0.220	0.040	0.095	0.210
0 s	Postprocessed using Inertial Explorer	0.01	0.02	0.020	0.010	0.009	0.042
10 s		0.02	0.02	0.020	0.010	0.009	0.042
60s		0.35	0.10	0.030	0.011	0.014	0.048

Table 1. PwrPak7D-E1 SPAN, NovAtel published performance figures.

In the SPAN setup the Land Profile and ALIGN heading updates will be used but wheel encoder (DMI) will not, NovAtel documentation differentiates DMI and non DMI performance as follows [2] :

Average SPAN land vehicle performance at 1 hour complete GNSS outage at 65 km/h average speed				
IMU grade	Average Error Over Distance Travelled (%) over 1 hour		Azimuth Error (degrees) 1 sigma Standard Deviation	
	Land profile	Land profile with DMI	Land profile	Land profile with DMI
Entry level S1	0.28	0.15	1.76	1.59

Table 2. NovAtel SPAN Land profile performance study results.

- ## Antennas

As it was not possible for me to source high quality, zero centered, geodetic grade GNSS antennas that could be used for this data take I had to resource to my ex Rokubun colleague Vladimir Suvorkin, who kindly provided two high quality antennas lent by Grup d'Astronomia Geodèsica (GAGe) of Universitat Politècnica de Catalunya (UPC):

1. **NovAtel Vexxis® GNSS-850** to be used as a main GNSS antenna for the PwrPak7D-E1 for positioning.
2. **Septentrio PolaNt-x MF** to be used as slave antenna for heading updates (NovAtel ALIGN updates to the SPAN Extended Kalman Filter).

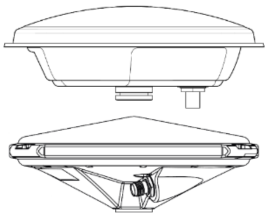

Figure 2. NovAtel and Septentrio antenna diagrams.

It is worth noting that while the NovAtel firmware was setup to apply an antenna model for the master antenna, in this case the NovAtel GNSS-850, it was impossible to apply an antenna model for the slave antenna, in our case the Septentrio, because NovAtel firmware does not allow for it (nor Inertial Explorer either).

● Test vehicle

As with the antennas I don't own a car that could be used to perform the data take but my ex Rokubun colleague Aleix Tejada Gimenez owns an all-terrain Mercedes-Benz GLB from 2024 with the important attribute of having a detachable Thule Touring M a 400-litter roof box space that happens to be enclosed in relatively RF transparent plastic which is ideal to assemble most of the technical equipment inside.

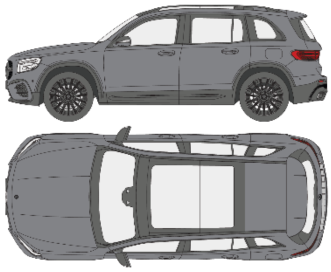

Figure 3. Mercedes-Benz GLB

Not only that the bottom roof box does have a few cuts that allow for the cabling to come in and out of the box but the sun roof opens to let all the cabling in to the interior of the vehicle which makes the installation of any equipment inside the roof box very convenient.

Figure 4. Extruded aluminum structure with equipment installed on top.

In many demonstrations I performed at NovAtel Support, SPAN enclosures were affixed with Velcro to the vehicle's floor mats due to time constraints, ensuring very easy installation and removal of the equipment. However, given that the objective here is to prevent relative movement between the SPAN enclosure and the vehicle frame, the installation was taken one step beyond.

Aleix, who is an industrial designer, designed using a Computer Aided Design (CAD) software, a frame skeleton made of extruded aluminum parts that was to be used to easily assemble all the equipment (antennas, receivers and cabling) on top using 3D printed base plates screwed on to the skeletal structure.

The extrude aluminum structure was affixed to the Thule roof box by using a strap that impeded any undesired movement due to car accelerations and vibrations. This ensures an installation that is as solid as possible to the car frame, yet still allows for easy access to all the equipment.

Figure 5. Detail of the GNSS receiver area of the aluminum structure at the back of the car.

To simplify the SPAN system installation as much as possible, it's customary to align the IMU body frame (as engraved on the SPAN enclosure) as closely as possible with the vehicle frame. In NovAtel's case, this frame is always Y-axis forward, X-axis right, and Z-axis up. This greatly simplifies the process of determining the Rotations Body to Vehicle (RBV), which can otherwise be tricky and confusing to find, especially if more than one axis rotation is involved.

In our case the cabling coming out of the PwrPak7D-E1 would have collided with the extruded aluminum frame prevented to point the +Y axis pointing the forward motion of the vehicle which meant that the +Y axis had to be installed pointing backwards motion of the car meaning that there was only one single rotation of 180 degrees around the Z axis, which is still easily easy to handle.

- ## Other hardware of choice

Anker 26800 USB mAh power bank.
Cerrxian USB Voltage converter from 5 Volts 2 Amps to 9 or 12 Volts. This component has been configured to output 9.1 Volts DC because the PwrPak7D-E1 internal power supply accepts from +9 to +36 Volts DC
Autosen AA043 sensor cable with M12 connector, 5 pin, 2 meters, IP69K

- ## Battery life testing and thermal dissipation evaluation.

When the SPAN system is installed in the car it is to be powered by a 26800mAh USB power bank from Anker with an intermediate 5 to 9 Volt converter. This power method would be able to sustain the PwrPak7D-E1 power needs for 14 continuous hours and 25 minutes, which is enough to feed the system for a full day data take.
The intermediate Voltage converter plus power bank were able to feed the PwrPak7D-E1 even though the inrush power consumption specifications of the PwrPak7D-E1 [7] far exceed the theoretical capabilities of the voltage converter at 1.5 Amps for less than 1.3 milliseconds @ 12 Volt; typical.

Figure 6. PwrPak7D-E1 connected to the USB power supply

During the process of evaluating how much time the Anker USB power bank would be able to power the PwrPak7D-E1, a concern came up, even though the environmental temperature was 25 degrees Celsius, which is a normal temperature for a June in Barcelona.

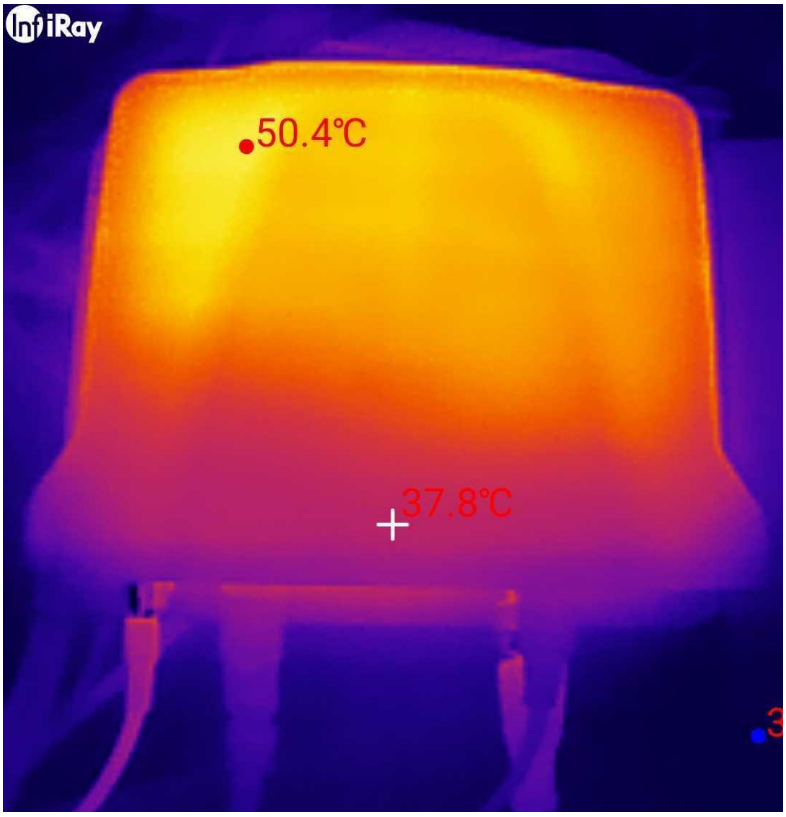

Figure 7. Thermal image of the PwrPak7D-E1 enclosure shell.

After many hours of having the PwrPak7D-E1 powered on, and therefore having reached the thermal equilibrium, the SPAN enclosure was getting noticeably warm to touch (see Figure 7) even though it was not being loaded with the vast number of outputs that typically are requested when using a SPAN system, in other words, without stressing much the OEM7720 CPU.

More concerning is the internal temperature of the CPU of the OEM7720 inside the PwrPak7D-E1 as can be seen in the following log output:

```
<HWMONITOR ICOM1 0 54.5 FINESTEERING 2370 148054.000 02000000 52db 17399
<     10
<          68.986572266 100
<          0.009523810 200
<          3.272283316 600
<          5.065690041 700
<          1.210012197 800
<          3.297924519 f00
<          1.826617837 1100
<          5.077411652 1500
<          0.000000000 1800
<          5.083272457 1900
```

Almost 69 degrees Celsius which creates a concerning perspective of exceeding NovAtel's maximum operational temperature for:

- PwrPak7D-E1 enclosure is 75 degrees Celsius.
- OEM7720 GNSS receiver is 85 degrees Celsius.
- Epson G320N IMU is 85 degrees Celsius.

The operating temperatures published by NovAtel are ambient air temperatures. The temperature sensors on the receiver PCB will reflect higher operating temperatures (refer to the HWMONITOR log). The PCB temperature sensors will trigger a receiver warning and receiver error at 100°C and 110°C respectively. The warning and error conditions are captured using the RXSTATUS log.
As a conclusion, RXSTATUS, HWMONITOR and RAWIMUX logs will all have to be monitored for temperature values and flags.

Field steps

In this section, all the steps required to perform the most precise SPAN installation possible will be covered in detail.

● Lever arm and RBV estimation

Due to logistical and agility considerations, performing a total station survey during a demonstration was completely outside the scope, as it's not strictly required for the system to operate. Approximate measurements done with a tape are often sufficient to obtain appealing results.

In this occasion the original intention was to perform the survey with total station to measure all the lever arms and the RBV rotations as precisely as possible, in fact Marc Calaf González, an old colleague of mine at UPC Enginyeria Tècnica en Topografia was ready with all the required surveying equipment, however, latter on this procedure was discarded because the accuracy of the measurements of the mechanical drawings of the extruded aluminum structure surpassed the accuracy of the total station measurements.

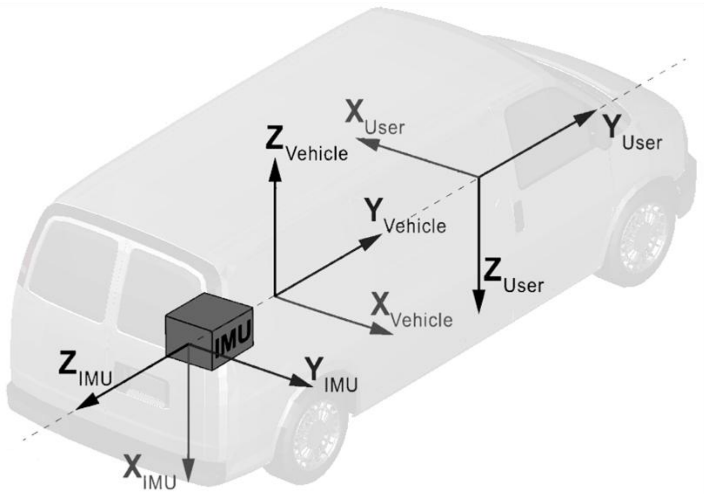

Figure 8. Example of NovAtel SPAN frames.

The main challenge of the total station survey was not to measure the lever arms but the measurement of the rotation angles between the IMU body frame and the vehicle frame due to the small baseline that represents the sides of the Pwrpak7D-E1 enclosure which cause that any small error in the measurement has a big impact in the latter measurement of the slave antenna positioned at about 1 meter from the SPAN enclosure, this was all solved with the aluminum structure designed by Aleix.

The lever arms and rotations were computed as follows[1][2]:

```
<INSCONFIG FILE 0 62.0 FINESTEERING 2379 366559.000 02000200 bba4 17399
<     EPSON_G320 5 50 20 LAND ffbbf AUTOMATIC ROVER FALSE 0 0 0 20 0 00000000 0 0 0 0 3
<          ANT1 IMUBODY 0.0000 0.0000 0.1675 0.0100 0.0100 0.0100 FROM_COMMAND
<          ANT2 IMUBODY 0.0000 -1.0874 0.1055 0.0100 0.0100 0.0100 FROM_COMMAND
<          USER IMUBODY 0.0000 0.0000 0.0931 0.0000 0.0000 0.0000 FROM_COMMAND
<     3
<          RBV IMUBODY 0.0000 0.0000 180.0000 5.0000 5.0000 5.0000 FROM_COMMAND
<          USER IMUBODY 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 FROM_COMMAND
<          ALIGN IMUBODY -3.2633 0.0000 180.0000 1.1289 4.4752 1.0734 FROM_DUAL_ANT
```

[1] IMU to ground height (evaluated in postprocessing by comparing trajectory against LIDAR): -1.764m
[2] The outputs of the Z axis of the NovAtel PwrPak7D-E1 were offset +93.1mm at the MEDEA receiver.

- ## Connectivity preparation

NovAtel SPAN systems are delivered with factory default settings that may or may not suit a particular application. In this case, the PwrPak7D-E1 was delivered in an unknown configuration. In either scenario, it's advisable to ensure the system's configuration meets the requirements of the mission, especially concerning connectivity, as this will determine your ability to communicate with and reconfigure the SPAN system if needed.

The first step is to return the PwrPak7D-E1 to its factory default settings. To do this, there's no need to connect the receiver to an antenna feed; simply connect the receiver to power and USB or serial communication[3]:

`FRESET COMMAND`	[8] Reset to factory defaults except ephemeris, almanacs, approximate position and a few other minor details.
`FRESET ETHERNET`	Revert back to factory defaults to the Ethernet port configuration. ETHCONFIG ETHA AUTO AUTO AUTO AUTO IPCONFIG ETHA DHCP

Table 3. NovAtel factory default commands.

The next step will be to clear out any remaining data from the internal flash so continuing connected over USB i would issue:

`FILEMEDIACONFIG INTERNAL_FLASH`	Switch the storage medium of interest to internal flash.
`FILEDELETE *`	Delete all files in the PwrPak7D-E1 flash memory
`ANTENNAPOWER OFF`	As I don’t have a DC block in my RF splitter and I already have a receiver powering the antenna I disconnect the OEM7720 antenna power supply

Table 4. NovAtel cleaning up commands.

Now it's time to configure the wireless connectivity, which will be used in the car to avoid running cables from the trunk, where the PwrPak7D-E1 will be installed.
In this setup the idea is to configure the Wi-Fi module in the very convenient 'Concurrent' mode, where the module acts as both an access point and a client simultaneously.
It may be noticed that a very verbose way to request logs is used; this follows the old programming adage, 'it is better to be explicit than implicit.'
Now it’s a matter to connect the PwrPak7D-E1 to an RF feed to download recent ephemeris and almanacs. This takes 12.5 minutes for GPS, which is the constellation that requires the longest time.

`LOG THISPORT WI-FISTATUSA ONCHANGED`	Monitor the Wi-Fi module's mode of operation

[3] All the command references made in this document are presented in sequential order of execution unless otherwise noted, sometimes the order in which the commands are issued to the receiver matters.

`WIFIMODE CONCURRENT`	Change the Wi-Fi module's operation mode to 'concurrent' (simultaneous AP and client)
`LOG THISPORT WIFINETLIST ONCHANGED`	List the SSIDs in range of the Wi-Fi client
`WIFINETCONFIG 1 ENABLE <SSID> <Passwd>`	My cellphone Wi-Fi hotspot details to establish a connection
`WIFINETCONFIG 2 ENABLE <SSID> <Passwd>`	My home Wi-Fi details to establish a connection
`INTERFACEMODE NCOM1 RTCMV3 NOVATEL OFF`	Configure the NTRIP port 1 to receive RTCMv3 logs and output NMEA logs
`LOG NCOM1 GPGGA ONTIME 5 0 HOLD`	Output positions to NTRIP port 1 to feed the NTRIP caster for Virtual Reference Station operation. The 'HOLD' modifier is used to ensure these logs are not disabled by a subsequent UNLOGALL command.
`NTRIPCONFIG NCOM1 CLIENT <NTRIPversion> <host/IP> <mountpoint> <user> <password>`	Connect to the NTRIP caster
`LOG THISPORT IPSTATUS ONCE`	Output the IPs used for the PwrPak7D in Ethernet, Wi-Fi AP, and Wi-Fi client modes.
`WIFIAPIPCONFIG <IP> <Subnet Mask>`	If the two IPs mentioned above are the same, then change the AP IP to the desired value. Note that the receiver IP must be known to be able to communicate using the AP.
`WIFIMODE CONCURRENT`	Reset the Wi-Fi module to apply the new SSID and password selected above.
`LOG THISPORT IPSTATUS ONCE`	Check that the newly configured IP is in effect.
`WIFIAPSSID <SSID>`	The default Wi-Fi SSID will be changed to hide the PwrPak7D-E1's Product Serial Number and also shorten the already recognizable SSID.
`WIFIAPPASSKEY <Password>`	It is a good practice to change preconfigured passwords. For Wi-Fi, due to its exposure, 14 characters or more is advisable, even though the field allows for 8 to 64.

`WIFIMODE CONCURRENT`	Reset the Wi-Fi module to apply the new SSID and password selected above.
~~`SBASCONTROL ENABLE EGNOS`~~	Enables the European Satellite-Based Augmentation System (EGNOS) as a fallback positioning correction source if RTK becomes unavailable. Great for open sky scenarios not so great for urban areas where GPS only may be detrimental to the Dilution Of Precision.
`THISANTENNATYPE NOV850`	Tells the receiver firmware to use the NovAtel GNSS-850 antenna model for the master antenna, slave antenna can't be configured as per the current firmware implementation.
`NMEATALKER AUTO`	With SPAN enabled, the NMEA logs change theirs IDs to IN in single and multi-constellation use cases, except the GPGSA, GPGRS, GPHDT logs, which report a GN talker ID, and GPGSV. Useful for the NMEA logs used to monitor the progress of the data take in QGIS in the following command sets.
`LOG ICOM2 GPGGA ONTIME 1 0 HOLD`	Positioning real time solution in NMEA format on TCP port 3002 to be processed by QGIS as a moving map.
`LOG ICOM2 GPGSA ONTIME 1 0 HOLD`	GPS DOP and active satellites in NMEA format on TCP port 3002 to be processed by QGIS as a moving map.
`LOG ICOM2 GPGST ONTIME 1 0 HOLD`	Estimated error in position solution in NMEA format on TCP port 3002 to be processed by QGIS as a moving map.
`LOG ICOM2 GPGSV ONTIME 1 0.05 HOLD`	Satellites in view in NMEA format on TCP port 3002 to be processed by QGIS as a moving map. A small temporal offset is required to avoid sky plot flickering.
`LOG ICOM2 GPRMC ONTIME 1 0 HOLD`	GNSS specific information in NMEA format on TCP port 3002 to be processed by QGIS as a moving map.
`SAVECONFIG`	Store all configurations in the PwrPak7D's Non-Volatile Memory.

Table 5. NovAtel connectivity and antenna configuration.

This configuration will provide:

- PwrPak7D-E1 Wi-Fi Client sending GGA logs to a remote caster who is going to return us the raw GNSS observables of a Virtual Reference Station in RTCM version 3 format.
- PwrPak7D-E1 Wi-Fi access point, which will be used for real-time receiver monitoring using the NovAtel Application Suite on a Windows laptop.
- System monitoring over QGIS.

Rotation Body to Vehicle double pass calibration

To compute the most accurate RBV angles, it's necessary to drive the SPAN system while running the RBV calibration routine twice over the same straight path (page 116 of [9]), once in each direction. This technique ensures that errors due to terrain slopes are canceled out, as they would be observed in opposite ways in each direction. Conversely, vehicle slopes would always be measured in the same way in each direction.
An accurate RBV calibration is important because SPAN constraints are applied in the vehicle frame domain, and the RBV rotations define the relationship between the IMU body frame, frame where the IMU sensors are referenced to, and the vehicle frame.

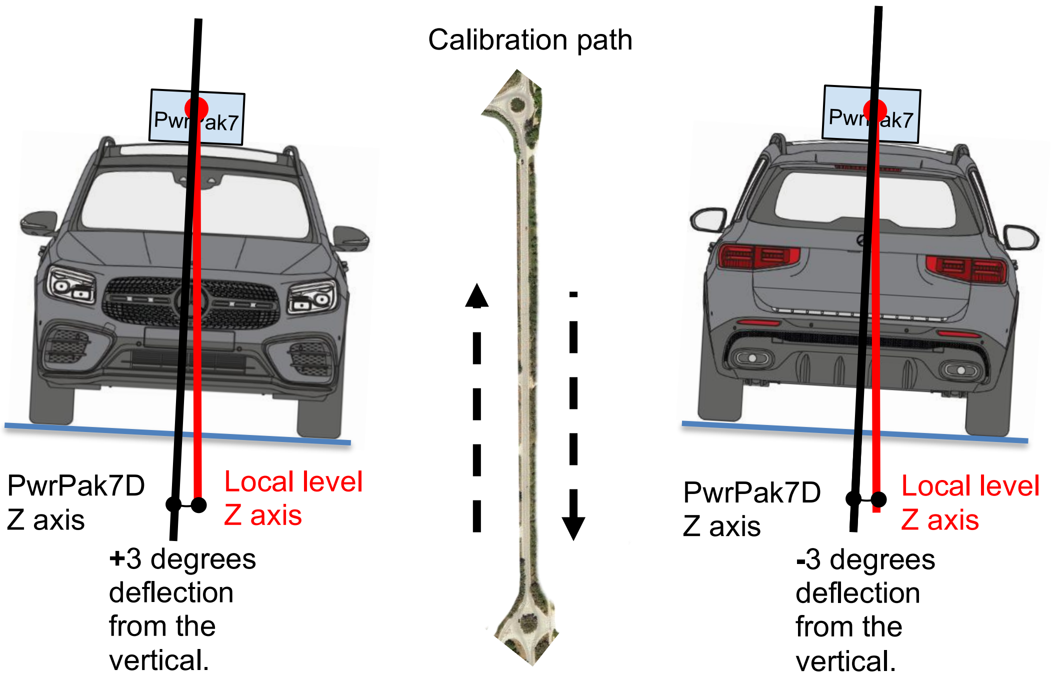

Figure 9. Mercedes-Benz GLB car displaying a lateral terrain slope (roll) of 3 degrees which deflects de vertical.

After a wide-area search for a straight pathway that would legally allow driving in both directions over the same path, and which is 250 meters or more in length, the following was found (see Figure 10): a 450-meter straight path with almost no transverse slope and little longitudinal slope:

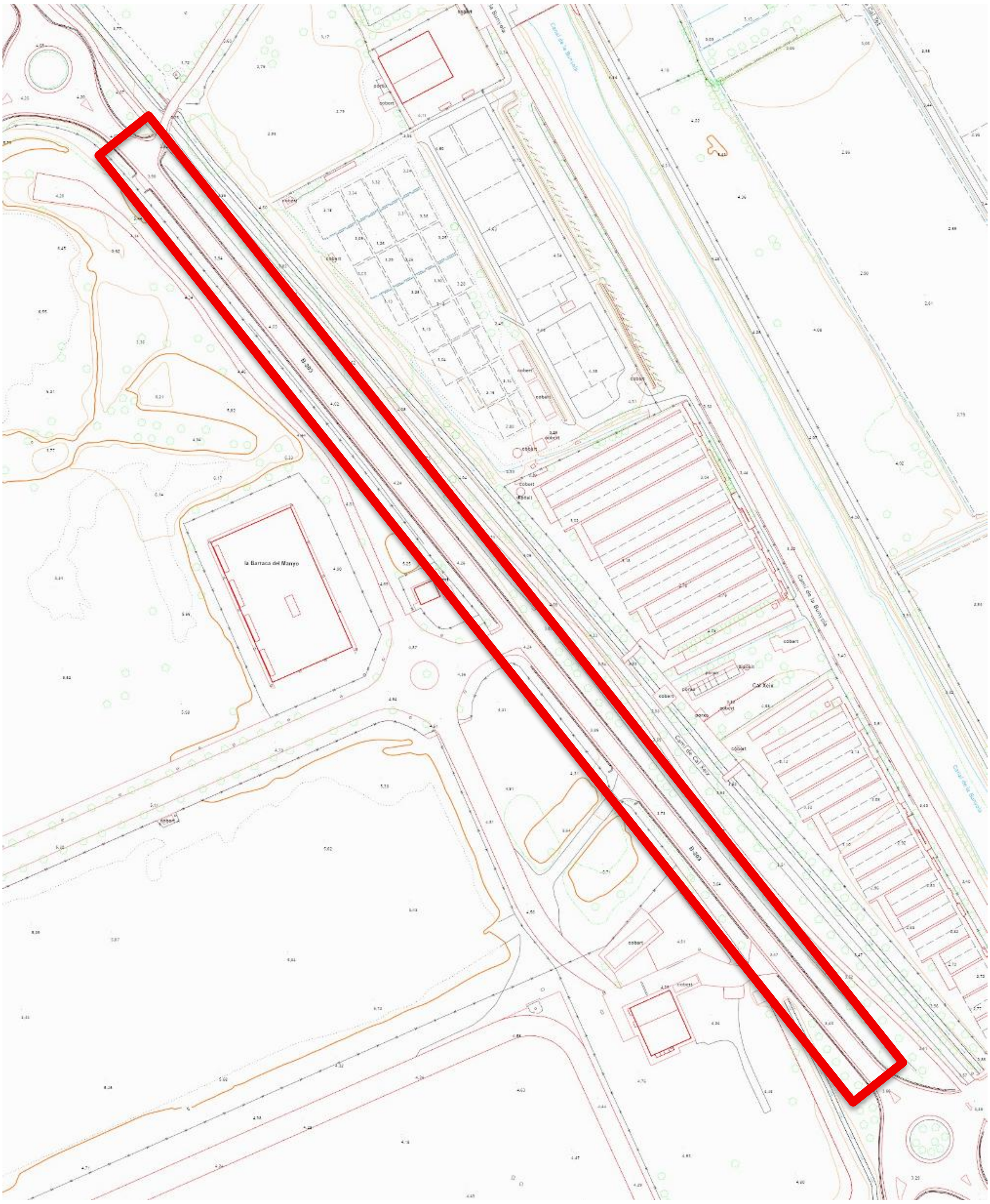

Figure 10. Map courtesy of Institut Cartogràfic i Geològic de Catalunya displaying the chosen SPAN calibration area

In Catalunya the government provides non comercial cartographic products, such as LiDAR point clouds, which allowed to precisely measure the path's slope before visiting the physical location.

