ROKUBUN

Title **SPEAR performance white paper**

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# VERSION CHANGE HISTORY

| Date | Version | Author | Brief Comment |
|---|---|---|---|
| 2022-04-28 | 0.1 | IHE | Initial content |
| 2022-05-06 | 0.2 | XBC | Initial corrections |
| 2022-05-12 | 0.3 | IHE | Minor refinements |
| 2022-07-05 | 0.4 | IHE | Trimming unnecessary parts |
| 2022-07-06 | 0.5 | IHE | Add plots and tables with testing results |
| 2022-07-11 | 0.6 | IHE | Refine the abstract and the introduction |
| 2022-11-10 | 0.7 | IHE | Trim unnecessary parts |
| 2022-11-25 | 0.8 | MED | Add HAS results |

# 1. ABSTRACT

This document reviews the performance, in terms of accuracy and other relevant metrics, of SPEAR, Rokubun's Positioning Engine, in combination with several COTS GNSS receivers and chipsets. The performance metrics of a given combination of GNSS receiver hardware plus GNSS positioning engine is of paramount importance when evaluating the fitness of that combination for a particular navigation and /or positioning application. The document contains different sections, one per each scenario and processing strategy considered, with the corresponding performance figures. The methodology that has been used to compute these performance metrics is based on collecting, for post-processing, several GNSS measurements datasets in a zero baseline configuration with several receivers, all of them connected to the same GNSS antenna through a RF splitter. The complete setup and equipment used are described in the annexes of this document.

## 2. SPEAR Positioning Engine

SPEAR is a highly flexible, low-level, platform agnostic software positioning engine, implemented as a software development kit (SDK), able to deliver navigation solutions which are equivalent to the following industry standards:

- Single Point Positioning (SPP), both code only and code & phase
- Differential Global Navigation Satellite System (DGNSS)
- Precise Point Positioning (PPP)
- Real Time Kinematic (RTK) / Post Processed Kinematic (PPK)

However, instead of using the traditional methods to compute those solutions it uses an undifferenced and uncombined approach which leads to a seamless mathematical process that enables the user to mix the aforementioned positioning methods in a best effort basis or, for instance, use multiple base stations in a continuous differential solution without having to resource to the Virtual Reference Station (VRS) approach if the user doesn't want to. SPEAR Positioning Engine's particular mathematical approach overperforms classical engines, especially in challenging conditions, such as handling GNSS reference stations' handovers.

SPEAR positioning engine (PE) is programmed using low level programming language (C) so that it can be easily integrated into any platform whether it is at an OS level (e.g. embedded) or at application level (e.g. Android). It is designed to provide the end user with robust and accurate navigation, including the latest Galileo services: HAS (High Accuracy Service) or OS-NMA (Open Service - Navigation Message Authentication) among others. SPEAR is ready to ingest precise positioning corrections from augmentation services (OSR and/or SSR) as well as is able to hybridize GNSS with Wi-Fi ranging measurements[1] (ieee 802.11mc) for resilient positioning in harsh GNSS scenarios such as urban canyons or mild indoors. SPEAR is ready to be expanded to other navigation opportunity technologies (IMU, UWB, 5G Bluetooth, …), aiming at getting the best of the customer's navigation hardware platform.

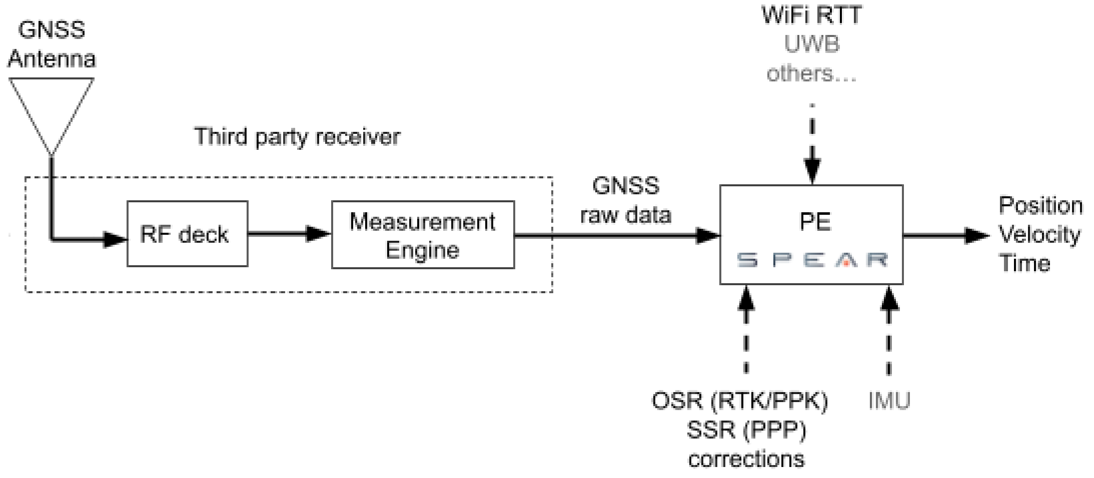



*Figure 1: SPEAR in the GNSS Receiver value chain*

In its current state-of-the-art, SPEAR features are as follows:

- Code and Carrier Phase Single Point Positioning (SPP)
- Code only Differential positioning (DGNSS) using a base station

[1] Round Travel Time (RTT) measurements provided by the 802.11mc protocol

- Precise Point Positioning (PPP) using precise clocks and orbits
- Carrier phase differential network positioning (RTK like) using one or more base stations
- Combined PPP + RTK like positioning
- Galileo High Accuracy Service (HAS) positioning
- Galileo OS-NMA decoding for Authentication
- GNSS + WiFi RTT hybrid positioning

Currently SPEAR is able to use GPS, Galileo and Beidou Global Navigation Satellite Systems constellations.

Major features that are Work In Progress not yet released:

- GLONASS constellation support
- Ambiguity fixing
- IMU coupling
- GNSS + Ultrawideband (UWB) hybrid positioning

In the current version of the present paper we will review SPEAR's performance in a basic scenario, namely:

| Date | Dynamics | Location |
|---|---|---|
| 2022-05-10 | Static | Antenna at Rokubun's HQ rooftop |

*Table 1: Scenarios currently in Rokubun's GNSS database for SPEAR testing and validation.*

The performance results presented henceforth have been obtained in post-processing for the sake of assessing the SPEAR performance in different processing modes using the data gathered in a single acquisition campaign. The general methodology leading to the results reported in the present document consisted in gathering GNSS measurements from all the receivers under test during the acquisition campaign in order to subsequently undergo post-processing navigation computation, using the different configurations of SPEAR for the different receivers used. Nonetheless, SPEAR has been in parallel successfully executed in real time in an embedded applications ARM processor, in Rokubun's MEDEA GNSS computer, whose details are provided in the annex. Real time SPEAR performance results will follow in subsequent versions of this paper.

# 3. Key Performance Indicators

SPEAR's performance is to be evaluated based on industry standard KPIs by comparing positioning and/or navigation results against a truth value.

The following metrics will be provided:

- **Horizontal, vertical and 3D position error:**
  - Time series (plot).
  - Root Mean Square Error.
  - 95th percentile (2-sigma).
- **CDF:** Horizontal error  Cumulative Distribution Function (plot).