The plot in Figure 11 shows the longitudinal slope of those 450 meters, as points in the LiDAR point cloud were plotted in a vertical flat plane. Note the significant difference between the Y-axis and X-axis scaling (2 meters vs. 450 meters), resulting in a pronounced vertical exaggeration (x225 times).

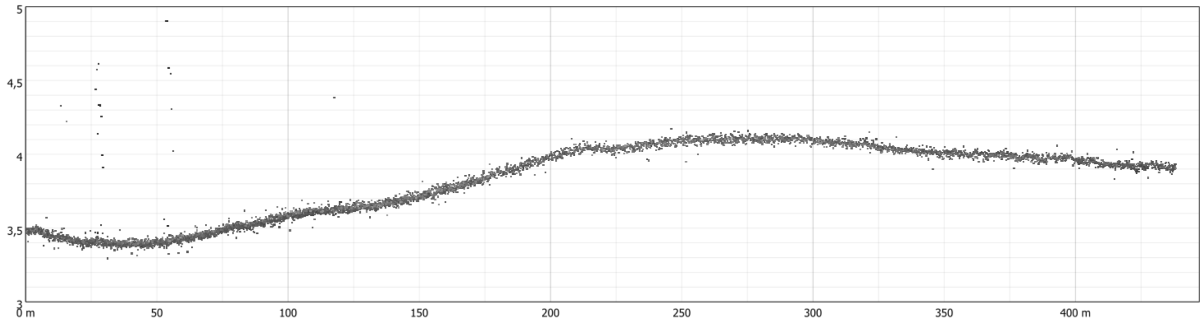

Figure 11. Longitudinal slope of the chosen calibration path.

While it's not possible to include them in this document for brevity, the same analysis performed on the longitudinal axis was also conducted transversely to the path's axis. This revealed no relevant slopes, indicating a well-suited test site.

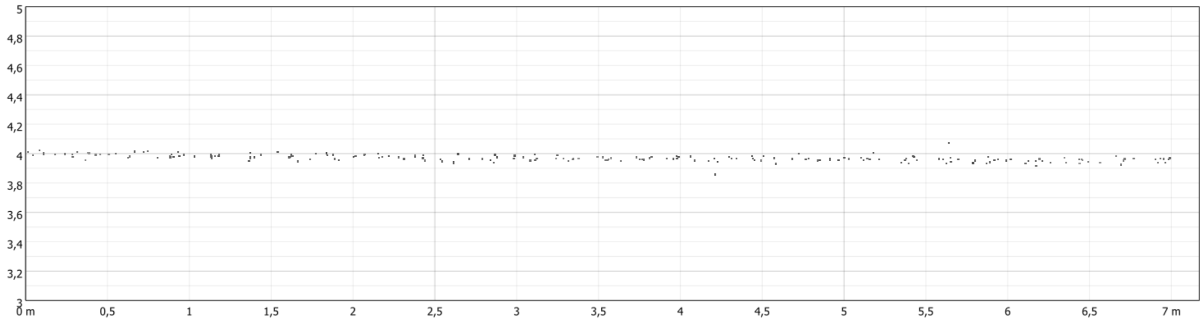

Figure 12. Sample transversal profile

Let's now see how the PwrPak7D-E1 was configured before leaving the parking in Barcelona city center following NovAtel documentation advice which lists the basic SPAN configuration commands as follows:

Required Information	**Required Command**
IMU type and communication port	CONNECTIMU
IMU to primary antenna lever arm	SETINSTRANSLATION ANT1
IMU to vehicle frame rotation	SETINSROTATION RBV

Common User Settings	Appropriate Command	Notes
IMU to secondary antenna lever arm	**SETINSTRANSLATION** ANT2	Only required for dual antenna systems
IMU to output position offset	**SETINSTRANSLATION** USER	Default output position is at the IMU center
IMU to output frame rotation	**SETINSROTATION** USER	Default output frame is the vehicle frame as defined by SETINSROTATION RBV input
Vehicle type	**SETINSPROFILE**	
Minimum alignment velocity	**SETALIGNMENTVEL**	

Table 6. NovAtel documentation recommended basic SPAN commands.

To configure the system PwrPak7D-E1 will be connected over the Wi-Fi access point and PuTTY terminal emulator will be connected on ICOM port number 1 at TCP port 3001 (factory default). Keep in mind that the default IP address when connecting to the PwrPak7D-E1 over the Wi-Fi access point is 192.168.19.1:

`ANTENNAPOWER ON`	It is necessary to power the GNSS main antenna now that the receiver is no longer connected to the home RF splitter; otherwise, the PwrPak7D-E1 would not work.
`SETINSTRANSLATION ANT1 0 0 0.1675 0.01 0.01 0.01`	Primary antenna ARP X, Y and Z in IMU frame as provided in the CAD drawing
`SETINSROTATION RBV 0 0 180 5.0 5.0 5.0`	As mentioned earlier, the IMU body has been installed with its +Y axis backward motion and +X axis right and +Z axis up, with a rotation along Z axis to match the vehicle frame (+Y forward, +X right and +Z up).
`SETINSTRANSLATION ANT2 0 -1.0874 0.1055 0.01 0.01 0.01`	Secondary antenna L1 phase center X, Y and Z in IMU frame as provided in

	the CAD drawing (not to ARP because no antenna model is used)
SETINSTRANSLATION USER 0 0 0.0931 0 0 0	The intention is to only offset the Z-axis of the outputs so that the SPAN trajectory is approximately at MEDEA's height.
SETINSROTATION USER 0 0 0 0 0 0	Because there is no interest in rotating the axes in which the SPAN outputs are provided. The outputs will be Y axis forward X axis right Z axis up.
SETINSPROFILE LAND	NovAtel engineers have developed algorithms that significantly improve SPAN performance simply by specifying that the vehicle it's a car.
SETALIGNMENTVEL 5.0	To start the SPAN alignment, the vehicle's speed should exceed 18 km/h. Unless strictly necessary, it's not a good idea to decrease this default value.
LOG THISPORT INSCONFIGA ONCHANGED	Output a single log of the entire SPAN configuration that has just been inputted, useful for troubleshooting, post-processing, and future reference.
LOG ICOM1 INSPVAXA ONTIME 1.0 0.0	Monitor all real-time Position Velocity Attitude Time SPAN outputs in ASCII at a 1 Hz output rate (once per second).
LOG ICOM1 INSCALSTATUSA ONCHANGED	Outputs the status of the RBV calibration routine, allowing us to track the procedure's progress in real time.
SAVECONFIG	Store all configurations in the PwrPak7D-E1's Non-Volatile Memory.

Table 7. SPAN basic configuration commands.

After the several-kilometer trip from the car parking to the calibration site, the SPAN solution is well converged, and there a reasonably open-sky visibility—perfect conditions to execute the RBV calibration routine.

As the vehicle traverses the calibration zone, efforts are made to quickly reach 18 km/h to maximize the calibration range, keeping in mind that areas where the vehicle was not driving above 18 km/h will not be included. The following commands will be used in the calibration area; note that this list is not expressed in sequential order, so use them at your discretion:

INSCALIBRATE RBV NEW	Starts the recording of data for the calibration process

INSCALIBRATE RBV STOP	Stores the current 'leg' of the calibration; this command is used at the end of each straight calibration run..
INSCALIBRATE RBV ADD	Begins recording data for an additional 'leg' of the calibration process.
INSCALIBRATE RBV RESET	Drops the data from the current calibration 'leg' so it is not considered in the final calibration.

Table 8. unordered SPAN calibration commands.

The routines to calibrate the IMU-to-GNSS antenna lever arms are not available for the lowest SPAN grades, such as the PwrPak7D-E1. Therefore, a manual survey is essential in our case.

The results of the SPAN RBV calibration are as follows:

```
<INSCONFIG FILE 0 18.5 FINESTEERING 2379 371614.000 02008200 bba4 17399
<     EPSON_G320 5 50 20 LAND ffbbf AUTOMATIC ROVER FALSE 0 0 0 20 0 00000000 0 0 0 0 3
<          ANT1 IMUBODY 0.0000 0.0000 0.1675 0.0100 0.0100 0.0100 FROM_COMMAND
<          ANT2 IMUBODY 0.0000 -1.0874 0.1055 0.0100 0.0100 0.0100 FROM_COMMAND
<          USER IMUBODY 0.0000 0.0000 0.0931 0.0000 0.0000 0.0000 FROM_COMMAND
<     3
<          RBV IMUBODY 1.4446 0.0736 179.7775 0.4403 3.0640 0.4316 CALIBRATED
<          USER IMUBODY 0.0000 0.0000 0.0000 0.0000 0.0000 0.0000 FROM_COMMAND
<          ALIGN IMUBODY -3.2633 0.0000 180.0000 1.1289 4.4752 1.0734 FROM_DUAL_ANT
```

- ## Barcelona trajectory planning

The 32.2 kilometers long planned trajectory within the city of Barcelona goes through the following streets, avenues and roads:

1. Start
2. Avinguda Meridiana
3. Carrer de Bartrina
4. Carrer del Palomar
5. Passeig de Torras i Bages
6. B-10 Ronda Litoral
7. Avinguda Paral·lel
8. Gran Via de les Corts Catalanes
9. Ronda General Mitre
10. Travessera de Dalt
11. Ronda del Guinardó
12. Avinguda de l’Estatut de Catalunya
13. Carrer de les Ciències
14. Carrer de Dante Alighieri
15. Passeig Maragall
16. Carrer Pintor Casas
17. Carrer de Cartellà
18. Carrer de Costa i Cuixart
19. Carrer d’Escòcia
20. Carrer de Concepció Arenal
21. Carrer Sòcrates

22. Carrer Neopatria
23. Carrer Llenguadoc
24. Carrer de les Monges
25. Carrer del Montsec
26. Carrer de Pare Secchi
27. Carrer d'Ignasi Iglesias
28. Carrer gran de Sant Andreu
29. Rambla Fabra i Puig
30. Carrer de Concepció Arenal
31. Avinguda Meridiana
32. Carrer de Rubén Dario
33. Carrer de Renart
34. Riera de Sant Andreu
35. End

This route was configured so that is representative of the different urban environments in a city like Barcelona but emphasis was made in crossing as many tunnels and underpasses as possible to test SPAN algorithms and a close second was the abundance of narrow street driving.

Figure 13. Google Earth Pro Planed trajectory within the city of Barcelona.

To monitor the car progress during the kinematic run Quantum GIS (or QGIS for short) GUI software will be used as it is one of the few freely available apps able to operate as a moving map processing NMEA (GGAs among others) sentences directly from a TCP/IP connection in real time, which is very convenient because in this way the Wi-Fi access point connection will suffice avoiding the need to run a USB or Serial cable from the PwrPak7D-E1.

● Barcelona city SPAN recording

Normally the calibration, previous step, and the actual trajectory recording are going to be two separate processes that typically happen at different moments in time, however in our case we wanted to record the path towards the calibration area and the return along the trajectory within Barcelona in one go.
Because of this, we executed all the commands of those two steps in one batch and in this way, we recorded the real-time dataset and all necessary post-processing data for further refinement and analysis within the powerful Inertial Explorer software for the whole trajectory, calibration included.
All logs recorded in the file stored in the receiver's memory are in binary, making them more compact and machine-friendly for computer interpretation. However, all logs outputted through the TCP/IP port for my own consumption are in ASCII format, as it is required to read them in real time and the logs for QGIS real time processing are in NMEA 183 format.
So, let's review the configuration commands required before starting our kinematic run:

`UNLOGALL ALL_PORTS`	Clear any output on all receiver ports to prevent previous receiver configurations where logs are outputted from consuming available receiver CPU idle time.
`FILEROTATECONFIG 0 4096 OVERWRITE`	The recordings should not be time-limited; the file size should be the largest possible file size (4 GB) and old files should be overwritten with new ones when the memory is full.
`FILECONFIG OPEN`	It's very important to start recording the file BEFORE adding logs to it; otherwise, important information could be lost, particularly on logs outputted ONCE or ONNEW / ONCHANGED.
`LOG FILE VERSIONB ONCE`	Uniquely identifies the receiver and the currently loaded firmware model, useful for traceability and troubleshooting.
`LOG FILE RXCONFIGB ONCE`	Outputs the receiver's command configuration, important for troubleshooting.
`LOG FILE GPSEPHEMB ONNEW`	GPS ephemeris for post-processing
`LOG FILE GLOEPHEMERISB ONNEW`	GLONASS ephemeris for post-processing

`LOG FILE GALINAVEPHEMERISB ONNEW`	Galileo ephemeris for post-processing. Broadcasted at E1 frequency which should always be enabled so this log will always be present for Galileo enabled receivers.
`LOG FILE GALFNAVEPHEMERISB ONNEW`	Galileo ephemeris for post-processing. Because it is broadcasted on the E5a frequency and standard SPAN systems are L1 and L2 but not L5 (E5a) it may well be that the receiver doesn't output this log.
`LOG FILE BDSEPHEMERISB ONNEW`	BeiDou ephemeris for post-processing
`LOG FILE THISANTENNATYPEB ONCE`	Master antenna information output for seamless transfer to Inertial Explorer.
`LOG FILE RXSTATUSB ONCHANGED`	Receiver status and error words, useful for troubleshooting.
`LOG FILE INSCONFIGB ONCHANGED`	All SPAN configurations (antenna lever arms, Rotations Body to Vehicle, etc.), useful for post processing and troubleshooting.
`LOG FILE HEADING2B ONNEW`	ALIGN heading updates from the slave antenna, to be used for post-processing
`LOG FILE HWMONITORB ONTIME 60 0`	Monitor hardware parameters, such as the OEM7720 CPU temperature.
`LOG FILE TIMEB ONTIME 1 0`	Provides temporal offsets to the post-processing software.
`LOG FILE RANGECMPB ONTIME 1 0`	GNSS raw observables in a compressed format at 1 Hz (no post processing benefit from recording this log at higher frequencies). Basic log for post processing
`LOG FILE RANGECMPB_1 ONTIME 1 0`	GNSS raw observables for the ALIGN slave antenna
`LOG FILE BESTGNSSPOSB ONTIME 0.1 0`	Best (presumed most accurate) GNSS only (no inertial aiding except for the receiver tracking loops steering) positioning solution
`LOG FILE BESTPOSB ONTIME 0.1 0`	Best position, redundant with INSPVAX log but NovAtel Application Suite unlike with INSPVAX can convert BESTPOS into Google Earth KML for quick and convenient trajectory quality assessment. 1Hz output rate is important as higher data rates may clog Google Earth with too much data, this is especially true on long data takes.

`LOG FILE INSPVAXB ONTIME 0.1 0`	Real-time computed Position, Velocity, and Attitude information at 10 Hz. While higher frequencies are possible, their benefit is dubious; at 80 km/h (the maximum allowed on Barcelona's fast routes), 10 Hz represents a position update every 2.2 meters.
`LOG FILE RAWIMUSXB ONNEW`	IMU raw readings at the native Epson G320N output rate (125 Hz). Basic log for post processing.
`LOG ICOM1 RXSTATUSA ONCHANGED`	Output for real-time monitoring of any errors that may occur in the system during recording.
`LOG ICOM1 FILESTATUSA ONTIME 60 0`	Output for real-time file size monitoring every 10 seconds.
`LOG ICOM1 HWMONITORA ONTIME 60 0`	Output for real-time monitoring of the OEM7720 CPU temperature.
`LOG ICOM1 RAWIMUSX ONTIME 60 0`	Output the IMU raw data to analyze the temperature of the sensors
`LOG ICOM1 INSPVAXA ONTIME 1 0`	Real-time monitoring of the SPAN real-time PVA solution plus the SPAN solution status bits.
`LOG FILE LOGLISTB ONCE`	Store the complete list of logs being outputted in the file, useful for troubleshooting.
~~`SAVECONFIG`~~	Store all configurations in the PwrPak7D-E1's Non-Volatile Memory. Not really useful in our case because logs outputted as ONCE are not stored in the list of logs to be outputted therefore if the receiver is power cycled the file created after the power up would be incomplete.

Table 9. Kinematic run logging and monitoring commands.

After all those commands have been issued QGIS is connected to TCP port 3002 to provide a real time representation of the trajectory.

In this configuration set, there's no mention of datum/reference frame configuration, this is because NovAtel receivers do not apply datum transformations to code only DGNSS and RTK solutions. Therefore, the datum/reference frame in which the base station's coordinates are expressed will be the same as the outputted position at the rover receiver. In Europe, RTK networks are typically configured in the ETRS89 reference frame, which differs from the WGS84/ITRF2020 datum used by GPS, Google Maps, and Google Earth. Bear this in mind when plotting the real-time trajectory, as a constant offset may become obvious when plotting over Google cartography.

Inertial Explorer software does not have the same reference frame/datum transformation limitations as SPAN receivers, so it can transform DGNSS and RTK solutions to any datum/reference frame.
After Barcelona's city run is finished, it's time to adequately close the open file and ensure the file size is reasonable before powering down the system.

FILECONFIG CLOSE	Close the open file
UNLOGALL ALL_PORTS	Clear all outputs
LOG THISPORT FILELISTA ONCE	Output the file status and file size

Table 10. Kinematic run closure commands.

Office based work

In this chapter we will review all the steps that will lead to a final trajectory product from the postprocessing software.

● Google Earth quick trajectory quality assessment

Not long after we arrived at our finishing landmark and the kinematic data take ended, all the material was disassembled; the real time trajectory was dumped from the PwrPak7D-E1 onboard memory to quickly gaze if everything went well or on the contrary there was some sort of issue.

This exercise led to two main conclusions:

1. The SPAN filter convergence phase does show inconsistencies (broken trajectory / substantial position jumps) for the first 2.7 minutes of kinematic trajectory (see Figure 16) as the typical figure eights drawn with the vehicle were not performed at the beginning of the path because it was not possible in the city streets and therefore this was a totally expected situation that was deemed as “likely to be solvable with post processing” (backwards post processing).
2. The exits of the long tunnels (2.3 minutes of driving the longest one) show noticeable position snaps (return to correct path after deviation) due to IMU drift (see Figure 15), this is expected, especially for low grade IMUs like the Epson G320N, and was deemed as “likely to be mitigable with post processing”.

The areas of the trajectory not affected by the aforementioned two expected issues looked fine and therefore it meant that the data take was successful.

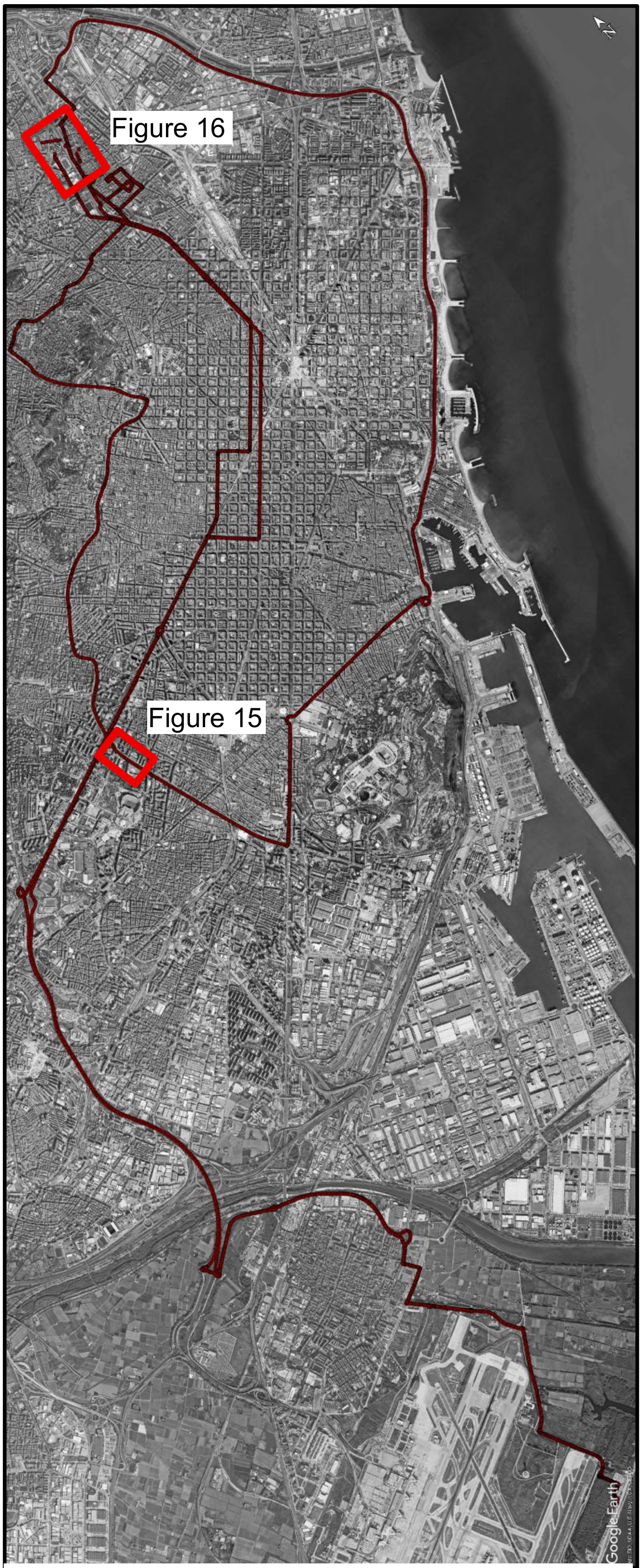

Figure 14. Google Earth real time BESTPOS output

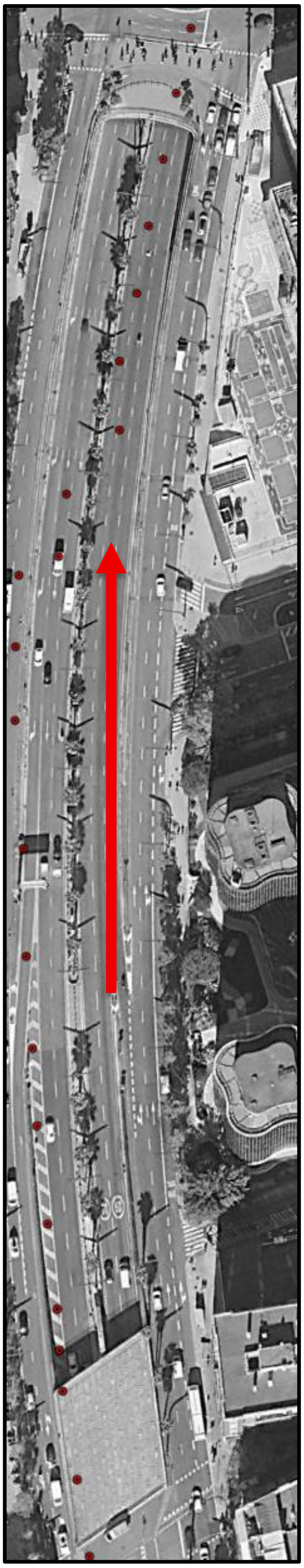

Figure 15. Long tunnel exit with position snap.