# 4. Scenarios

## 4.1. Standalone static

This scenario corresponds to the best possible case: open sky conditions in a stationary location with a mid/high-range antenna. For this scenario, SPEAR was run with the following strategy: **standalone (broadcast ephemeris) code and phase, multi-constellation, multi-frequency and full kinematic stochastics.**

**95th percentile error**

| Rx ID | Horizontal | Vertical | 3D |
|---|---|---|---|
| STM TeseoV | 0.493 m | 1.164 m | 1.264 m |
| u-blox ZED-F9P | TBD | TBD | TBD |
| Septentrio AsteRx-U | 0.426 m | 0.917 m | 1.011 m |

*Table 2: 95th percentile error obtained with SPEAR processing for receivers under test.*

The truth value of the antenna position comes from:

- Stationary dataset → presurveyed position with a long stationary session processed by either NRCAN, AUSPOS and / or NGS OPUS using data collected from ROK1 CORS GNSS (Septentrio AsteRx-U + Tallysman VSP6037L VeroStar™)

### 4.1.1. Setup

The GNSS antenna[2], mounted in a fixed mast at Rokubun's office rooftop (clear view with no obstructions), is a Full GNSS Precision Antenna +L-band with a low noise amplifier typical gain of 37 decibels connected to 65 meters of HF400 50Ω low loss coaxial cable. Data was collected on 5th November 2022, as shown in the table below:

| Rx ID | Start (GPS time) | Finish (GPS time) | Duration | Rate |
|---|---|---|---|---|
| STM Teseo V | 05:13:17 | 12:26:40 | 07:13:23 | |
| u-blox ZED-F9P | 05:13:19 | 12:26:40 | 07:13:21 | 1 Hertz |
| Septentrio AsteRx-U | 05:00:00 | 12:26:40 | 07:26:40 | |

*Table 3: Temporal characteristics of all the datasets processed in this run.*

The geographic location of this dataset, in Rokubun's offices rooftop, is shown in the figure below:

[2] Tallysman VSP6037L VeroStar™

*Figure 2: Position of ROK1 base station antenna indicated by a red triangle in the center of the aerial image.*

The following table shows the GNSS observables used by SPEAR in this standalone processing.

| Receivers | Observables |
|---|---|
| STM Teseo V | GPS L1 C/A + L5, Galileo E1 + E5a |
| u-blox ZED-F9P | GPS L1 C/A + L2C, Galileo E1 + E5b |
| Septentrio AsteRx-U | GPS L1 C/A + L2 + L5, Galileo E1 + E5b + E5a |

*Table 4: Observables as used by SPEAR engine.*

#### 4.1.2. Results

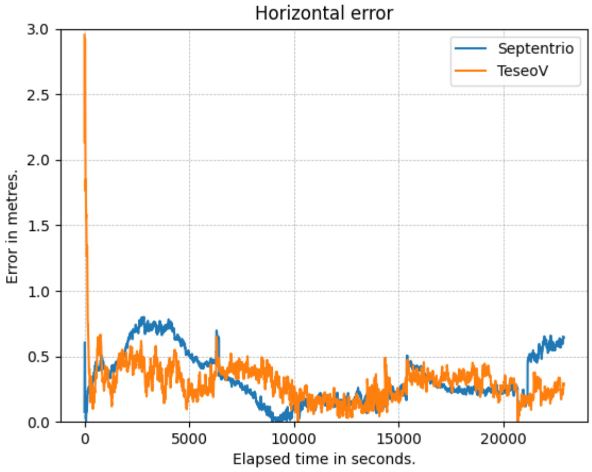
After SPEAR processing of the GNSS measurements from different receivers, the error figures for the 2D (horizontal) and 3D error are summarized in the table below:

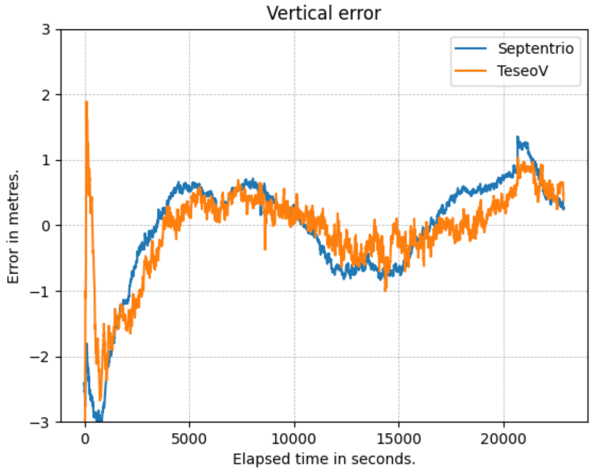
**Root Mean Square error**

| Rx ID | Horizontal | Vertical | 3D |
|---|---|---|---|
| STM Teseo V | 0.349 m | 0.659 m | 0.746 m |
| u-blox ZED-F9P | TBD | TBD | TBD |
| Septentrio AsteRx-U | 0.377 m | 0.859 m | 0.939 m |