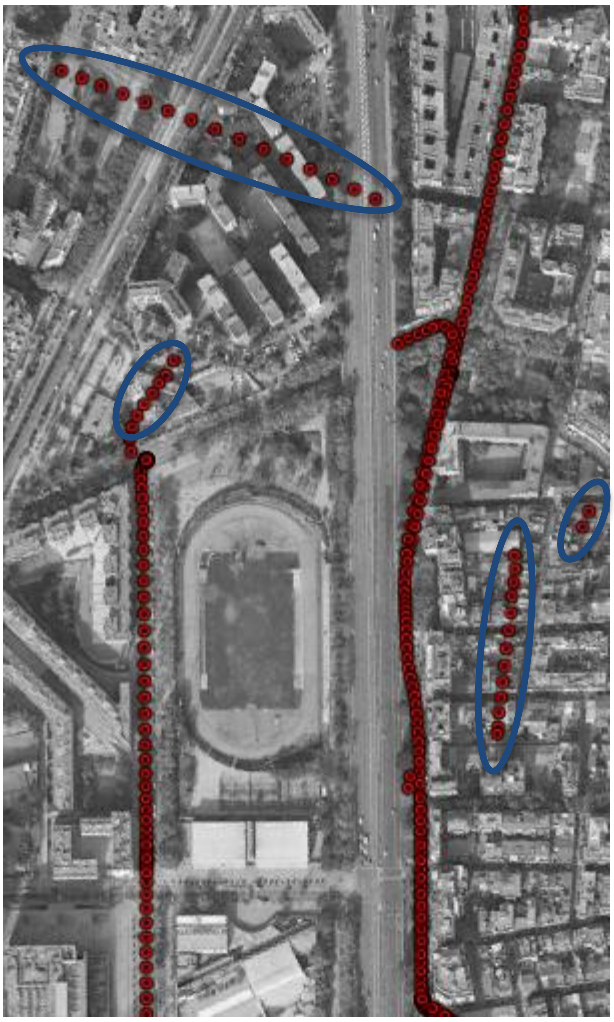

Figure 16. Pre convergence trajectory position ramblings outside the expected path.

Inertial Explorer is the industry standard when it comes to inertial and GNSS coupling post processing software bringing the highest levels of accuracy and quality assurance to the table. In this section Inertial Explorer post processing settings will be reviewed.

The post processing of this dataset was made possible thanks to the implication of Vladimir Suvorkin who is preparing his doctoral thesis within GAGe at UPC, institution who kindly lend temporarily the software license for the preparation of this document.

● Base station data gathering and raw data preparation for post-processing

The two basic elements required to post process any GNSS dataset are:

1. The kinematic dataset recorded in Barcelona containing the GNSS raw data from the PwrPak7D-E1 receiver memory.
2. The GNSS raw data of the base station or base stations that cover the whole SPAN trajectory.

In the previous step we assessed that the first dataset seems to be complete but now we have to gather the RINEX (raw data) files from the stations we are going to use in our post processing.
The Institut Cartogràfic I Geològic de Catalunya (ICGC) has the Servei de Posicionament Geodèsic Integrat de Catalunya (SPGIC) network of stations that cover the entirety of the Catalan territory and is paid with taxes so it's open to the public use without additional charges.

As it will become obvious by looking at the map of stations of Figure 17 Barcelona is surrounded by 3 GNSS stations:

- GARR (Garraf)
- PLAN (Les Planes)
- MARE (Maresme)

Knowing that we have 3 different choices to move on:

1. Download and use one of the stations hoping that the baseline rover – base does not become too long (remember that under ideal conditions, which in urban environment is not our case, error grow in PPK is dictated by equation 1 centimeter plus one part per million of the baseline length, so the longer the baseline the bigger the position errors).
2. Create a VRS (Virtual Reference Station) with the web user interface to obtain a virtual station positioned in the center of the trajectory, which requires us to estimate the coordinates to be inputted in the web UI.
3. Download and use the 3 stations, knowing that the processing times are going to be noticeably longer.

In our case we have chosen to go with the third option as we have no temporal constraints and the post processing strategy is clear which means that unless we face problems we don't expect to reprocess much.

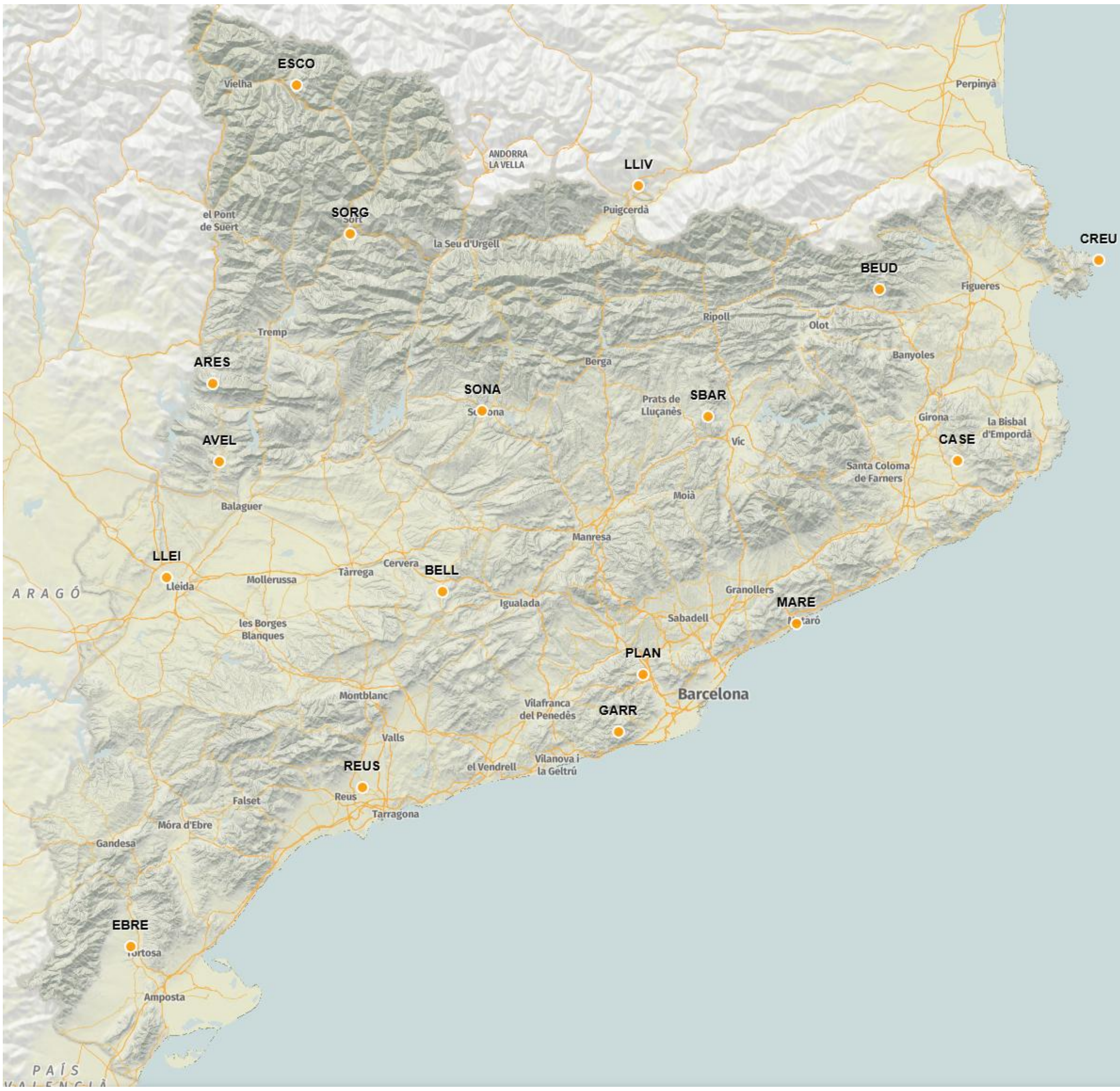

Figure 17. ICGC SPGIC GNSS network of stations.

Because every web service is likely to be different, we won't dive in to the specifics of the download procedure but in the end, we have to end with a list of RINEX files that cover the temporal span of the SPAN rover file, in our example from 05:45:00 GPS time to 09:29:59 GPS time (3.75 hours) at 1Hz (one GNSS observation every second) which is:

garr226f45.25f	plan226f45.25f	mare226f45.25f
garr226f45.25g	plan226f45.25g	mare226f45.25g
garr226f45.25l	plan226f45.25l	mare226f45.25l
garr226f45.25n	plan226f45.25n	mare226f45.25n
garr226f45.25o	plan226f45.25o	mare226f45.25o
...	...	...
...	...	...
...	...	...
...	...	...
...	...	...
garr226j15.25f	plan226j15.25f	mare226j15.25f
garr226j15.25g	plan226j15.25g	mare226j15.25g
garr226j15.25l	plan226j15.25l	mare226j15.25l
garr226j15.25n	plan226j15.25n	mare226j15.25n
garr226j15.25o	plan226j15.25o	mare226j15.25o

The file name structure, read from left to right, is as follows:

1. First four letters are the station ID
2. Next three numbers are the day of the year
3. A single letter of the alphabet:
    a. a from 00:00:00 to 00:59:59 GPS time.
    b. b from 01:00:00 to 01:59:59 GPS time.
    c. c from 02:00:00 to 02:59:59 GPS time.
    d. d from 03:00:00 to 03:59:59 GPS time.
    e. e from 04:00:00 to 04:59:59 GPS time.
    f. f from 05:00:00 to 05:59:59 GPS time.
    g. g from 06:00:00 to 06:59:59 GPS time.
    h. h from 07:00:00 to 07:59:59 GPS time.
    i. i from 08:00:00 to 08:59:59 GPS time.
    j. j from 09:00:00 to 09:59:59 GPS time.
    k. k from 10:00:00 to 10:59:59 GPS time.
    l. l from 11:00:00 to 11:59:59 GPS time.
    m. m from 12:00:00 to 12:59:59 GPS time.
    n. n from 13:00:00 to 13:59:59 GPS time.
    o. o from 14:00:00 to 14:59:59 GPS time.
    p. p from 15:00:00 to 15:59:59 GPS time.
    q. q from 16:00:00 to 16:59:59 GPS time.
    r. r from 17:00:00 to 17:59:59 GPS time.
    s. s from 18:00:00 to 18:59:59 GPS time.
    t. t from 19:00:00 to 19:59:59 GPS time.
    u. u from 20:00:00 to 20:59:59 GPS time.
    v. v from 21:00:00 to 21:59:59 GPS time.
    w. w from 22:00:00 to 22:59:59 GPS time.
    x. x from 23:00:00 to 23:59:59 GPS time.
4. Two numbers representing the hourly quarter that can be:
    a. 00
    b. 15
    c. 30
    d. 45
5. Period signifying that after the sign comes the extension of the file.
6. Two numbers representing the year
7. One letter that can be:
    a. "O": Observation file, contains the raw GNSS observables (code pseudo-range, carrier phase cycle, frequency doppler shift and the carrier to receiver noise ratio).
    b. "N": GPS Navigation message
    c. "G": GLONASS Navigation message
    d. "E": Galileo Navigation message
    e. "C": BeiDou Navigation message
    f. "J": QZSS (Japan) Navigation message
    g. "I": NavIC / IRNSS Navigation message
    h. "M": Mixed navigation (multiple constellations in one file)

To be used in the Inertial Explorer processing all GNSS raw data must be converted to the proprietary file format GPB by using the converter provided with Inertial Explorer.

Proceed as follows:

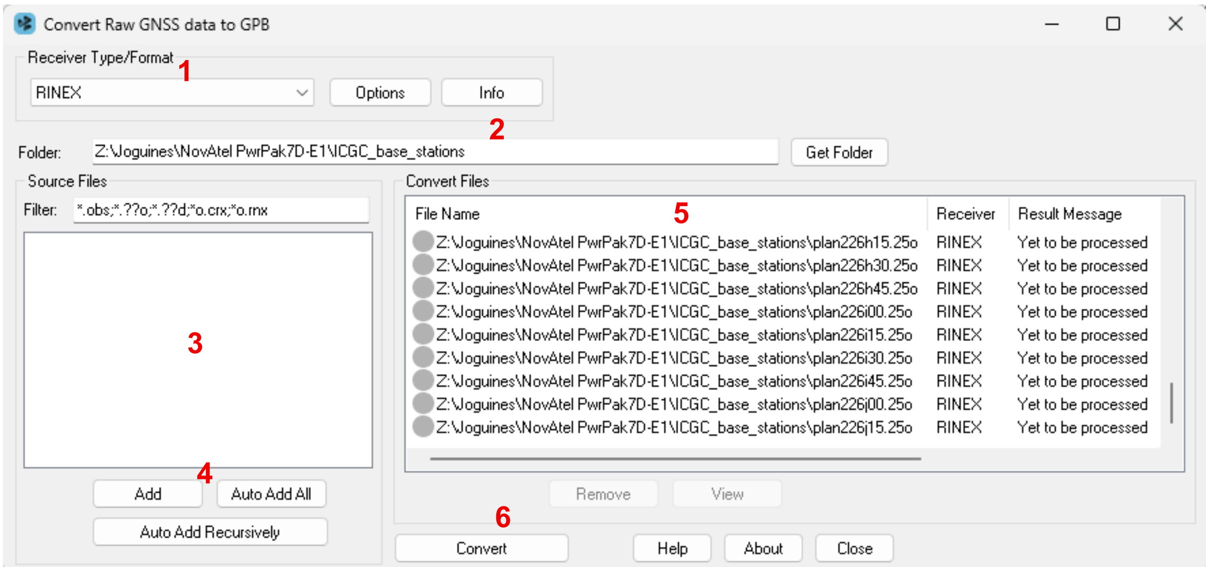

Figure 18. Inertial Explorer GPB Converter.

1. Check that the file format selected is corresponding to the files you want to convert, in our case it's RINEX.
2. Select the folder where you stored all the raw GNSS files by clicking on "Get Folder" button.
3. A complete list of all the files matching your file type selection on step 1 will be presented here.
4. Click "Auto Add All" button, after doing this operation the list of files that you had in window number 3 will automatically be transferred to window 5 with a "Result Message" for every file "Yet to be processed"
5. We are ready to perform the conversion.
6. Press "Convert", an iterative process will start which may take a while.

After the processing you would end up with the following new files:

garr226f45.sta garr226f45.gpb garr226f45.epp garr226j15.sta garr226j15.gpb garr226j15.epp	mare226f45.sta mare226f45.gpb mare226f45.epp mare226j15.sta mare226j15.gpb mare226j15.epp	plan226f45.sta plan226f45.gpb plan226f45.epp plan226j15.sta plan226j15.gpb plan226j15.epp

As can be seen the first part of the file name is identical to the RINEX name but now we have less files and the extensions are different:

- .STA ➔ station file, contains the header of the RINEX observation file, can be opened in a normal text editor as the contents are plain text.
- .EPP ➔ contains the amalgamation of all the ephemeris files (RINEX "N", "G", "E", "C", "J", "I" and / or "M"), can be opened in a normal text editor as the contents are plain text.
- GPB ➔ contains the raw observables from the RINEX observation "O" file, it's binary, can only be read with Waypoint GPB reader.

Finally, the many files for each of the three stations will have to be concatenated to obtain a single continuous file for each of the three stations using Waypoint "Concatenate, Slice and Resample GPB files" application and we will have to repeat the operation 3 times, once per every station file that we want to obtain:

1. Open the application
2. Click Add at the top right corner.
3. Add all the files form a single station (don't mix up stations or you will obtain a broken / unusable concatenated GPB file).
4. On the Output file select the name of the output file by clicking "Browse"
5. Click "Go" at the bottom of the user interface leaving the default options.
6. Wait for the process to finish.

This procedure is to be repeated for as many different stations as you have.

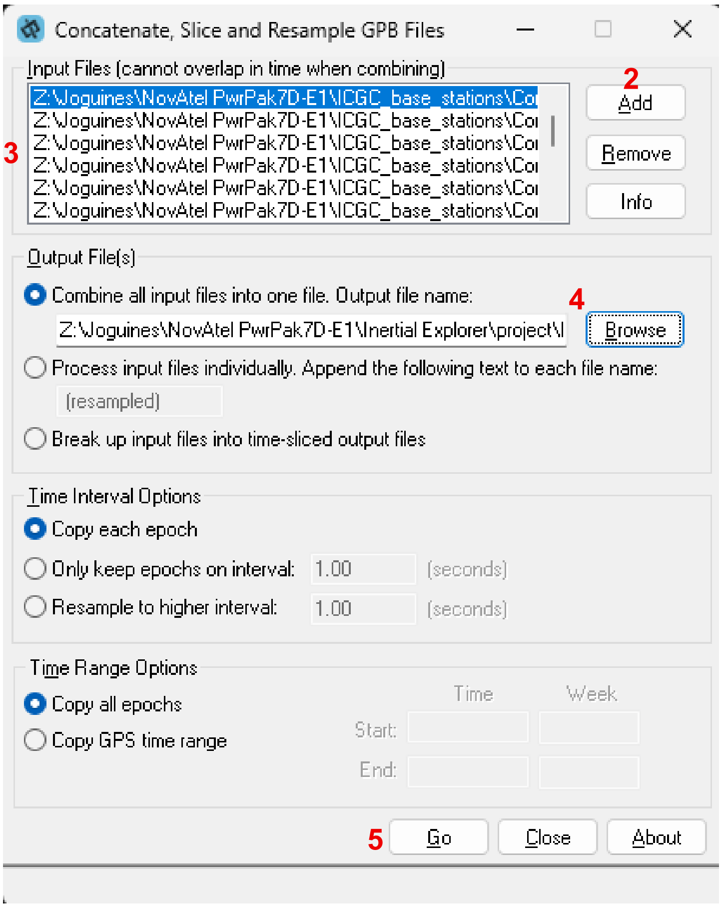

Figure 19. Waypoint Concatenate application.

This same process should be followed with the file coming out of the NovAtel PwrPak7D-E1 memory but it is going to be a single file that will be converted to 5 files, one .STA, one .EPP, one .GPB as explained above and two additional files:

- .IMR ➔ IMU raw data file, binary, can only be opened with Waypoints IMR viewer.
- .HMR➔ NovAtel ALIGN heading updates, binary, can only be opened with Waypoints HMS viewer.

Note that because NovAtel SPAN files are single continuous data sets there will be no need to concatenate anything.

• Inertial Explorer data post-processing

In this chapter we will review how to post process, using Inertial Explorer, a standard kinematic NovAtel SPAN dataset employing good all-around standard settings by using the guidance provided by the "Wizard".

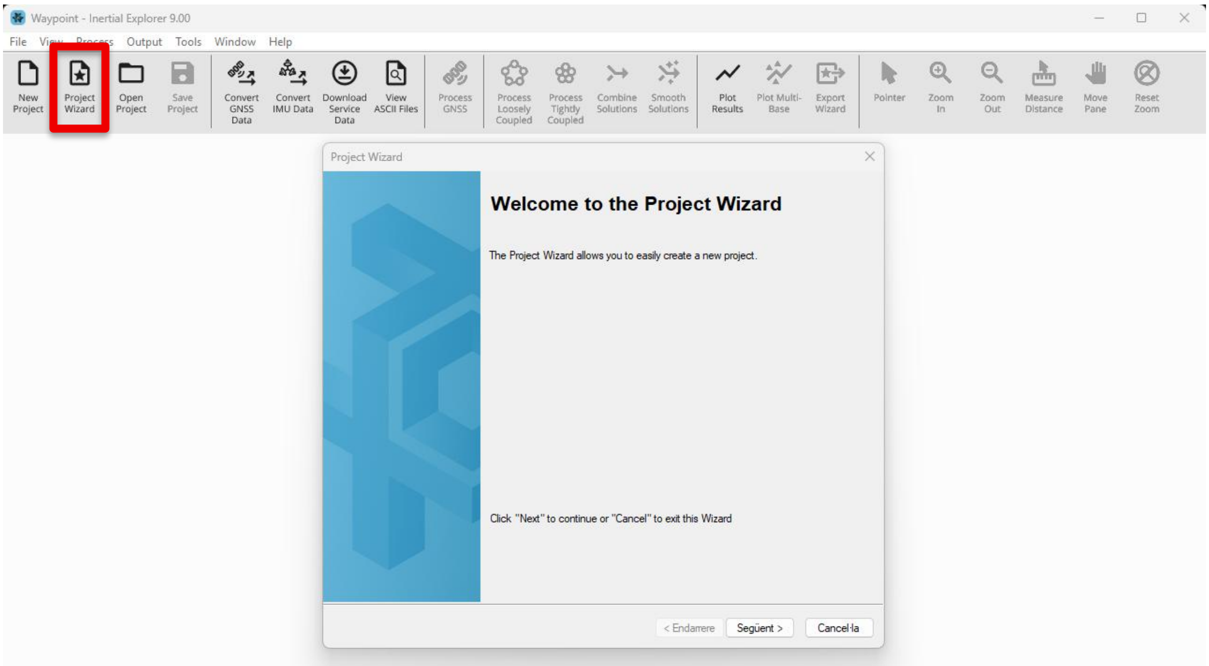

Figure 20. Inertial Explorer Wizard.

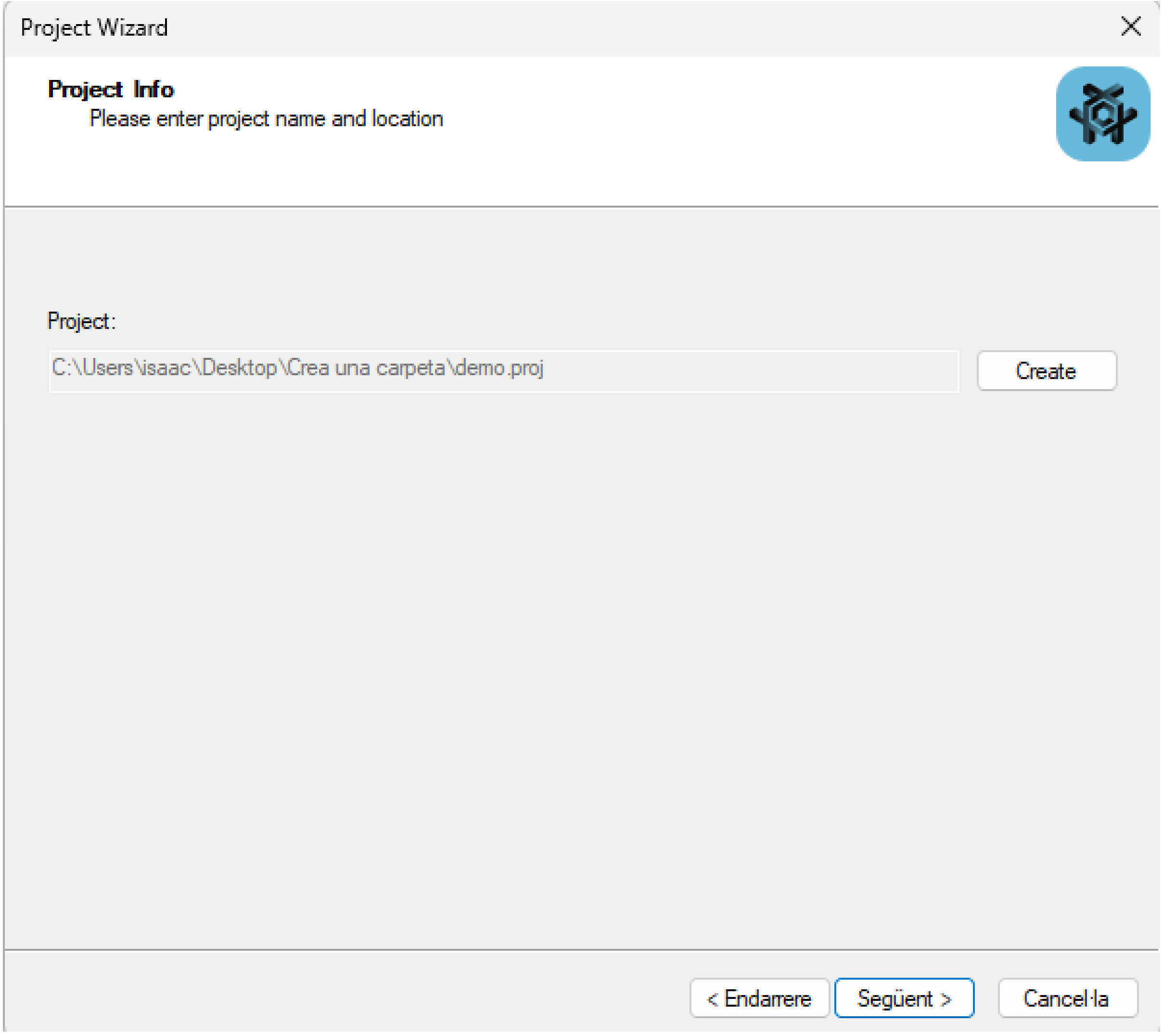

Figure 21. Give name to the post processing project.