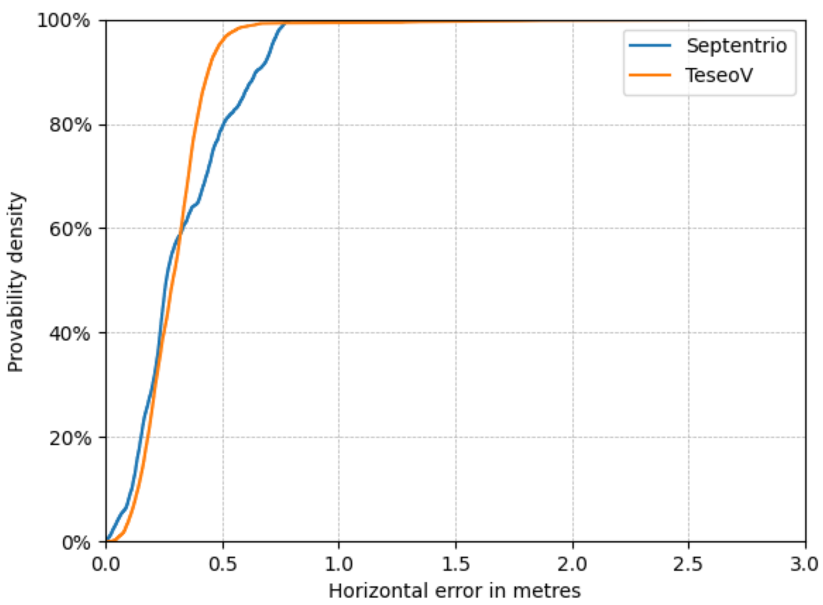
*Table 5: RMSE error obtained with SPEAR processing for receivers under test.*

The horizontal and vertical error time series as well as the CDF are shown in the plots below:




Cumulative Distribution Function (CDF)




The conclusion of the results presented in this section is that SPEAR delivers **decimetric accuracy positioning** for COTS GNSS receivers in its standalone configuration, with a 95th percentile horizontal error below 50 centimeters.

## 4.2. Standalone static + HAS

This data take processing aims at demonstrating the Galileo HAS-PPP capabilities of SPEAR. The methodology and truth are the same described for the Standalone static data take. In this case, E6-B capable GNSS receivers were used to extract the HAS message for post-facto processing with SPEAR. **Results have been obtained using code and phase with Galileo E6B High Accuracy Service (HAS) corrections (PPP like processing), multi-constellation, multi-frequency processing strategy.**

### 95th percentile error

| Rx ID | Horizontal | Vertical | 3D |
|---|---|---|---|
| STM Teseo V | 0.577 m | 2.007 m | 2.095 m |
| STM Teseo V + HAS | 0.514 m | 1.486 m | 1.686 m |
| Septentrio AsteRx-U | 0.688 m | 2.556 m | 2.577 m |
| Septentrio AsteRx-U + HAS | 0.320 m | 2.961 m | 2.975 m |

*Table 6: 95th percentile error obtained with SPEAR processing for receivers under test.*

### 4.2.1. Setup

The setup of this take is identical to the one used in the Standalone Static, except for that the number of epochs of study has decreased into 6000 in order to put the focus on convergence and performance in a shorter timespan.

| Receivers | Start (GPS time) | Finish (GPS time) | Duration | Rate |
|---|---|---|---|---|
| STM Teseo V | 05:13:17 | 06:53:17 | 01:40:00 | 1 Hertz |
| Septentrio AsteRx-U | 05:00:00 | 06:40:00 | 01:40:00 | |

*Table 7: Temporal characteristics of all the datasets captured in Standalone static + HAS data take..*

### 4.2.2. Results

After SPEAR processing of the GNSS measurements from different receivers using both the standalone configuration reported in 4.1 and HAS-PPP configuration, the error figures for the 2D (horizontal) and 3D errors are summarized in the table below:

### Root Mean Square error

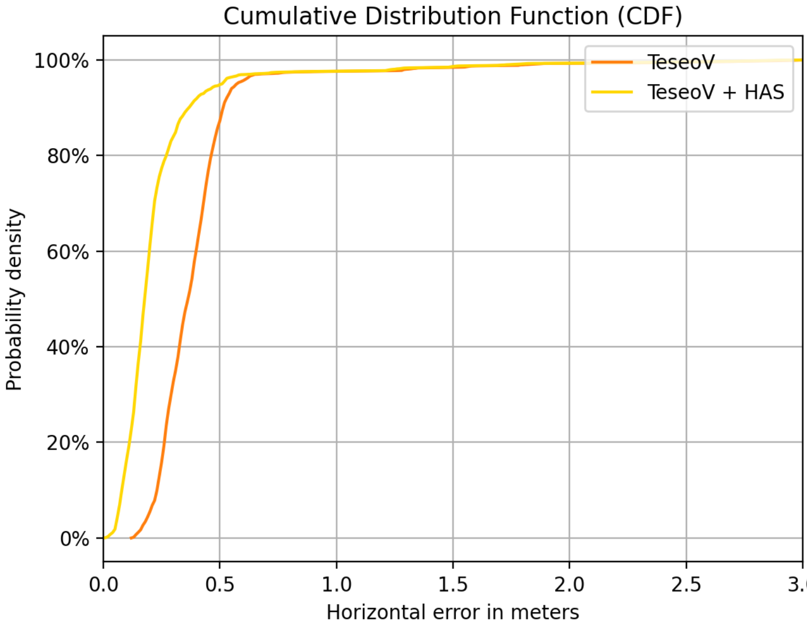
| Rx ID | Horizontal | Vertical | 3D |
|---|---|---|---|
| STM Teseo V | 0.483 m | 1.069 m | 1.174 m |
| STM Teseo V + HAS | 0.369 m | 0.790 m | 0.872 m |