Provide a name to the Inertial Explorer project and click "Next"

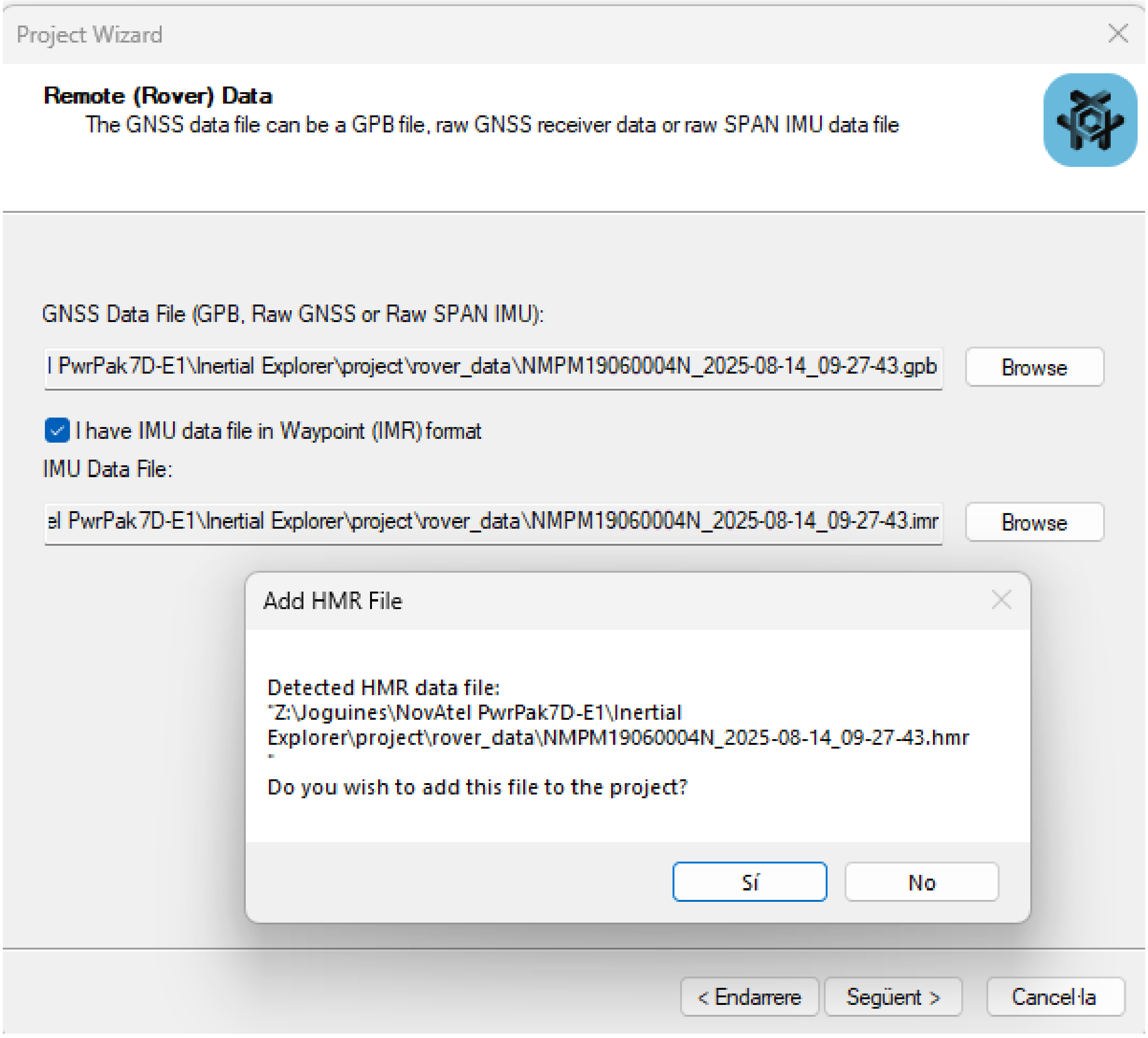

Figure 22. Add rover files.

Select the NovAtel SPAN GPB file and the rest of the files will be automatically added, click next.

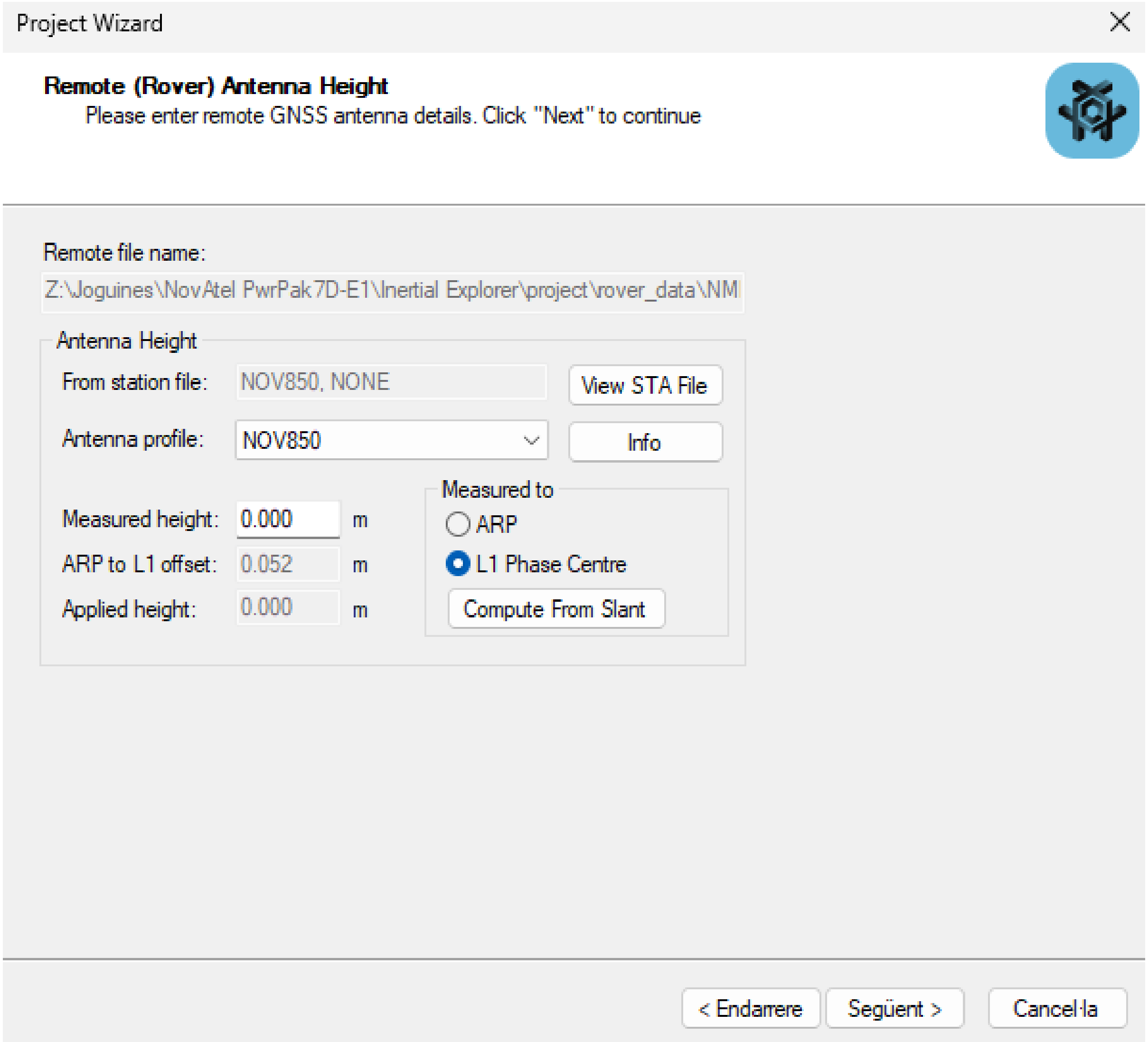

Figure 23. Check that the rover antenna information is correct.

heck that the antenna model is the same that we entered in the field by using the NovAtel command `THISANTENNATYPE`.
Don’t fooled the “Measured height” field, this is additional to the antenna lever arms and, in most cases, should be left at zero.

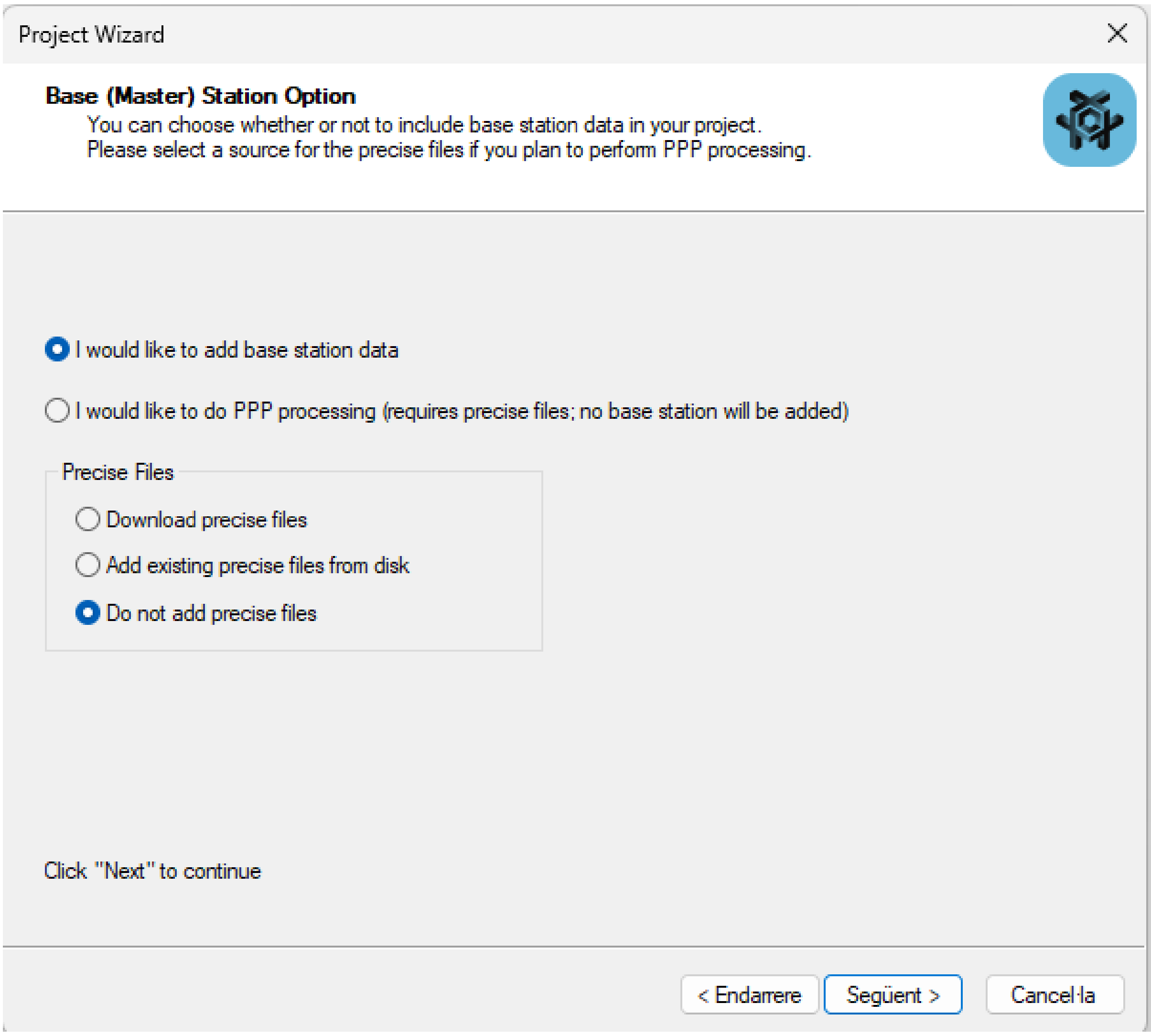

Figure 24. Adding base station data.

In our case we want to add the base station data we already downloaded, converted and concatenated so make sure the first bullet selects that we want to add base station data.
In our case, if we have base stations available to us Precise Files are not required so we were not going to add them but if you do add them, it will not hurt the post processing.

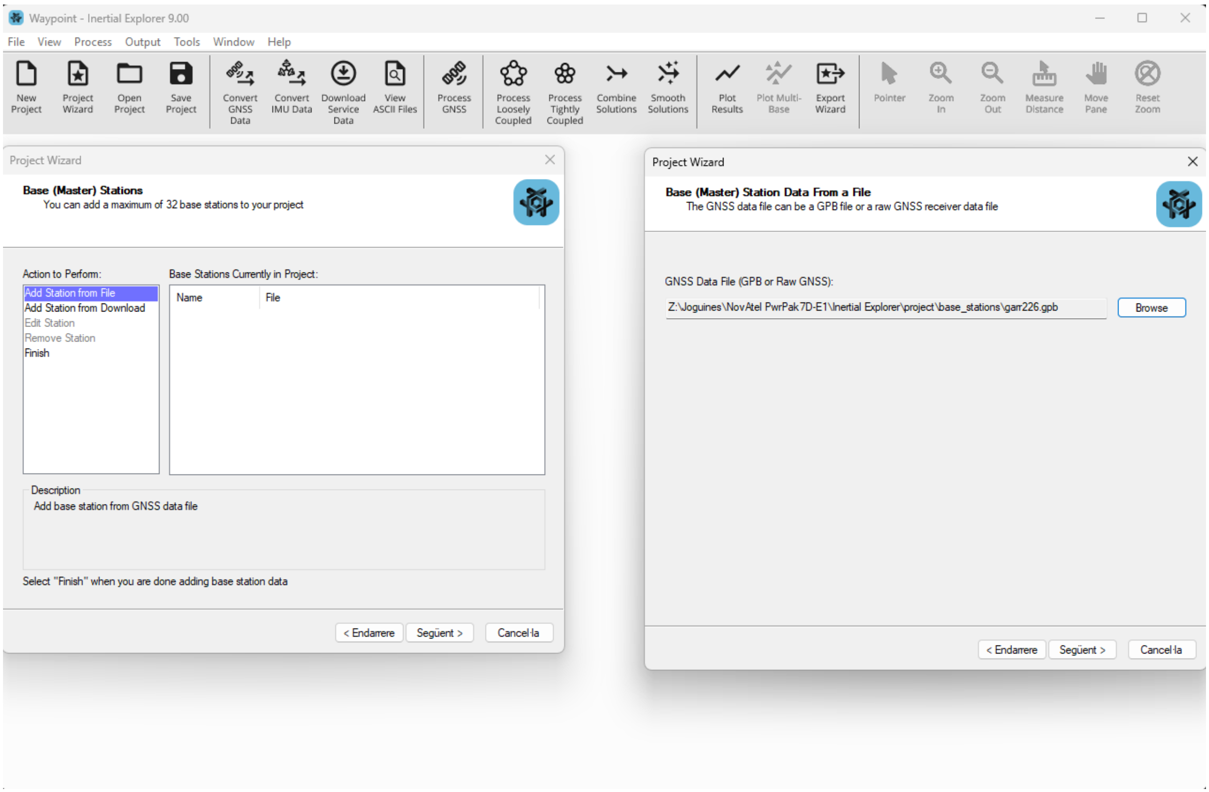

Figure 25. Base stations are to be added one by one.

We will have to repeat the base station addition one by one for each of the three stations.

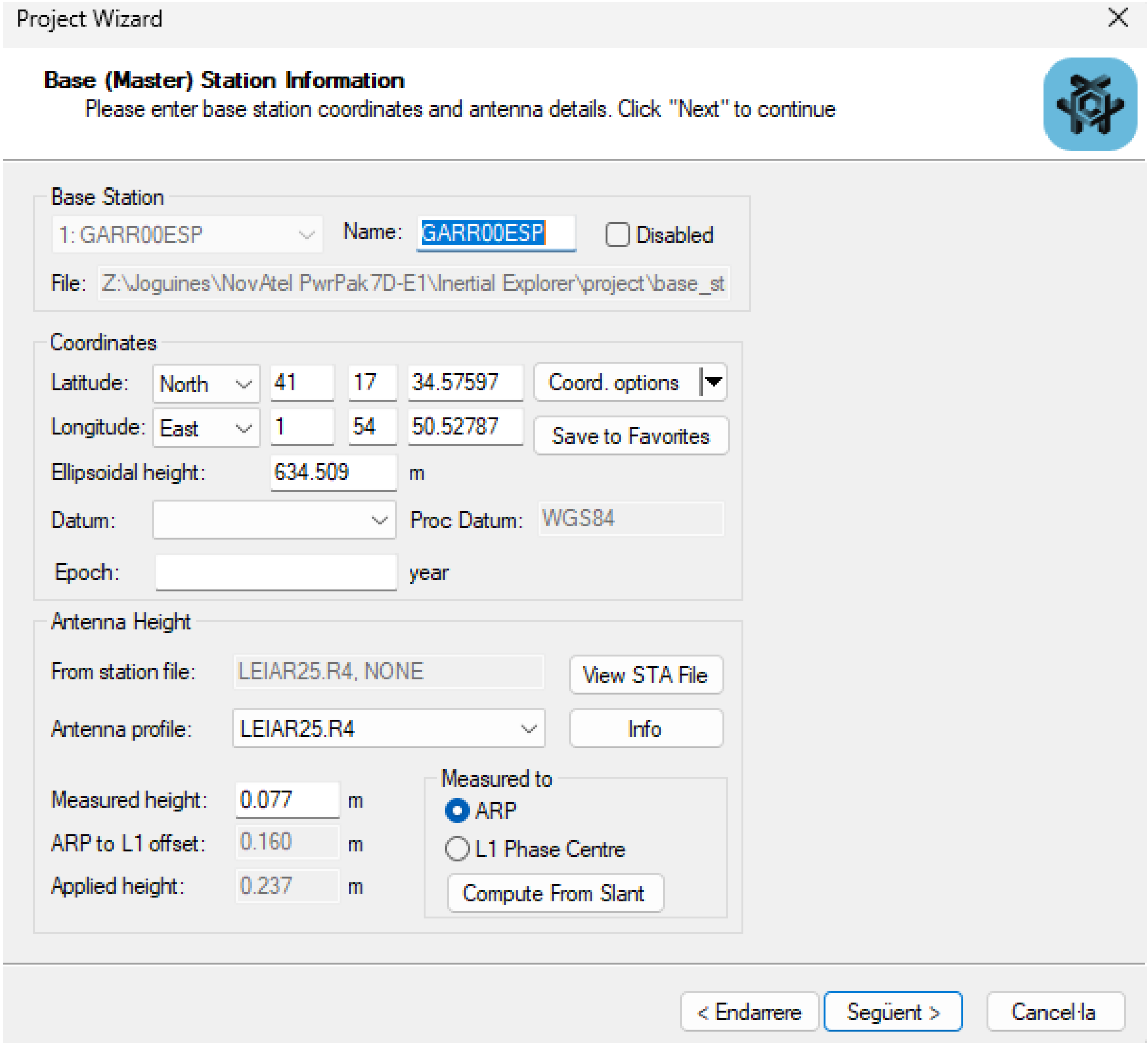

Figure 26. Base station details configuration.

The coordinates and the antenna models and height are automatically picked up from the GPB file, which in our case are taken from the RINEX observation file header so if they are correct in the RINEX file they will be correct here.

Do not forget to manually choose the Datum and the Epoch of the coordinates in the RINEX file as otherwise you may see positions shifts in the rover trajectory. In our case this information is provided by the ICGC and it is the same for all three stations:

Datum: ETRF2000 (which is the same as ETRS89)

Epoch 2017.0 year

Note that this information must always be manually entered because RINEX files do not contemplate Datum and epoch fields in its standardized structure.

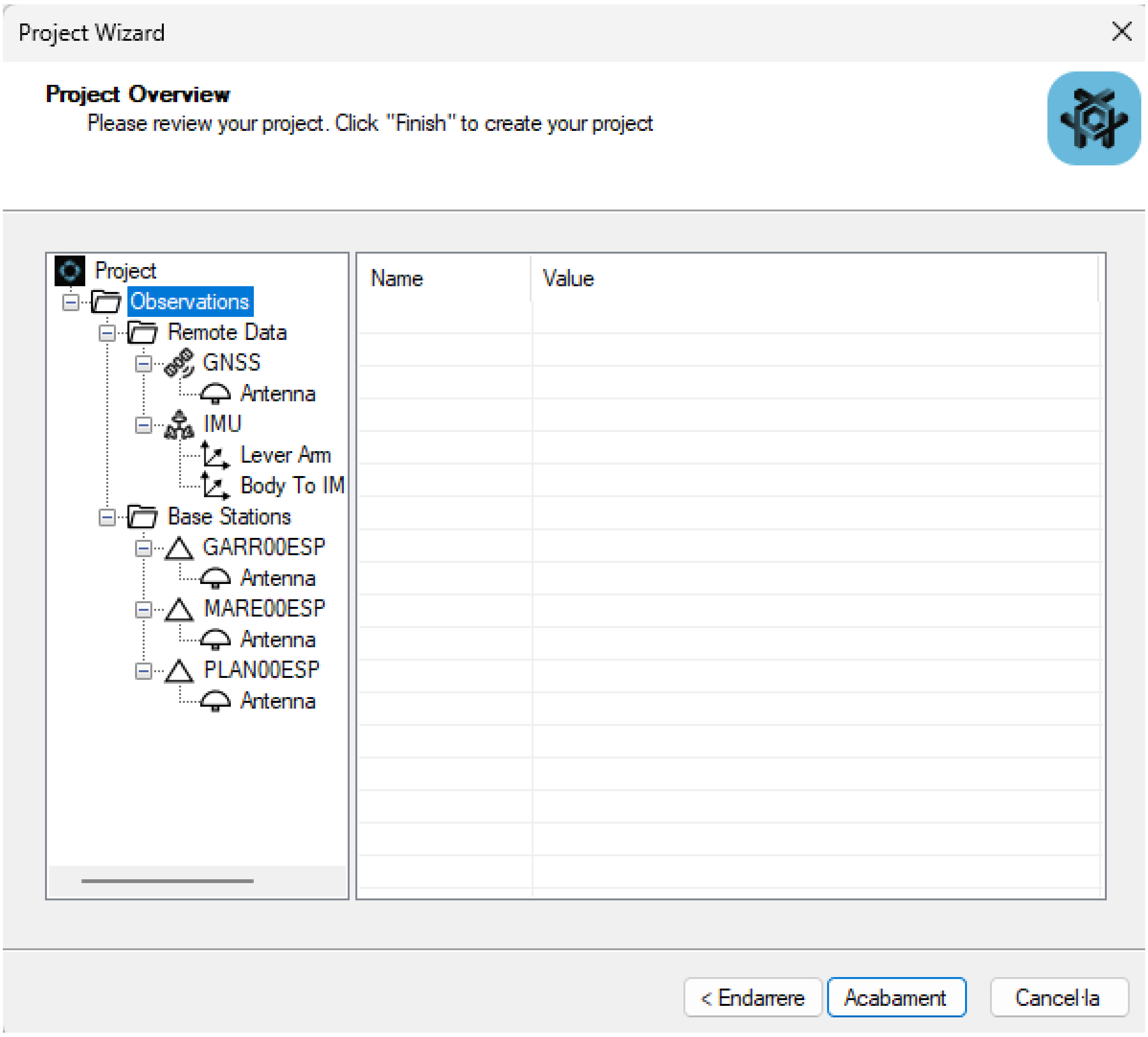

Figure 27. Review the inputs done.

Use this step of the wizard to review the values entered for the different elements of the Inertial Explorer project.