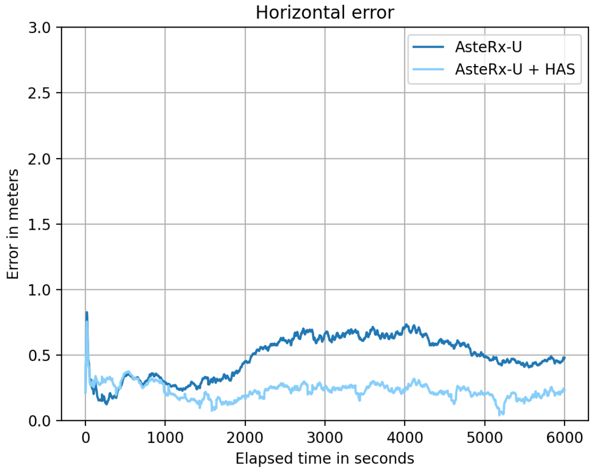
## Root Mean Square error

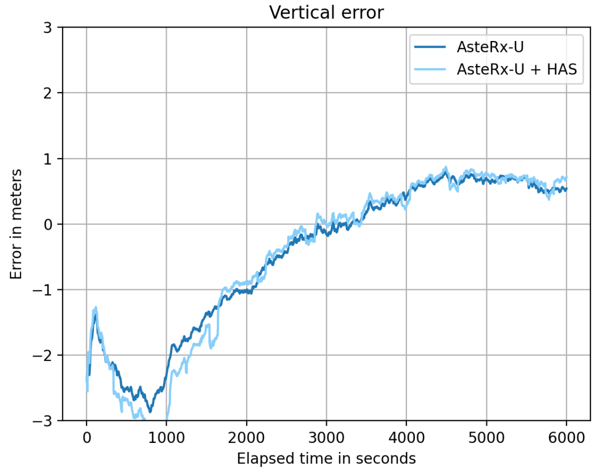
| Rx ID | Horizontal | Vertical | 3D |
|---|---|---|---|
| Septentrio AsteRx-U | 0.508 m | 1.219 m | 1.321 m |
| Septentrio AsteRx-U + HAS | 0.237 m | 1.362 m | 1.383 m |

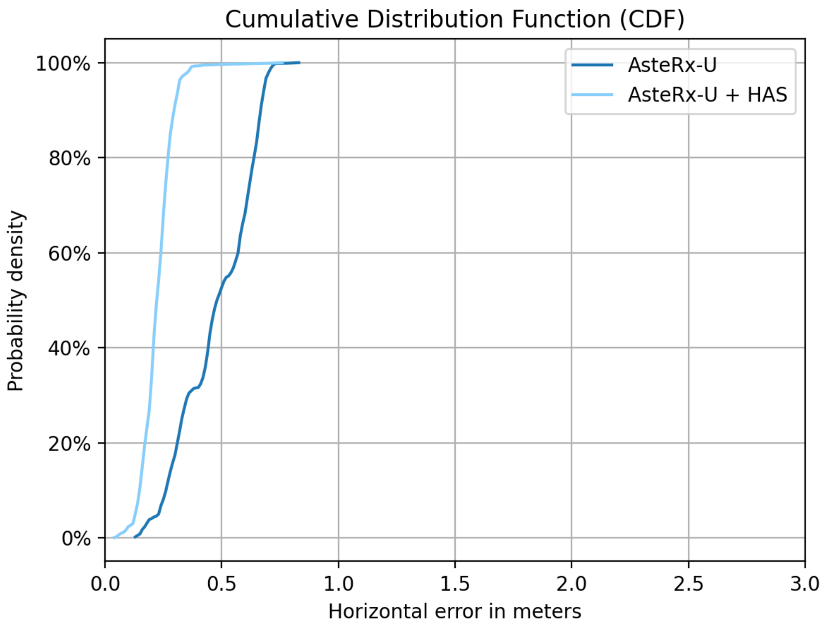
*Table 8: RMSE error obtained with SPEAR processing for receivers under test.*








The conclusion of the results presented in this section is that SPEAR is HAS-PPP capable, improving the performance with respect to the standalone configuration, for those GNSS receivers able to track E6 and retrieve HAS messages, achieving **decimetric accuracy positioning**.

# 5. ANNEX I: Equipment used

Different receivers are being used to assess SPEAR's performance, flexibility and capability to ingest raw data from different vendors. This section describes the receivers that have been used to obtain the results shown in this document.

In the current version of this white paper, SPEAR processing workflow implies that in most cases GNSS measurement data is obtained from the aforementioned receivers and then processed offline in a computer to obtain a positioning result in a post-facto paradigm.

## 5.1. Base station(s)

Although not all strategies adopted in the paper rely on differential processing, Data from a GNSS Base station has been gathered for those processing using a differential strategy.

In all the field data recordings at least one base station dataset overlapping with the rover raw dataset is available. The base can either be:

- Part of the "Institut Cartogràfic i Geològic de Catalunya" GNSS network CatNET (Leica GR50 enclosures).