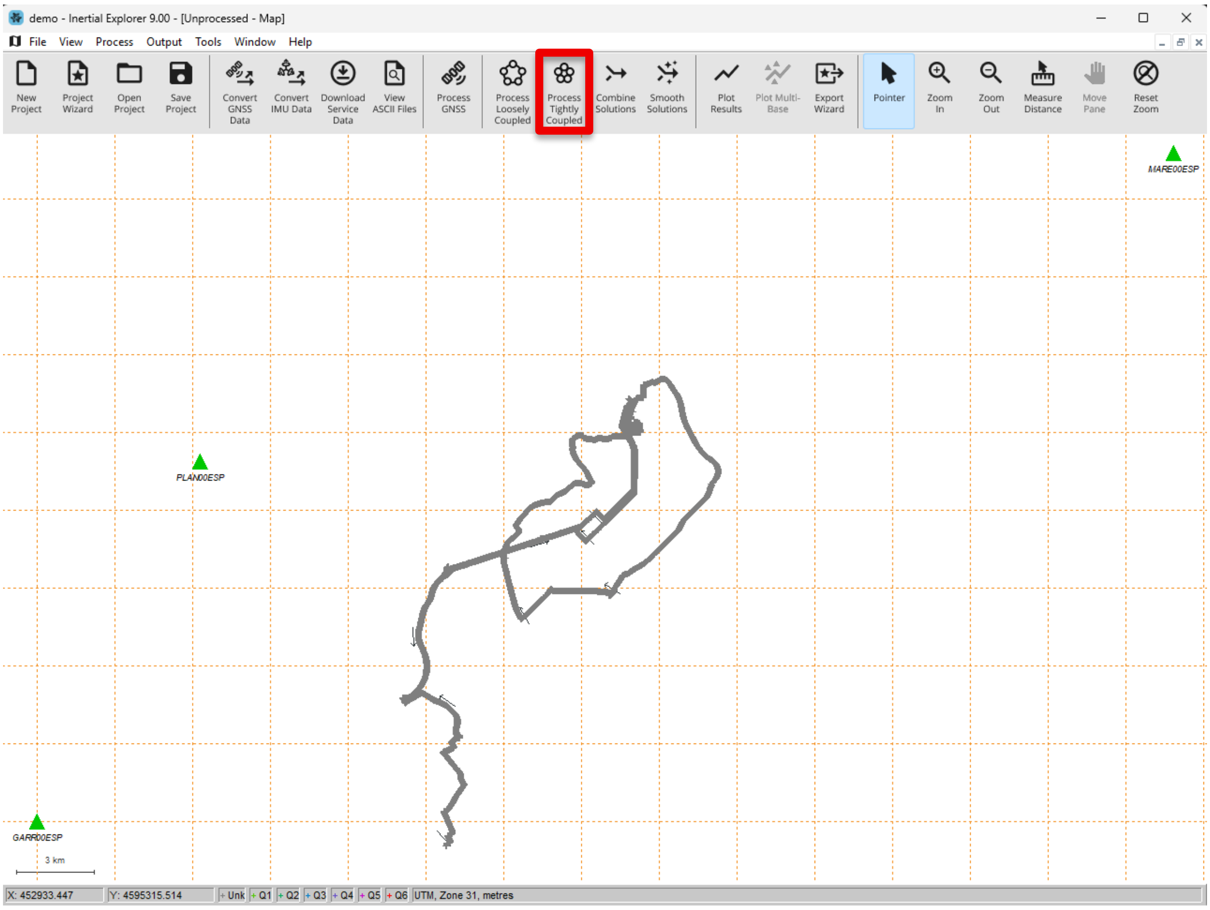

Figure 28. Inertial Explorer with a project loaded in the user interface.

In your Inertial Explorer user interface, you may see the color of the map in black background but to make this document printer friendly the background has been changed to clear color, this does not change the functionality of the software in any way.

This is the expected looks of the Inertial Explorer user interface after having successfully finished the wizard.

The trajectory shown on the map is grey color indicating that still is not post processed, by now it is just showing the real time trajectory from BESTPOS log.

Now we will need to process the trajectory and for that we have to click the button “Process Tightly Coupled” as this is the processing method that will bring the largest benefits to our trajectory, particularly in urban environment.

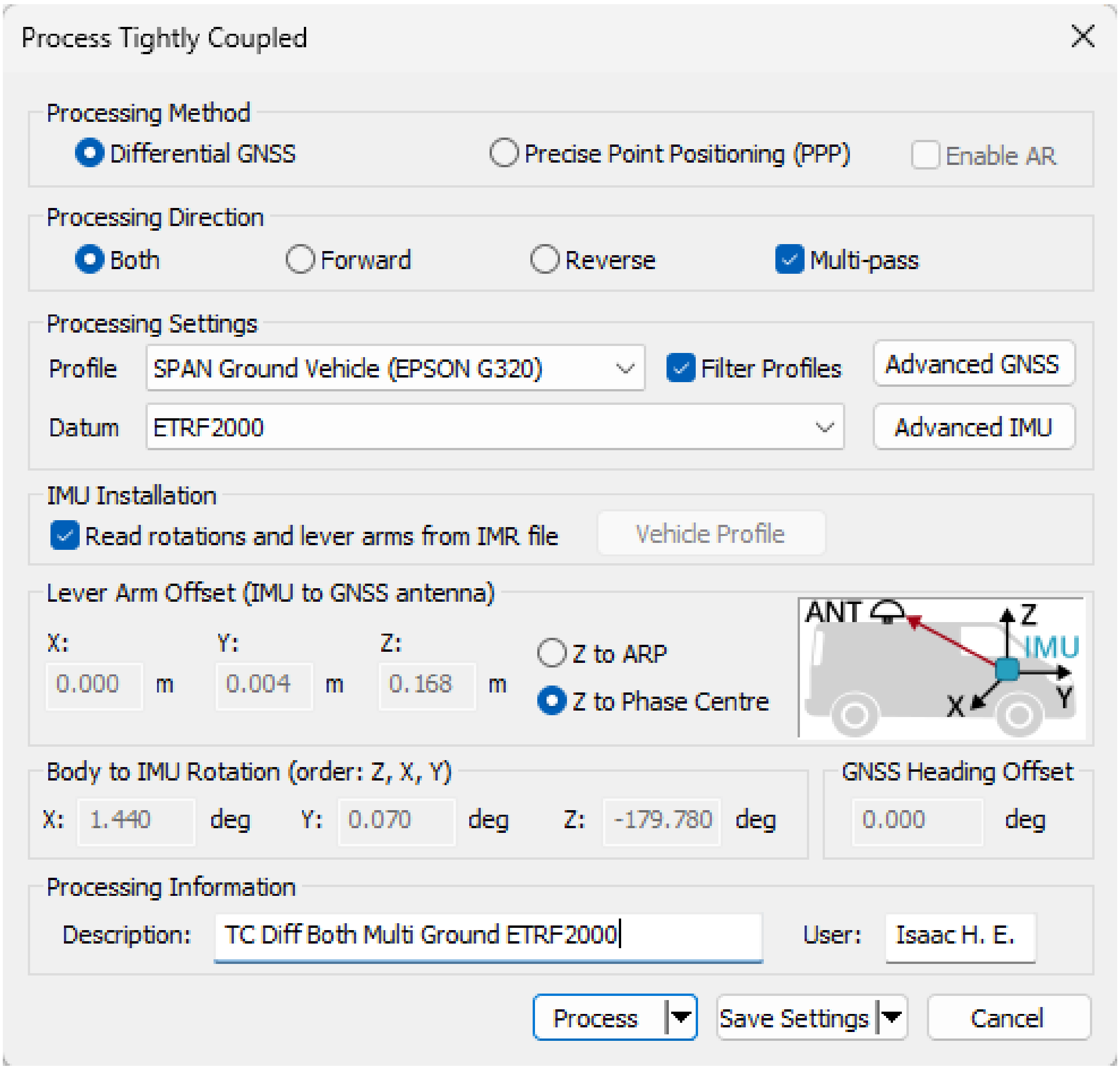

Figure 29. Inertial Explorer Tightly Coupled processing options.

- If we have base stations within reasonable range we will likely want to chose "Differential" processing, PPP is good for when there are no stations nearby or when the distance to the base stations is too long.
- Processing Direction set as "Both", we want to benefit from the backwards processing in time in addition of the forward time processing, which is the only thing you can do in real time.
- For low grade IMUs in challenging environments "Multi-pass" should be enabled as this processes the data Froward – Backward – Forward for the forward processing direction and the other way around Backward – Forward – Backward for the backward direction. Note that because they are interdependent, we will not be able to trust the plots that compare backward and forward solution
- The profile should be set to SPAN Ground Vehicle (EPSON G320) as this is the closest match to what we did on the field
- Datum is configured as the same datum as our base stations, ETRF2000, note that this datum only configures the processing results so you could leave this as WGS84 without issues, at a later stage we will be able to select the output datum.

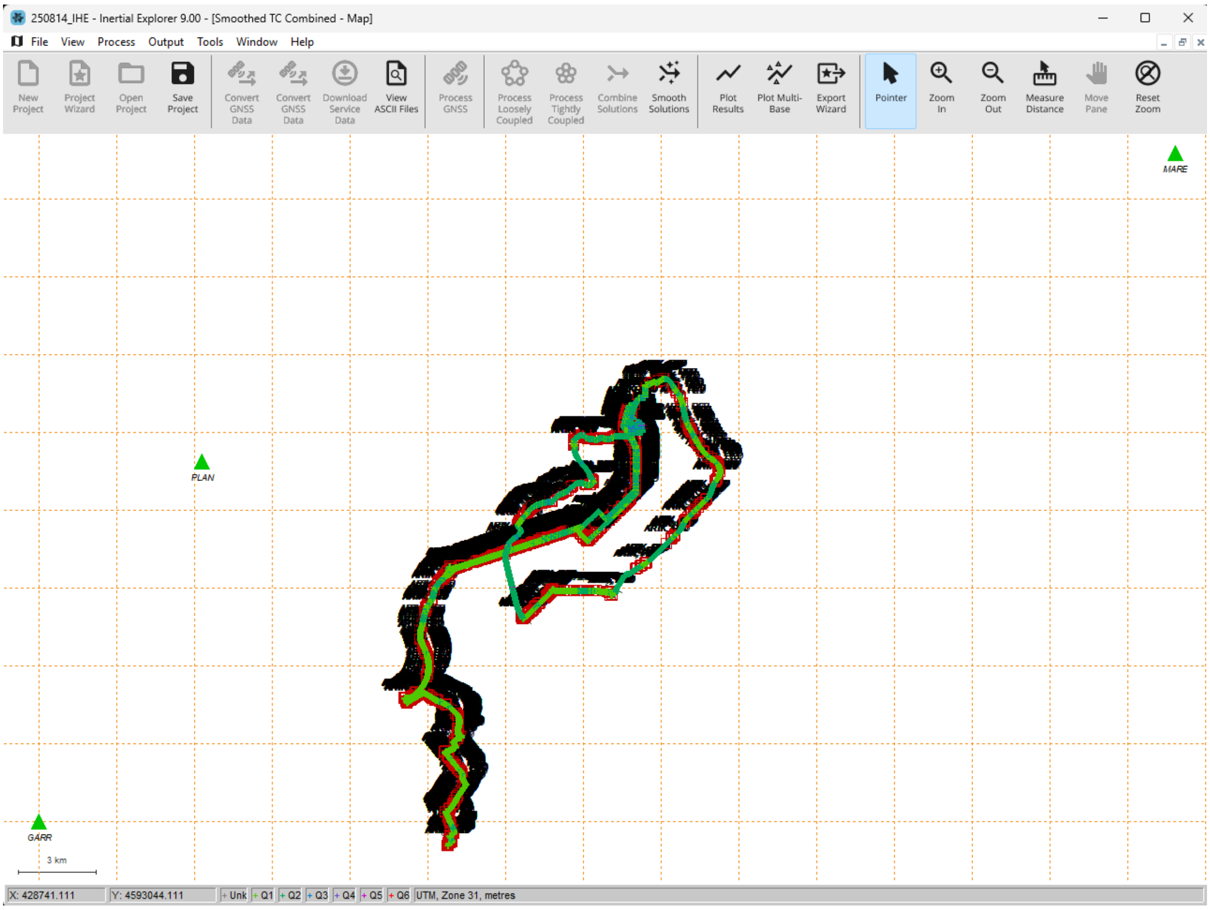

Figure 30. Process finished with the result on screen.

After the processing is finished the trajectory will no longer look gray but it will be colored with the Inertial Explorer Quality scale (from 1 to 6).

When the postprocessing is finished you can free up the floating license by returning it to the server like we did in this example as the export and the plotting does not require to have the license enabled.

To have better context in the assessment of the quality of our post processed trajectory we can export the result to Google Earth with a single click

Figure 31. Google Earth trajectory plotting

In this example we have eliminated the Kinematic Ambiguity Resolution (KAR) red square flags for better viewing of the trajectory itself.

Google Earth viewing is a very important quality assessment tool as it allows us to easily correlate week trajectory points with bad environmental conditions ensuring that there has been no technical issue during the data take.
For instance, a Q6 with a long tunnel which would mean that the Q6 is normal and not indicative of any problems in the original raw data.

As can be seen most of our example trajectory is green color (Q1-Q2) indicating a very successful result

The next general Quality Assessment tool is the Processing Summary Information

```
Program: Inertial Explorer
Version: 9.00.2207
Project: Z:\Joguines\NovAtel PwrPak7D-E1\Inertial Explorer\project\250814_IHE.proj

Solution Type:  Combined

Number of Epochs:
        Total in GPB file:      12534
        No processed position:  1
        Missing Fwd or Rev:     427

Measurement RMS Values:
        L1 Phase:       0.0144 (m)
        C/A Code:       3.04 (m)
        L1 Doppler:     0.073 (m/s)

Fwd/Rev Separation RMS Values:
        East:   0.323 (m)
        North:  0.441 (m)
        Height: 0.559 (m)

Fwd/Rev Sep. RMS for dual FWD/REV fixes (7669 occurances):
        East:   0.016 (m)
        North:  0.045 (m)
        Height: 0.050 (m)

Quality Number Percentages:
        Q 1:    53.1 %
        Q 2:    34.7 %
        Q 3:     3.5 %
        Q 4:     2.6 %
        Q 5:     6.1 %
        Q 6:     0.0 %

Position Standard Deviation Percentages:
        0.00 - 0.10 m:  90.3 %
        0.10 - 0.30 m:   6.4 %
        0.30 - 1.00 m:   2.1 %
        1.00 - 5.00 m:   1.2 %
        5.00 m + over:   0.0 %

Percentages of epochs with DD_DOP over 10.00:
        DOP over Tol:   6.9 %

Baseline Distances:
        Maximum:        29.611 (km)
        Minimum:        14.854 (km)
        Average:        23.903 (km)
        First Epoch:    27.627 (km)
        Last Epoch:     27.628 (km)
```

A trajectory that has 6.9% of double difference dilution of precision (we know it relates to tunnels and narrow streets because we know that we had no GNSS raw data discontinuity) that has 96.7% of positions with a standard deviation better than 30 cm is a great result. Also, we can see that the baselines were respectably short.

● Plot analysis

In this section we will review the main plots that Inertial Explorer is able to reproduce.

Due to the highly technical nature of the data displayed by Inertial Explorer, if you have to regularly undergo post processing sessions, it is advisable to undergo training by Waypoint group technical support team.

- ➢ Plots that provide additional insight on the trajectory Position Velocity Accelerations Attitude and Time.

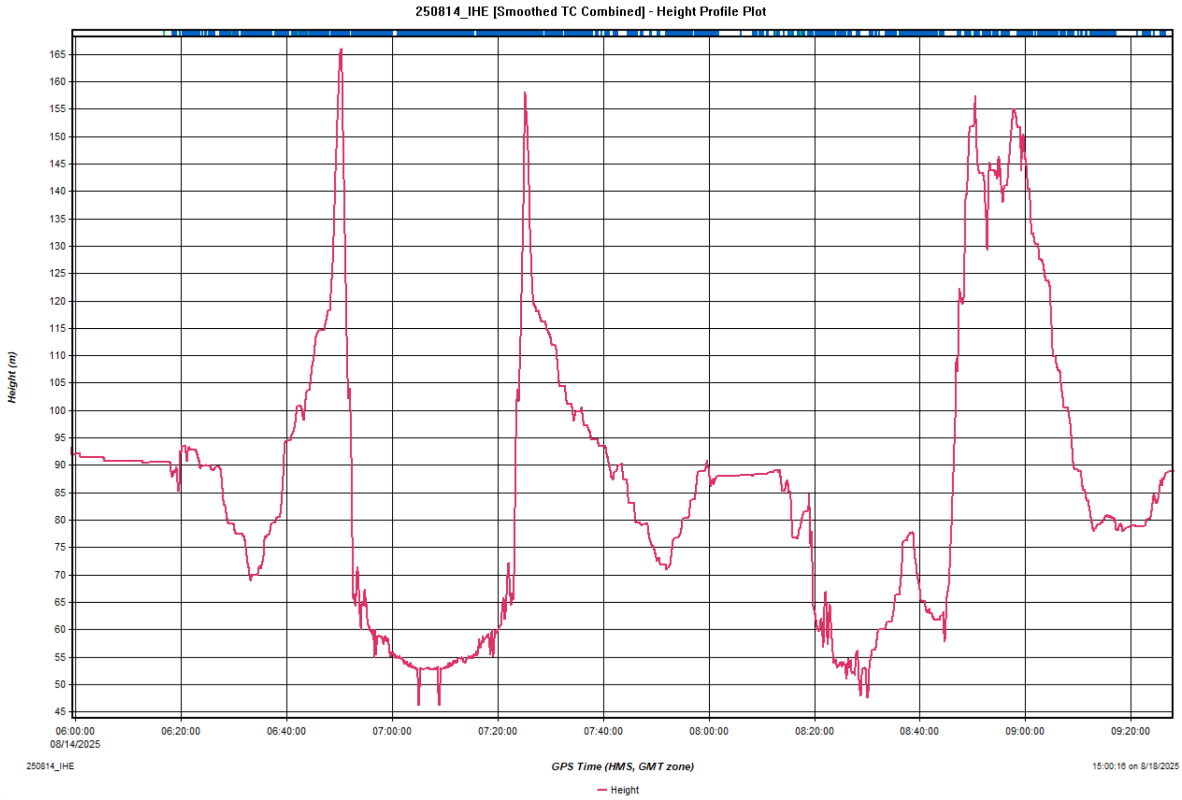

Figure 32. Height profile plot

A good advice for all plots is to keep in mind that for long datasets the X axis of the plot encompasses a large amount of time as opposed to the Y axis that contains a relatively small height difference (in other plots may be a different variable), this causes the plot to be jaggy and spiky in areas that in real life would have smooth gradual transitions, this is normal and expected.

Bear in mind that the displayed height does not have the geoid undulation applied which means that is ellipsoidal (over the ellipsoid), this means that in our case has a variable offset of around 50 meters with the orthometric height (over the geoid).

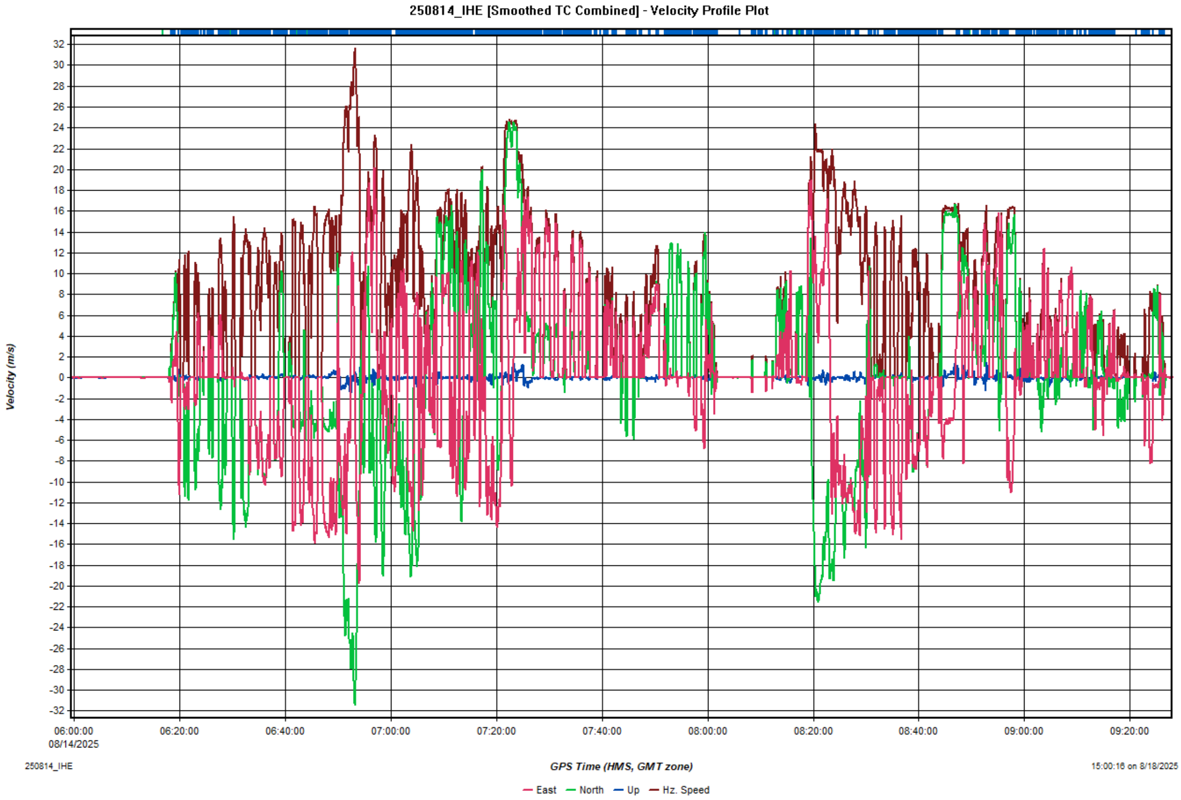

Figure 33. Velocity profile plot.

This plot helps us to identify the temporal windows when the car was stopped at the beginning and in the middle of the data take. These slow areas are likely to have much more error than the kinematic parts, specially in low grade IMUs.

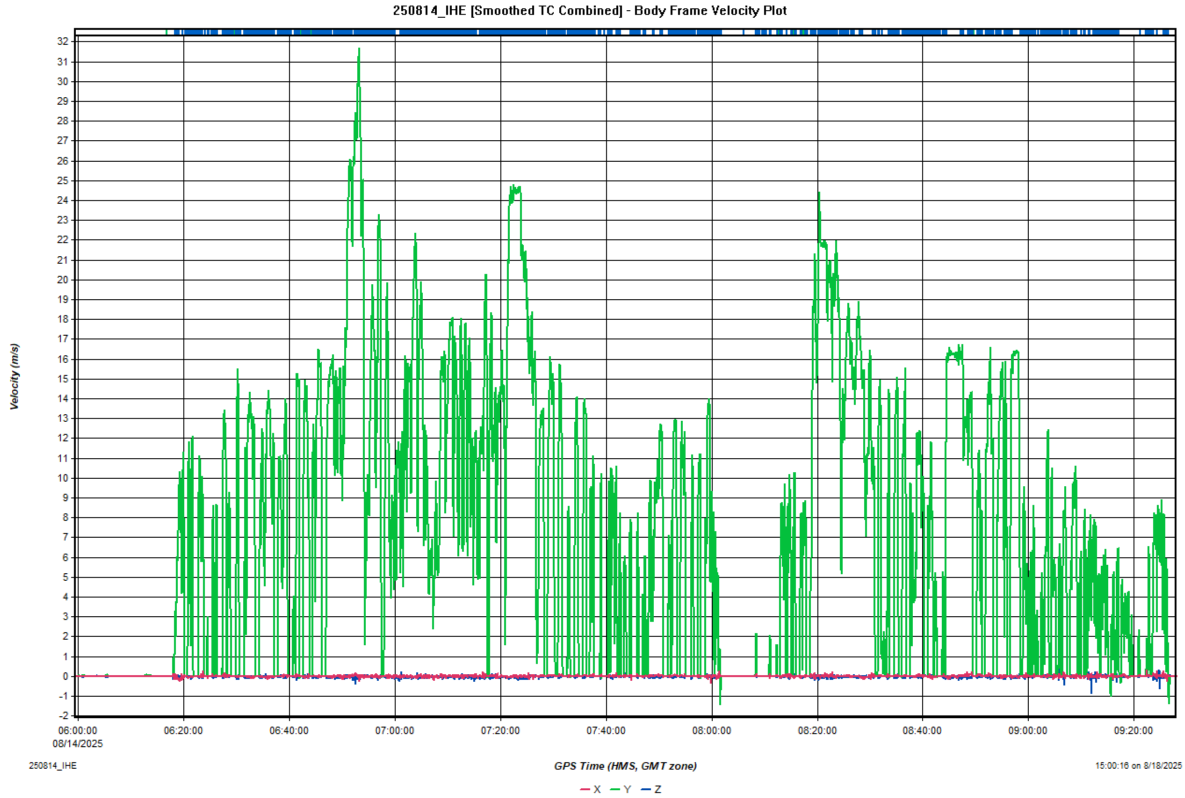

Figure 34. IMU Body frame velocity plot.

Velocities along the IMU axis help us to determine the orientation of the IMU, in this case it can be clearly seen that Y axis is registering all the velocity increments whereas Z and Z are almost stationary with just a bit of noise. This confirms that our IMU was setup as we intended.

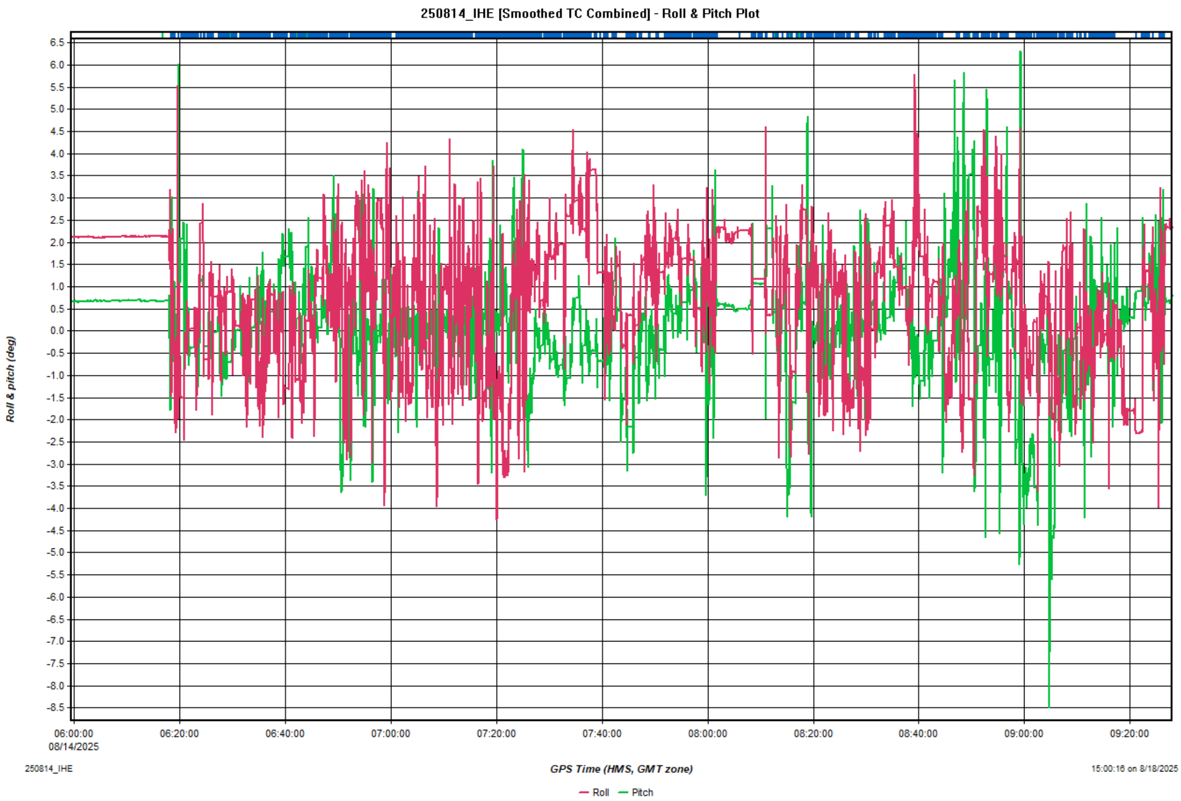

Figure 35. Roll and pitch plot.

The pitch and the roll in our case stay within very reasonable boundaries for a car, confirming that there was no installation issue with the IMU.

➢ Plots that provide an error estimation (standard deviations).

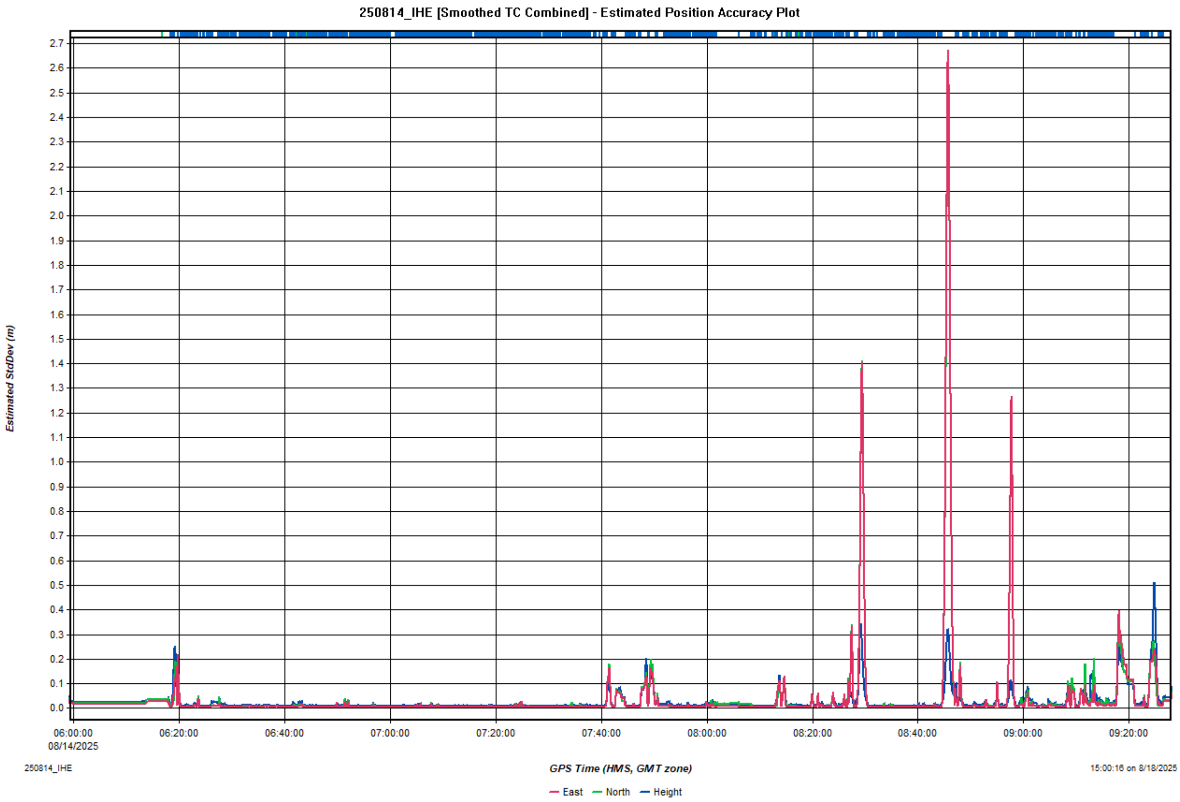

Figure 36. Estimated Position Accuracy Plot.

This plot help us to identify very clearly the tunnels and to be more precise the highest part of the peaks is the center of the tunnel because unlike in real time trajectories that are only computed forwards in time (because it's impossible to go backwards in time on a real time trajectory) where the largest error would be located at the end of the tunnel where GNSS is recovered in post processing each of the two solutions enters one side of the tunnel with good GNSS accuracy and they meet in the middle of the sky obstruction where the highest error occurs.

As a guidance the error committed in the real time solution was one order of magnitude (10 times) larger at the end of the tunnel than it is in the post processed solution standard deviation.

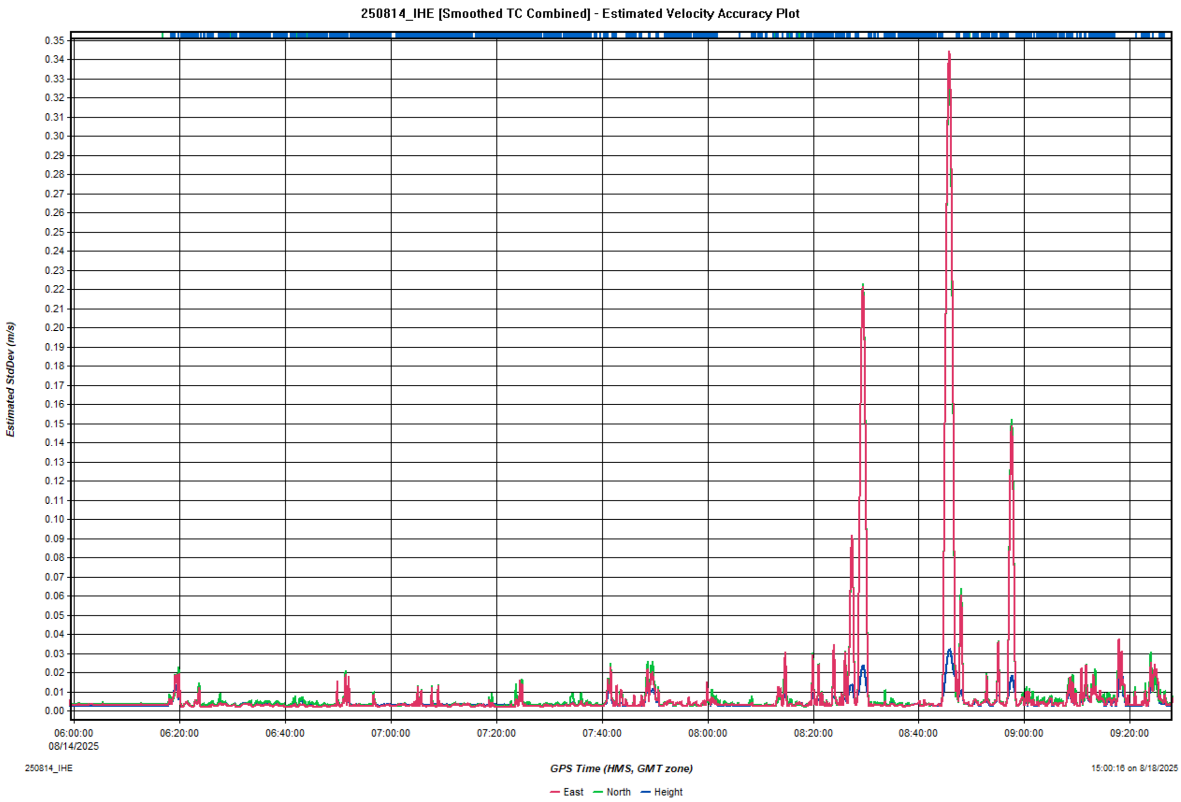

Figure 37. Estimated Velocity Accuracy plot.

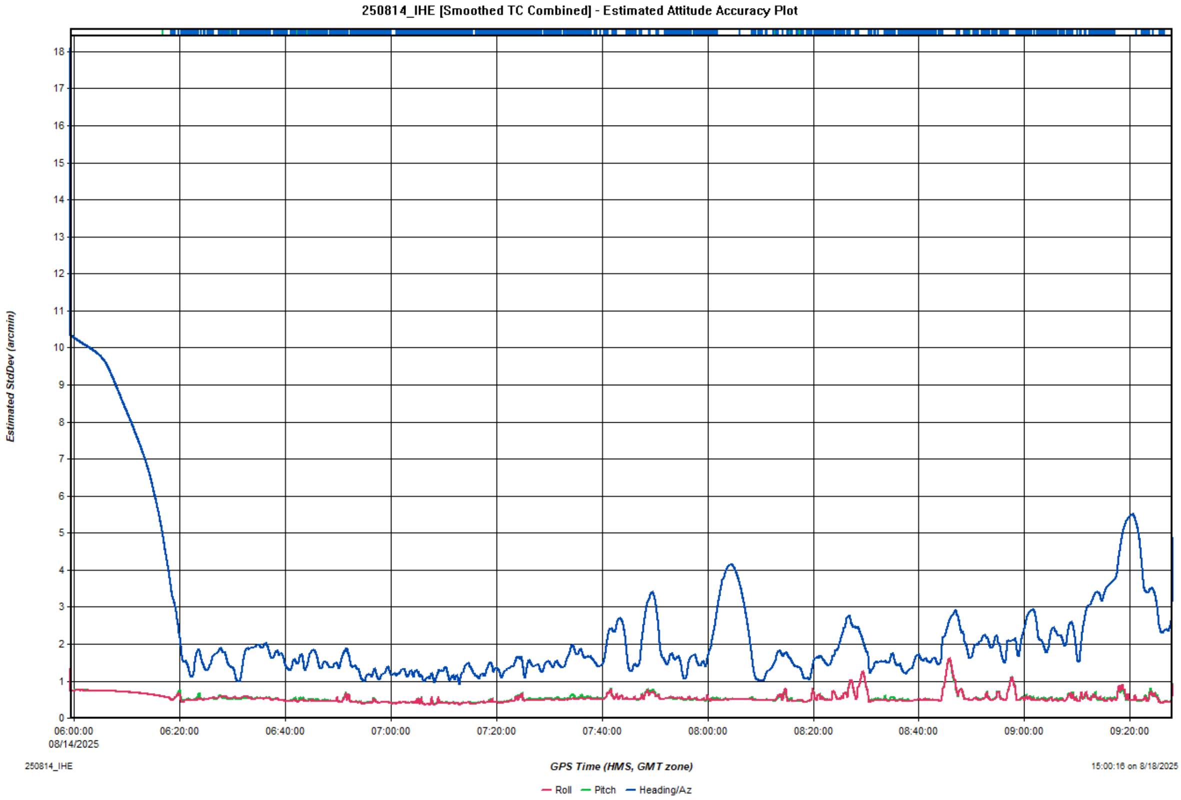

Figure 38. Estimated Attitude Accuracy plot.

Plot that proves that the largest angular errors are always related to the Azimuth determination as it is the hardest variable to estimate because pitch and roll angles have the constant input of the g force but Azimuth does not, being said that it is fairly impressive that that with a low grade IMU we are obtaining estimated errors in the orders of 5-6 arc minutes in worst case scenarios (not considering the initial stopped part).

➢ Other plots that are interesting to look at.

In our particular case, which does not display any problems, this list makes sense but other cases may require a different set of plots, there are many more, some of them very technically complex.

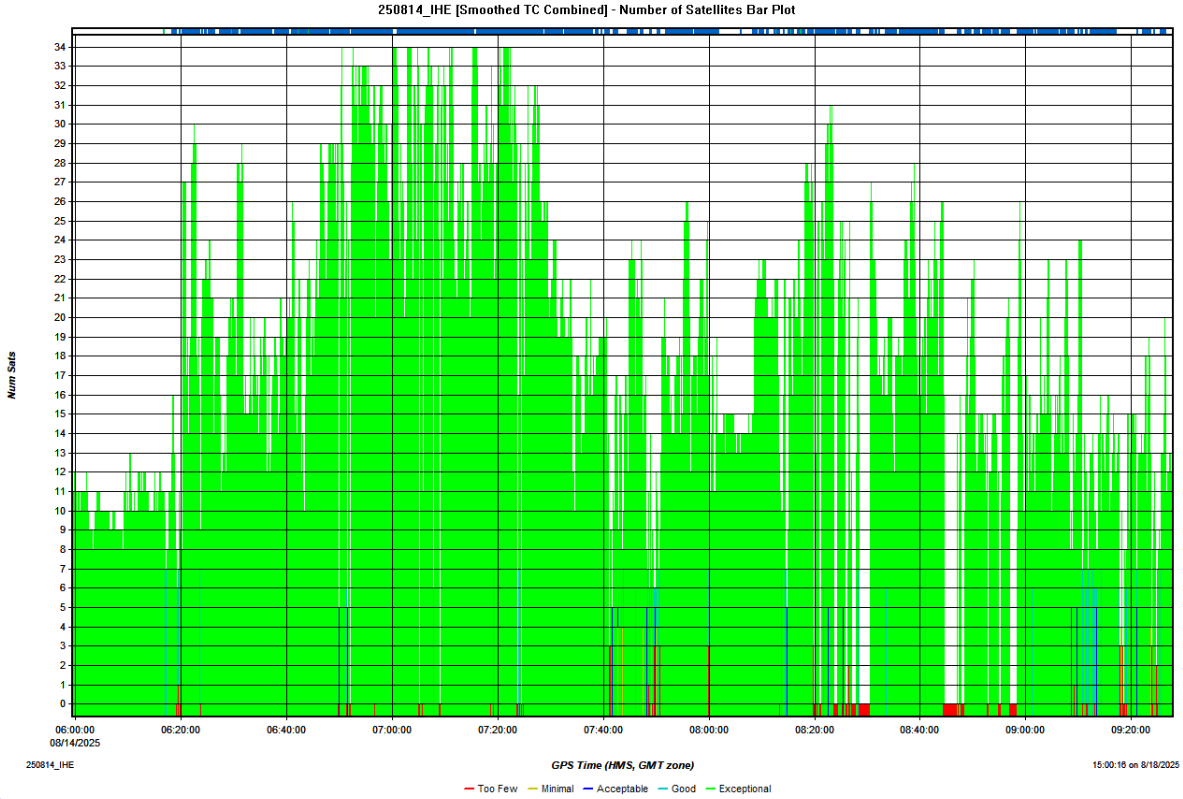

Figure 39. Number of satellites bar plot.

In this plot the tunnels can be easily inferred but also the part of the trajectory that occurred in more or less open roads / highways (more satellites tracked).

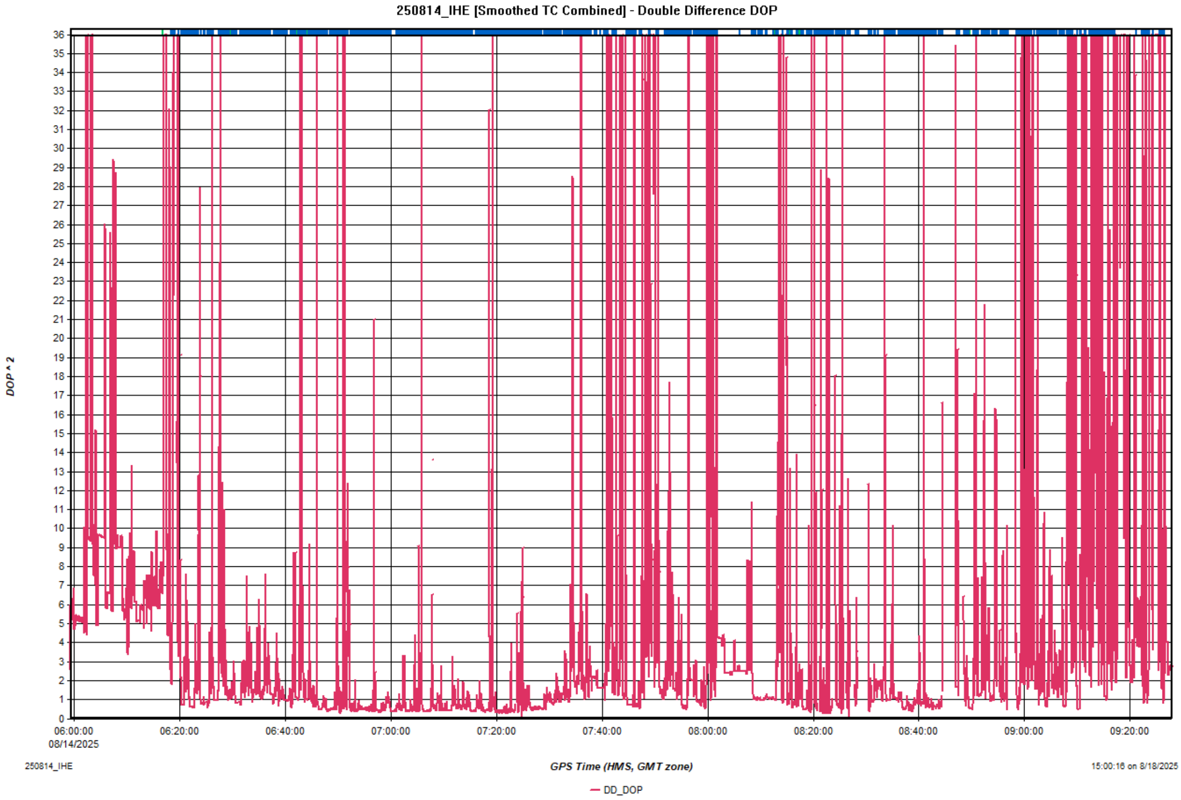

Figure 40. Double Difference Dilution of Precision plot.

This plot responds to the question of "how good was the satellite geometry of the combined solution between the rover and the base stations?". Here we can see that from GNSS standpoint not only tunnels were a challenge, the last part of the trajectory in very narrow streets of Sant Andreu neighborhood was also very challenging, exactly what we wanted.

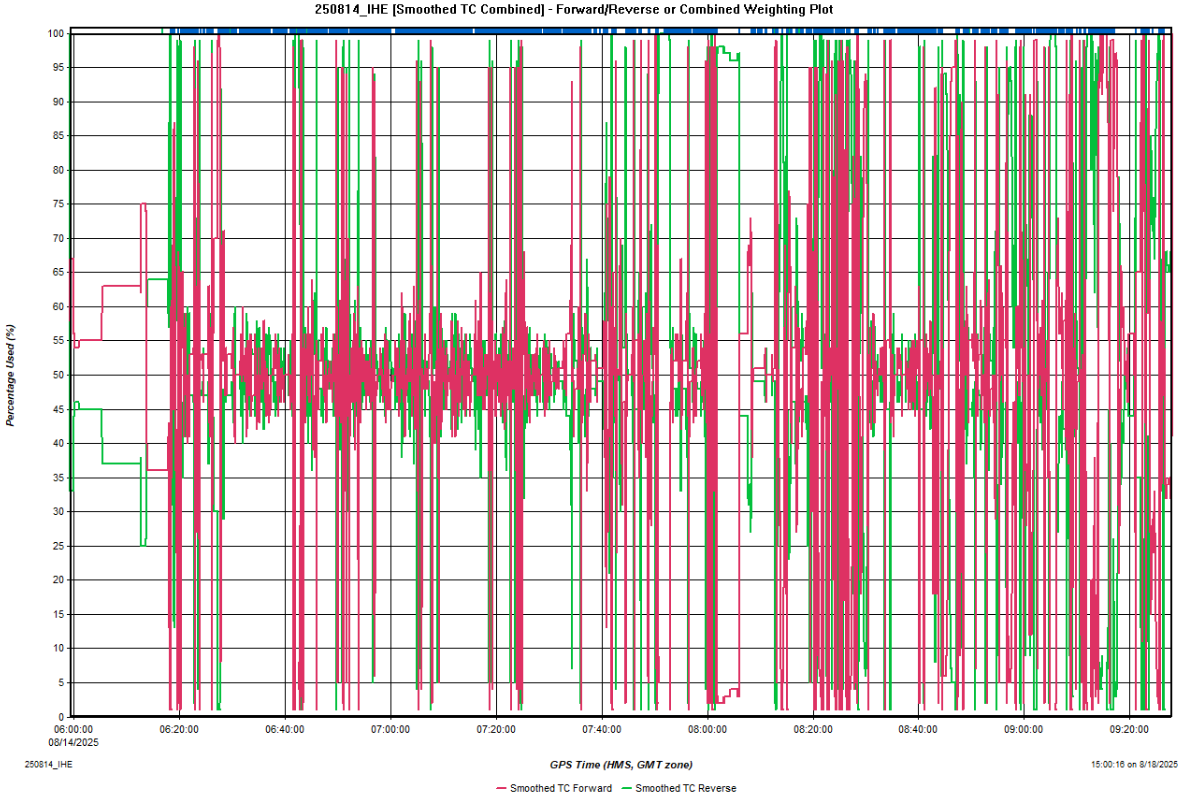

Figure 41. Forward / Reverse combined weighting plot.

This plot shows the weighting of the forward solution as opposed to the reverse, in open sky conditions is expected to be around 50 % on the other hand when going into a long enough tunnel the forward solution is expected to have 100% and the reverse 0% and gradually change until the forward solution becomes 0% and the reverse 100% at the exit of the tunnel.

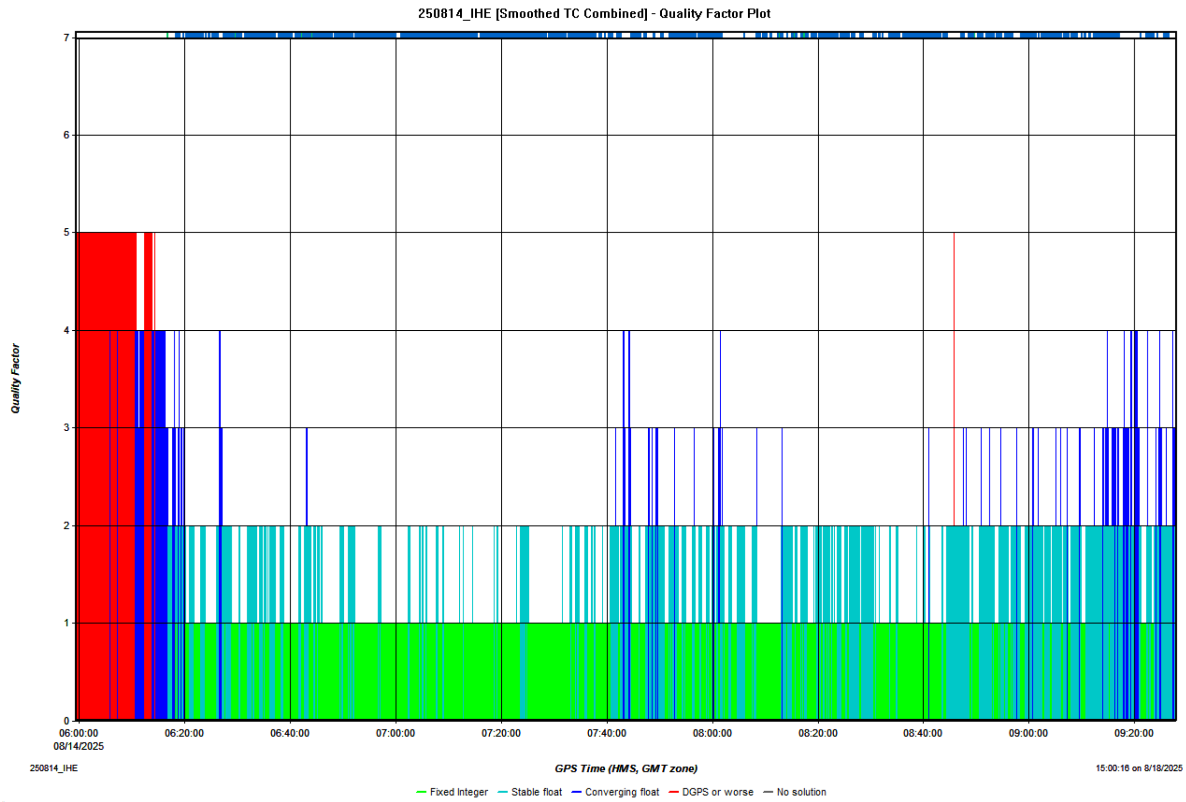

Figure 42. Quality Facotr plot.