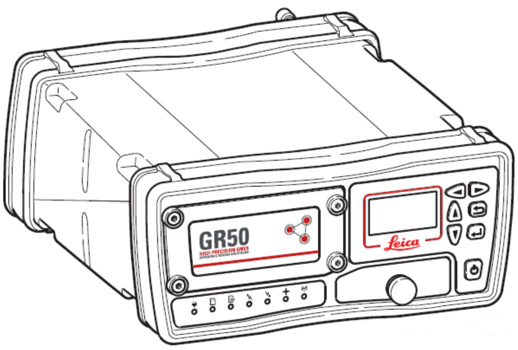



*Figure 3: Leica base station receiver.*

- Septentrio AsteRx-U enclosed base station receiver connected to ROK1 antenna (Tallysman VSP6037L VeroStar™) on the roof of Rokubun's office. This GNSS receiver is deployed as a Continuously Operating Reference Station (CORS) at Rokubun premises, and is used as reference in the standalone static dataset.


*Figure 4: Septentrio's base station receiver.*

In both cases the base stations receivers are full-fledged multi-constellation and multi-frequency capable.

## 5.2. Rovers

As one of SPEAR strengths is its ability to process GNSS measurements data coming from different receiver manufacturers, the white paper covers results obtained from several GNSS receivers' measurements:

### 5.2.1. Rokubun's MEDEA based on U-blox ZED-F9P RTK capable OEM module

MEDEA is Rokubun's GNSS computer based on the combination of a u-blox ZED-F9P and an ARM® Cortex®-A8 applications processor, plus additional sensors (IMUs, magnetometers, barometer...) and connectivity means (Ethernet, Wi-Fi...). MEDEA is used as a SPEAR development asset at Rokubun, which aims at emulating an average navigation OBU.