Most of the trajectory falls within the “Fixed integer” solution type, which is an impressive feat for a trajectory happening in urban environment. Only the very beginning static is bad (DGPS or worse) and the trajectory on the narrow streets gets on to Stable / Converging Float.

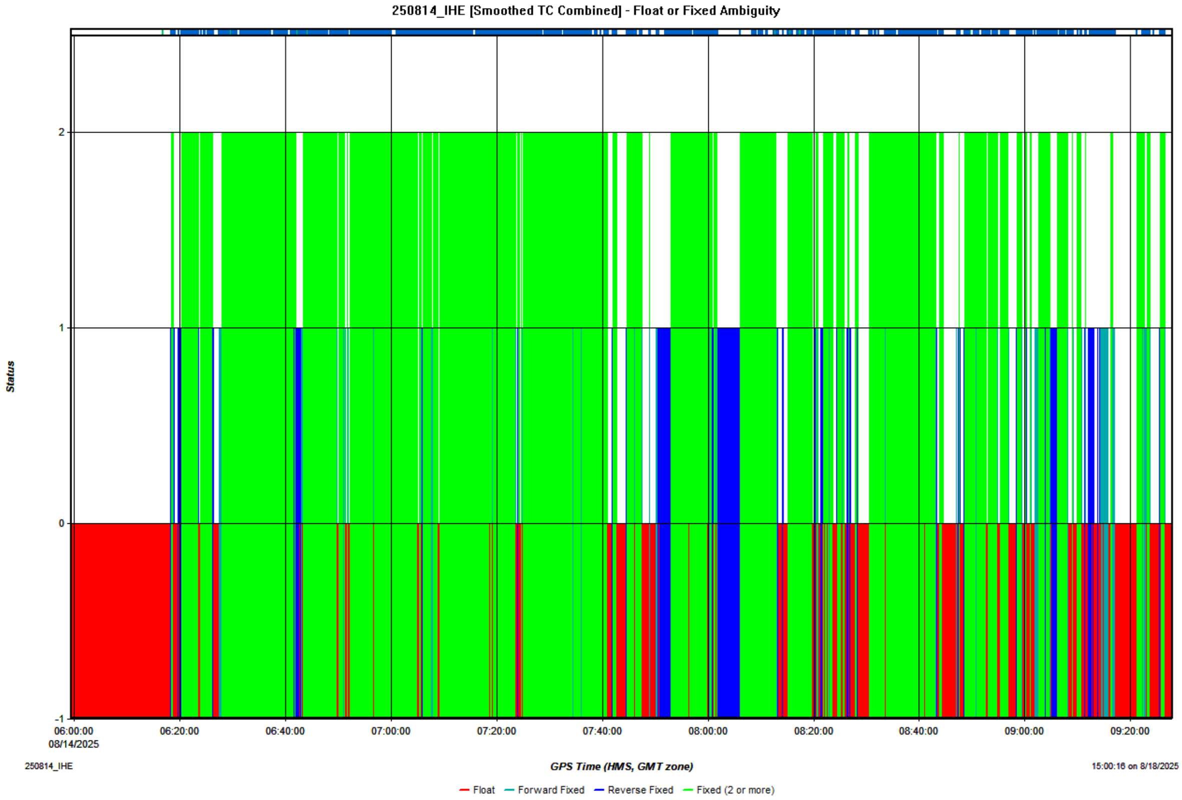

Figure 43. Float Fixed Ambiguity plot.

This plot gives us an insight of what processing direction can be trusted the most. For instance, if the backwards direction is fixed but the forward solution is not then it would not be a good idea to compare the output of the two solutions as the backwards solution would be expected to be much more accurate than the forward solution.

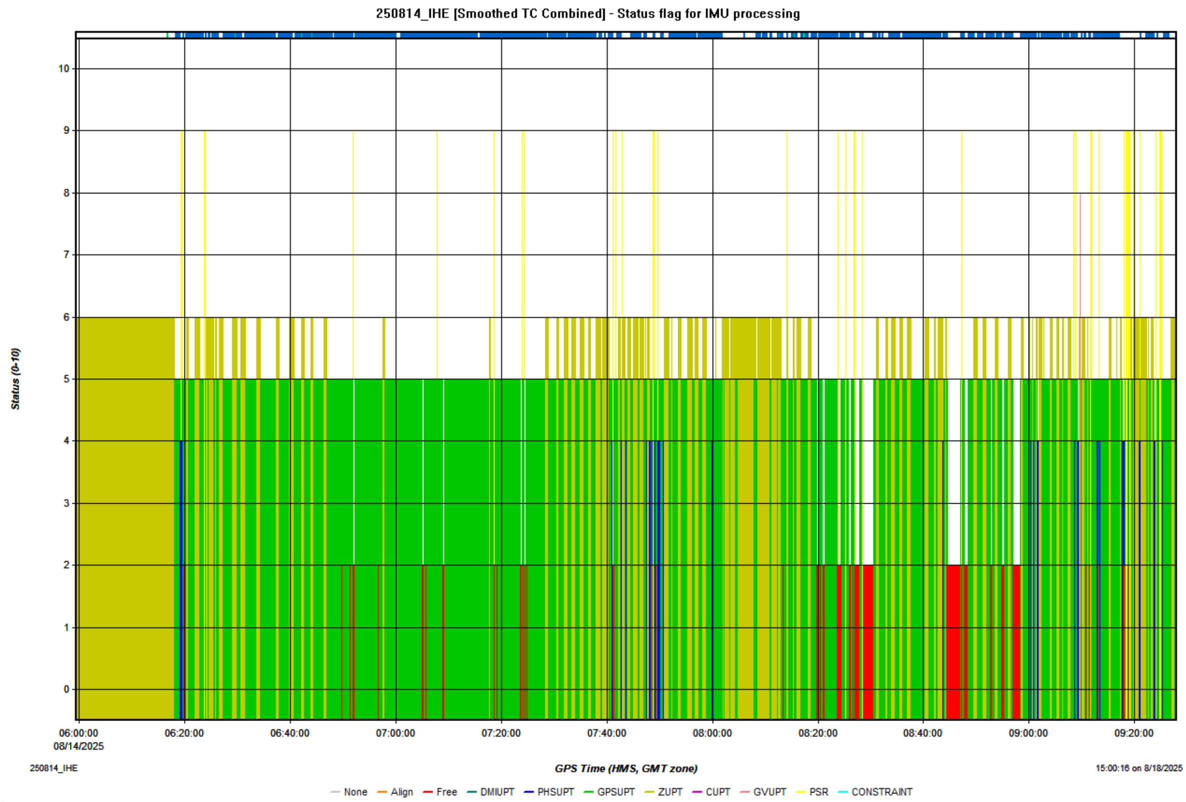

Figure 44. Status Flag for IMU processing plot.

The IMU raw data is always part of the Inertial Explorer filter however the other pieces of information, like GNSS, come and go, in this plot you can see what is updating the filter at any given time.

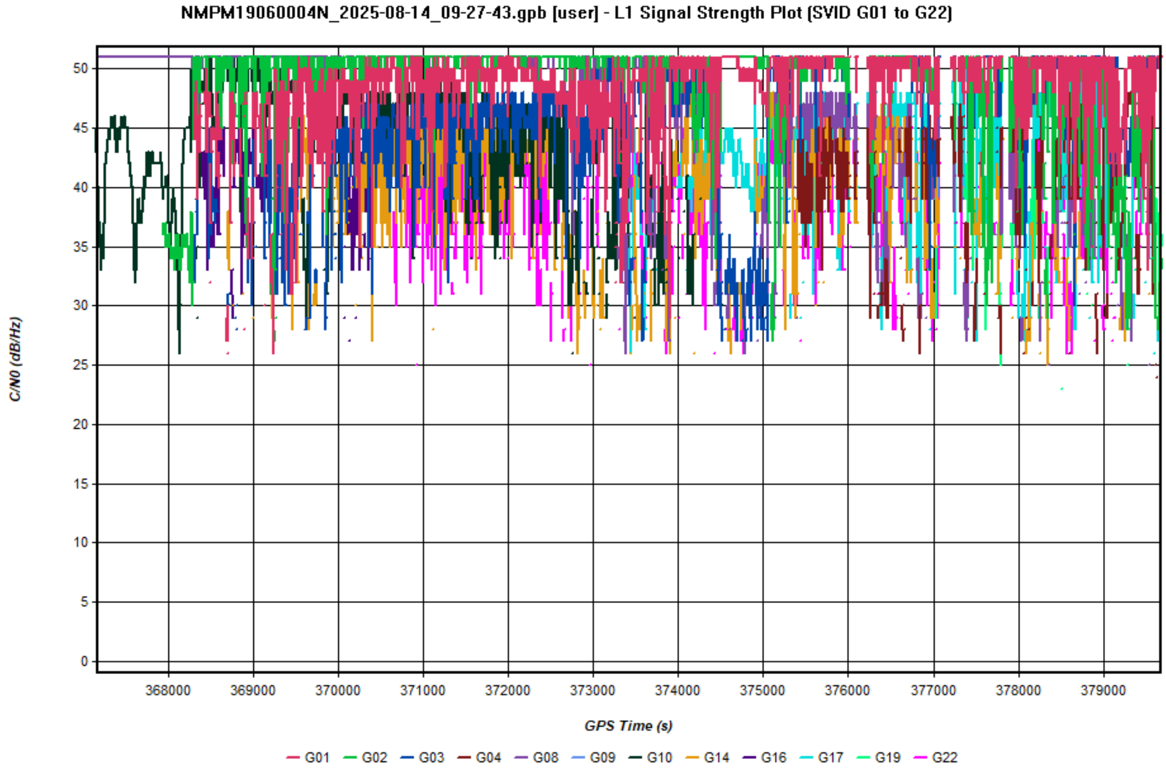

Figure 45. GPS L1 signal strength plot.

This is just a sample of 12 GPS satellites recorded during the test showing that the signal strength (carrier to receiver noise ratio) at its highest point was consistently hitting the 51 dB-Hz mark showing that the enclosure that was used for this test was, practically speaking, RF transparent and also that there was no antenna problem.

- Data output

The post processed results are useless if they can not be exported from within Inertial Explorer and for that there is a very powerful module.

To demonstrate the utility of this module I will guide you throughout the creation of an ASCII custom export style.

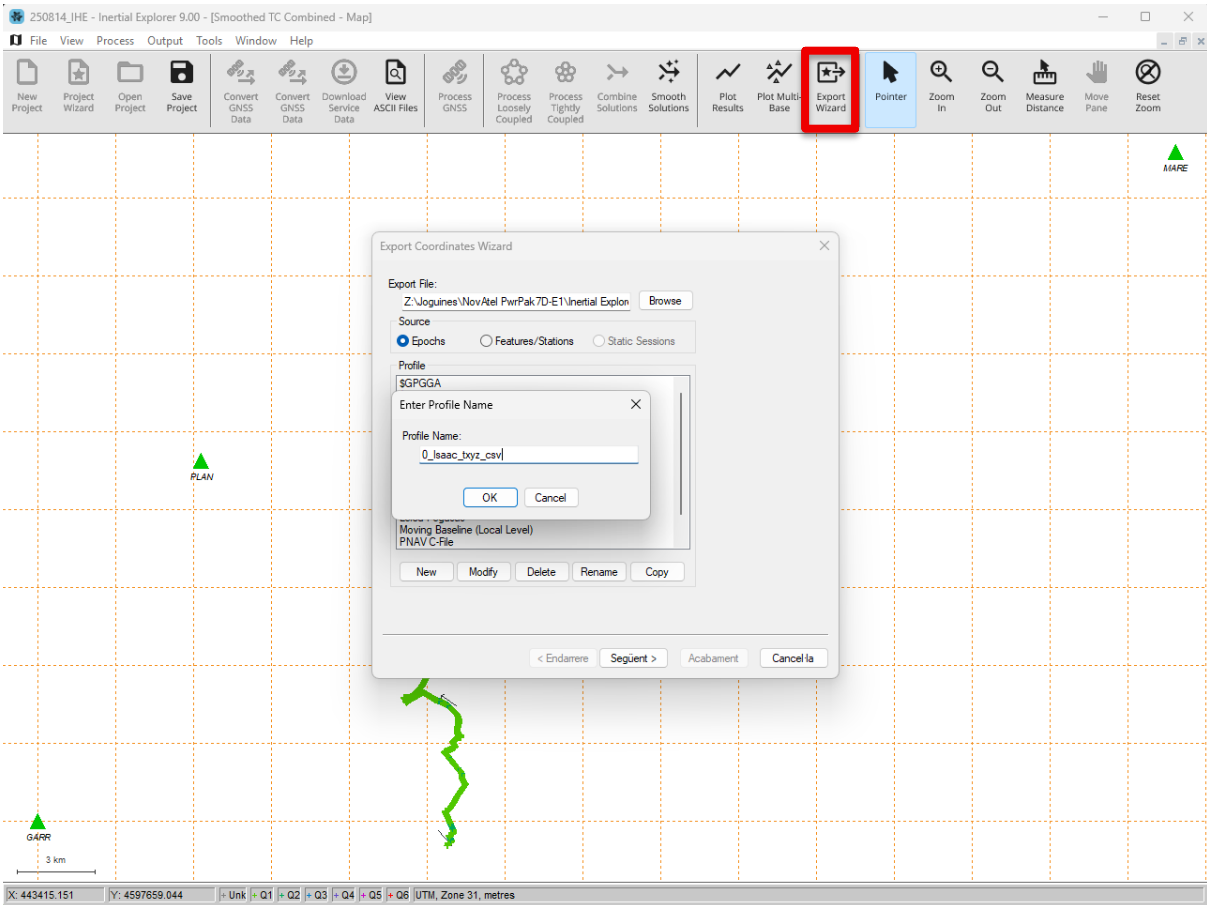

Figure 46. Export Wizard New profile creation.

To create a new profile first click "Export Wizard" button at the top toolbar, then click "New" button, provide a name for the new export style and click "OK".

In the new window you will define the export variables.

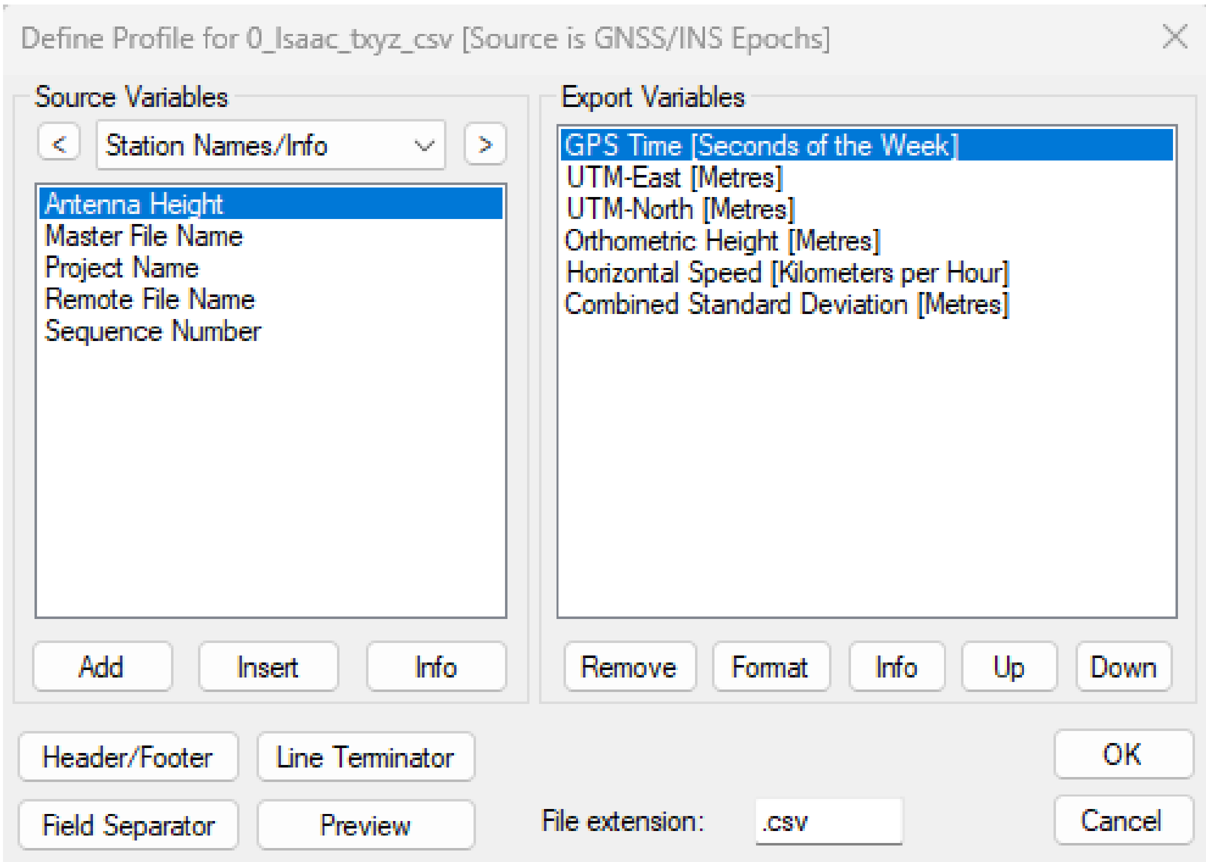

Figure 47. Export profile definition window.

The source variables left side of the user interface and it's where you pick the variables that you want to export from the many available within Inertial Explorer, which are categorized by the dropdown menu at the top.

On the right part of the user interface, you have the list of variables that will be used in your new file format.

To create a csv that doesn't look like a report but rather like a export file to be used on a third-party software you would have to click the "Format" button and uncheck all the check boxes from all the listed variables as well as ensure that all the variables have 3 decimal places.

Then click "Header/Footer" button and also uncheck al the checkboxes and click "OK", lastly click on "Field Separator" and select "Comma" and click "OK" and "OK" again in the export profile definition window.

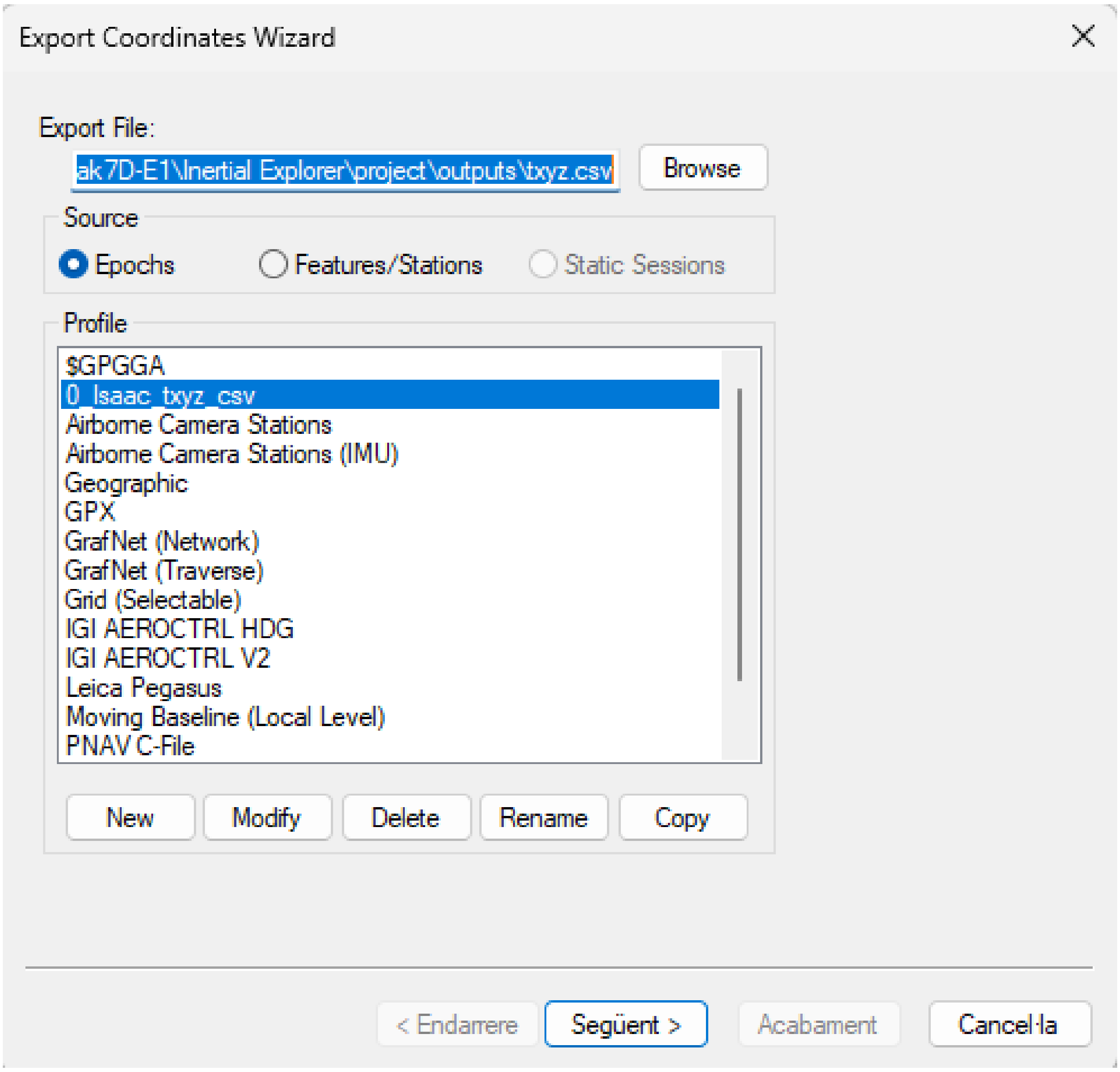

Figure 48. Selection of the profile in the Export Wizard.

Select your name profile in the “Export Wizard” and click “Next”.

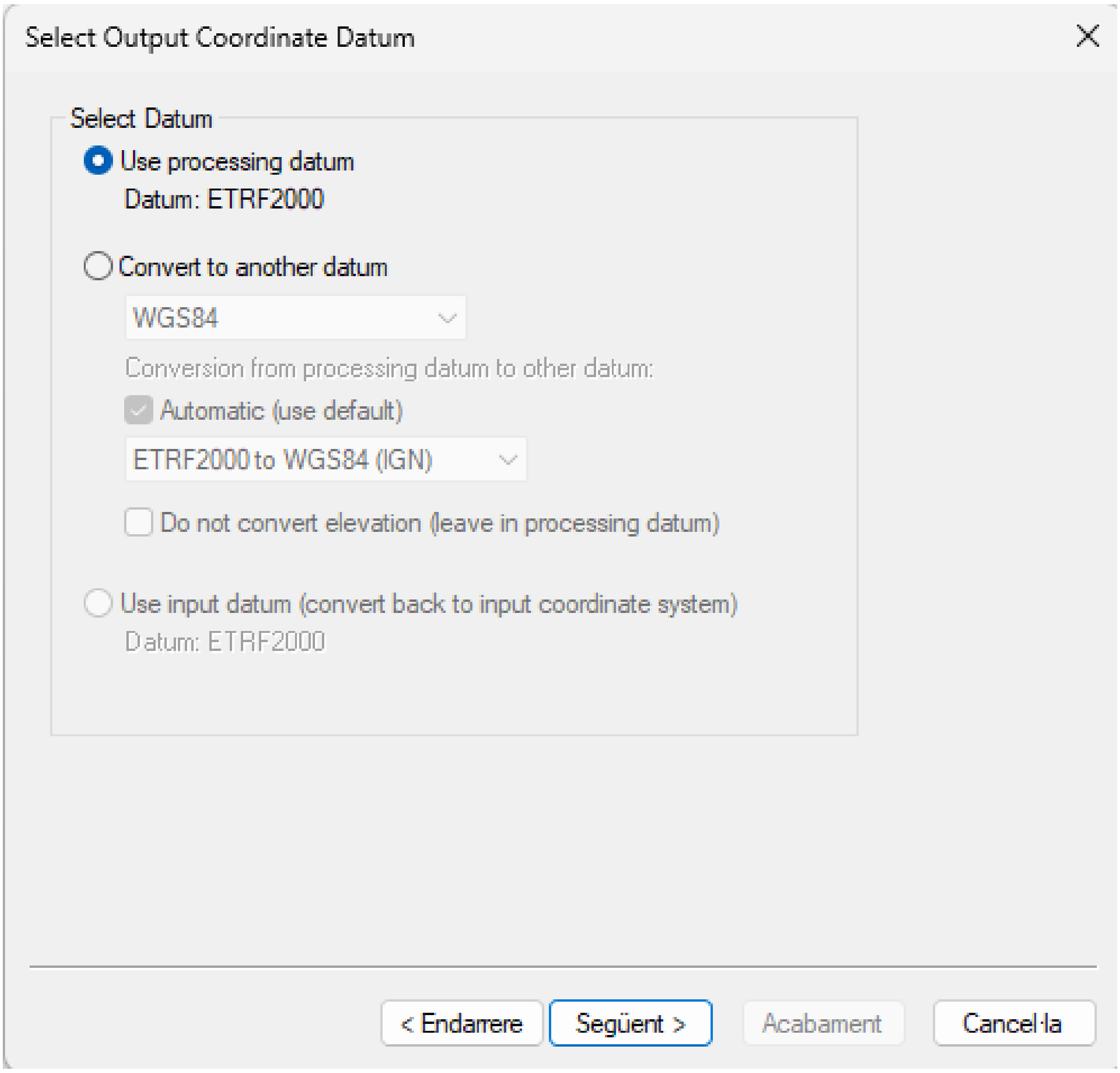

Figure 49. Datum selection

In our example, as we know we want to compare our post processed solution to our real time solution we will export in ETRF2000 datum because the real time solution was feed with RTK from a VRS station computed by the ICGC which is always expressed in that datum.

If you so desire you could choose any other datums that suit best your application.

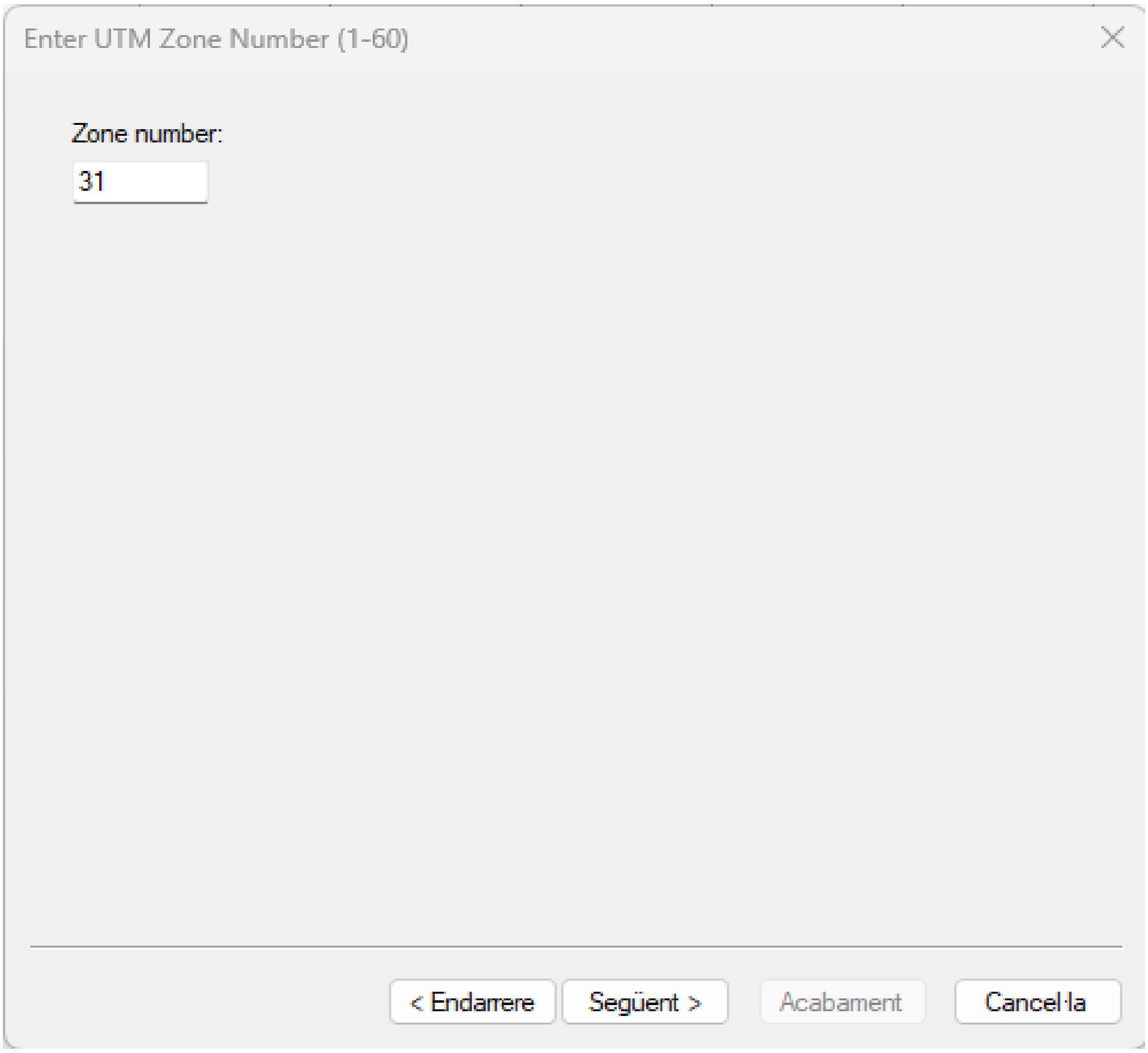

Figure 50. UTM Zone selection.

In our case, because Barcelona is all included in the Universal Transverse Mercator Zone 31 we choose 31 but for any other geographic area the most optimal number will be suggested by the software but you could tweak it to your liking.

Note that this window appears because we have selected UTM coordinates in the export variables otherwise we wouldn't see this window.

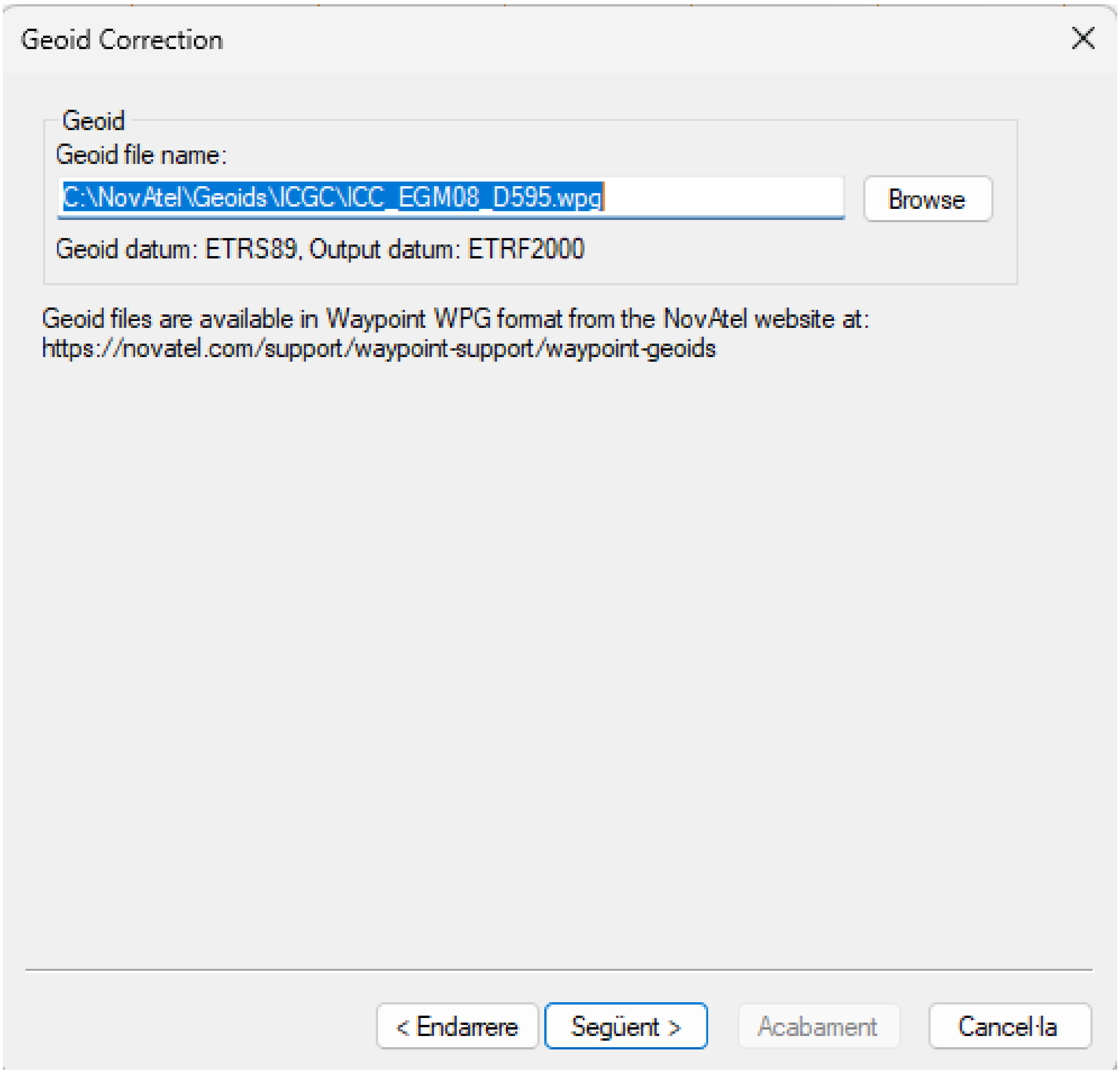

Figure 51. Geoid Undulation file selection.

In this window you must select the file that contains the geoid undulation table that establishes the relationship between the ellipsoid and the geoid.

In the example that you see pictured here a handmade geoid is selected, which is based (vertical offset of 595 millimeters) in the global EGM2008 but it only covers Catalunya. The procedure to create such a file will not be discussed in the present document.

Waypoint group provides[4] a series of pre made geoids that cover different geographic areas, if you don't know what to download, I suggest to use a good all around EGM2008 which covers the whole planet and provides reasonable values.

This window appears because we have selected orthometric height as one of our output fields, otherwise we wouldn't see this geoid selection screen.

[4] https://novatel.com/support/waypoint-support/waypoint-geoids

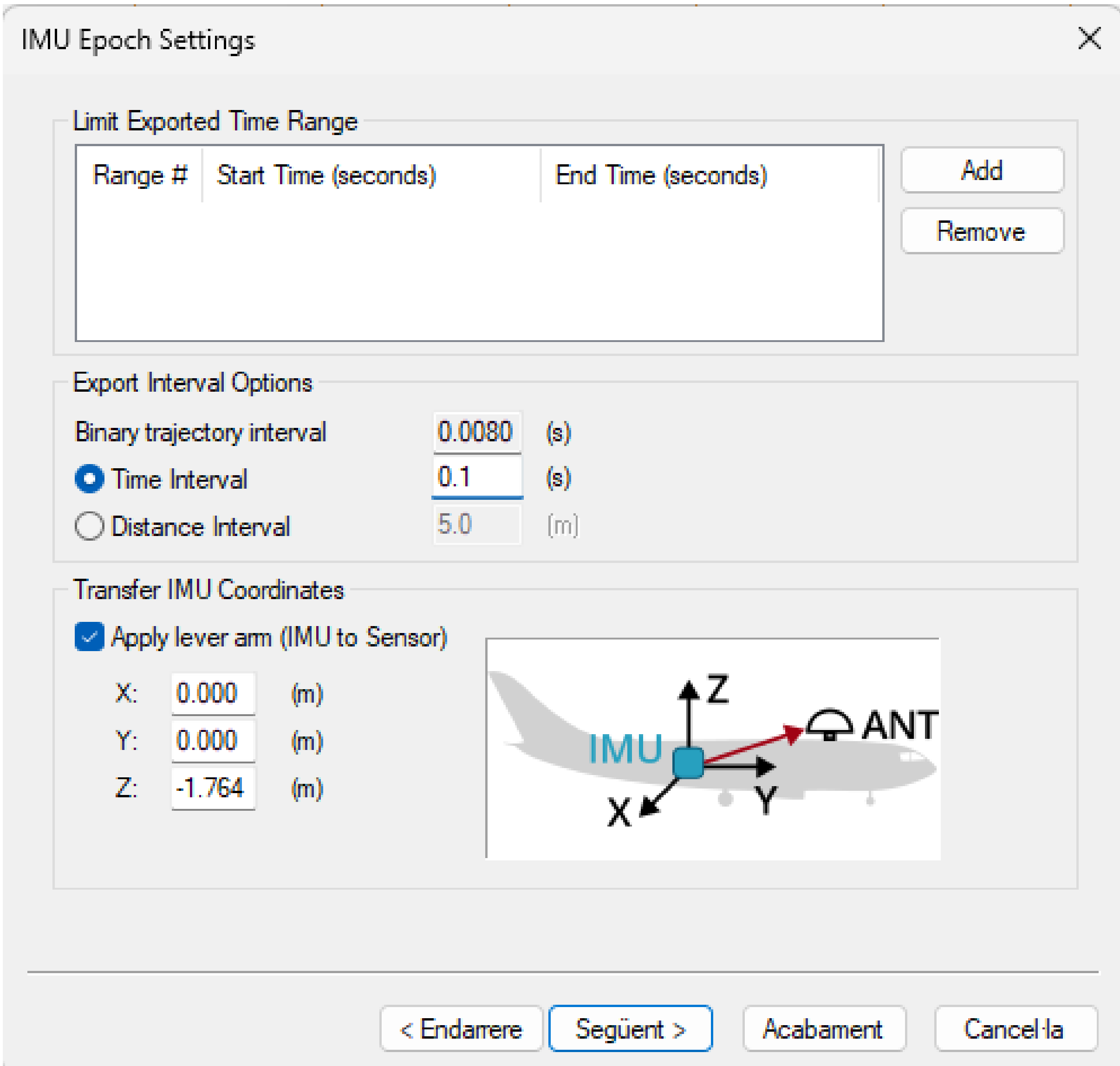

Figure 52. Output Frequency and output offset.

In our case we want to export the whole file temporal window so we will not set a limited time range.

Because the NovAtel receiver was configured to output the solution at 10 Hz (0.1 seconds interval) we set the Export Interval at 0.1 s but bear in mind that Inertial Explorer, when paired with an EPSON G320N IMU it can output data rates up to 125Hz.

Because we want our altitude at ground level, we input the SPAN IMU height over ground.

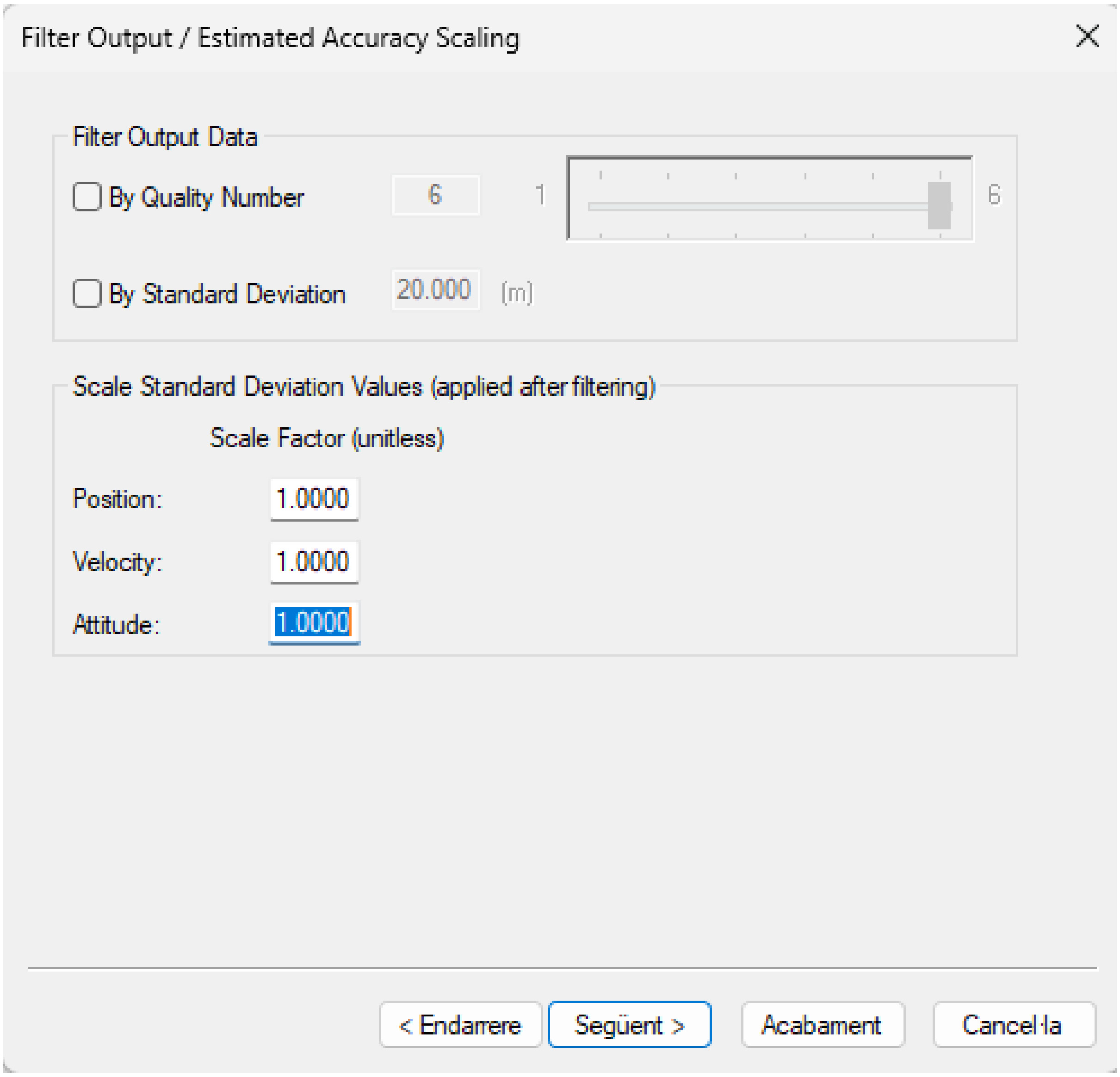

Figure 53. Quality and Standard deviation filtering and standard deviation sclaing.

We will leave this window as it is as we have no intention to filter out measurements nor scale standard deviations.

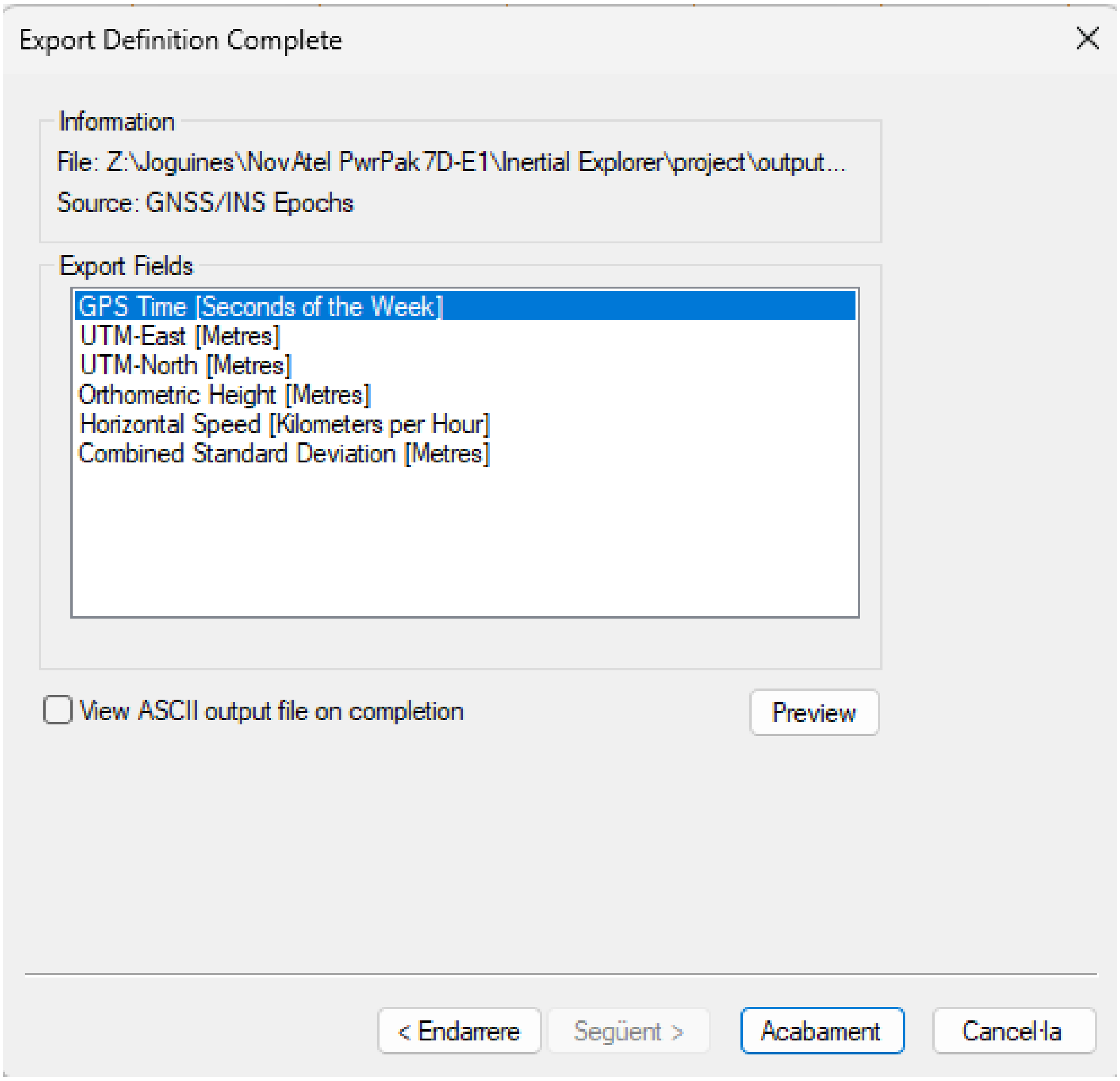

Figure 54. Export definition complete.

If everything went fine, we should obtain a file that looks like this:

```
369124.000,432040.228,4585215.203,25.557,41.056,0.018
369124.100,432040.218,4585214.063,25.552,41.242,0.017
369124.200,432040.206,4585212.924,25.548,41.429,0.017
369124.300,432040.196,4585211.783,25.542,41.412,0.017
369124.400,432040.184,4585210.638,25.527,41.280,0.017
369124.500,432040.172,4585209.488,25.505,41.214,0.017
369124.600,432040.159,4585208.334,25.483,41.460,0.017
369124.700,432040.148,4585207.183,25.468,41.736,0.017
369124.800,432040.134,4585206.031,25.460,41.710,0.017
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Acknowledgments

The author of this tutorial would like to knowledge the important contributions that some individuals made to make the writing of this document possible:

- **Marialluïsa Ester Subias**: My mum, who patiently purchased every single item of hardware I had in mind for the SPAN setup, which in most cases have not been cited in the document.
- **Glòria Ester Subias**: My aunt, who provided valuable inputs along the conceptualization process and originally proposed to use her car and also volunteered as a driver.
- **Raymond Sandgren Calderón**: A friend and the owner of the Spanish NovAtel dealership Orbital-GNSS, he provided valuable inputs along the process plus acted as wise advisor.
- **Marc Calaff Gonzàlez**: A friend and colleague from my land surveying degree at UPC, and Chief Executive Officer at Geolegnia SLP he provided valuable input as well as his professional tools of work and personal time to the project.
- **Vladimir Suvorkin**: A friend and colleague at Rokubun. He joined gAGE/UPC in April 2021 as a PhD candidate in the Aerospace Science and Technology PhD programme. He provided the GNSS antennas required for the kinematic data take, he helped to plan the trajectory and also required the final dataset for his own PhD related tasks.
- **Aleix Tejada Giménez**: A friend and colleague at Rokubun. He has been responsible of the design of the receivers / antennas mounting solution, some cable assemblies, as well as the provider of his own car which happens to be very well suited for the task of collecting GNSS data.
- **Mar Pujol Tejada**: She is a new engineer who occupies a junior position, she likes milk, Minions and cakes, she helped to assemble the extruded aluminum structure (see attached picture).