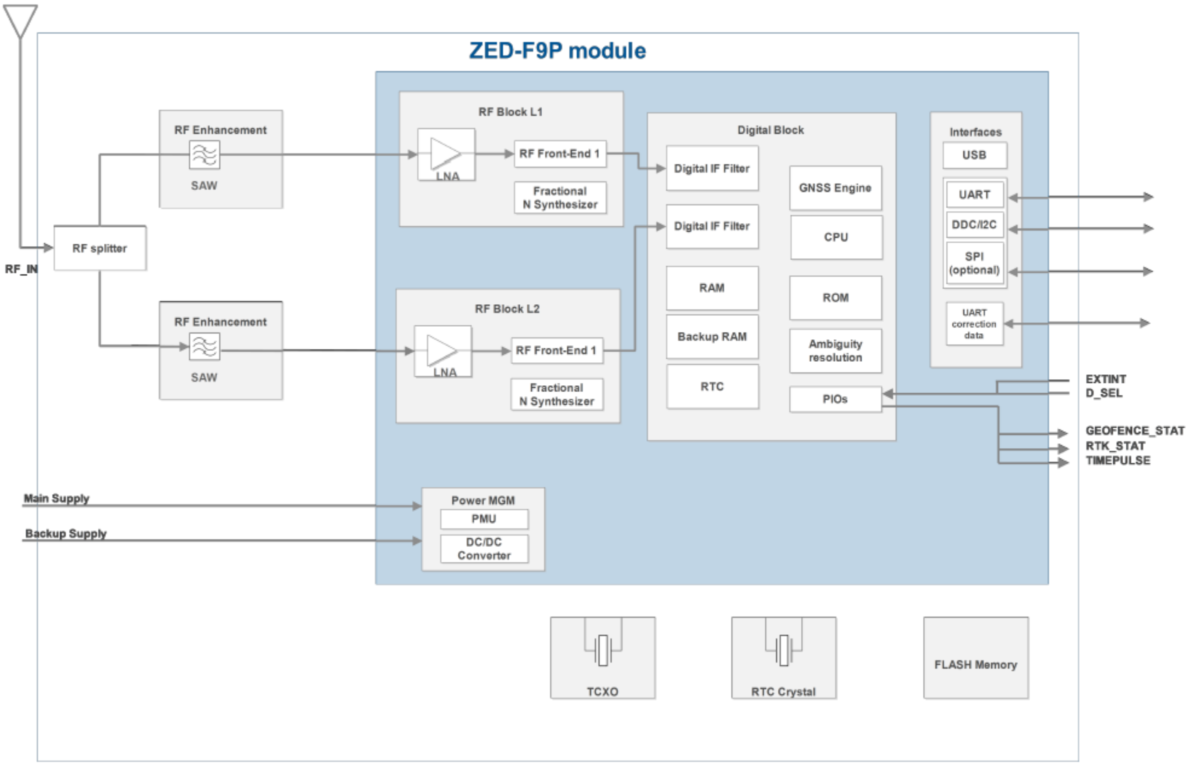



*Figure 5: u-blox F9P receiver general overview diagram.*

SPEAR has also been embedded for real-time navigation in MEDEA's applications processor SiP (System in Package) Octavo OSD3358-512M-BCB which integrates the following components in a 400 ball BGA package:

- Texas Instruments Sitara™ AM335x ARM® Cortex®-A8 Processor + 2x RISC cores
- 512MB DDR3L Memory
- TPS65217C Power Management IC
- TL5209 LDO
- 4KB EEPROM
- 4GB eMMC Non-Volatile Storage

Further SPEAR performance testing for the real-time positioning results obtained from the embedded version in MEDEA's processor SiP will be presented in subsequent sections of this paper.

### 5.2.2. STMicroelectronics Teseo-V EVB

Results reported in this paper were obtained using a TeseoV EVB for GNSS measurements acquisition. Additionally a specific engineering version of the TeseoV, able to track Galileo E6, was used in the Standalone static + HAS scenario. More details about this can be found in the ION 2022 publication *"A New Single Chip Receiver for Integrated Galileo, BeiDou and QZSS High Accuracy Services"* Gogliettino, Giovanni et al[3]

[3] https://doi.org/10.33012/2022.18464

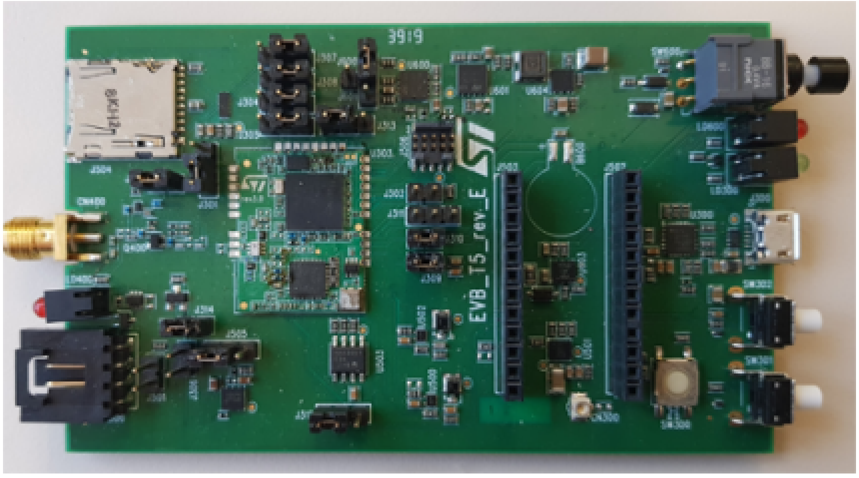



*Figure 6: Teseo V development kit PCB*

# 6. ANNEX II: ACRONYM TABLE

| | |
|---|---|
| AUSPOS: | AUStralia POSitioning PPP service provided by Geoscience Australia |
| BDS: | Chinese BaiDou satellite constellation |
| DGNSS: | Differential Global Navigation Satellite System |
| GAL: | European Union Galileo satellite constellation |
| GLONASS: | Russian satellite constellation |
| GNSS: | Global Navigation Satellite System |
| GPS: | United States Global Positioning System satellite constellation |
| HAS: | Galileo's High Accuracy Service |
| IMU: | Inertial Measurement Unit |
| KPI: | Key Performance Indicators |
| NGS OPUS: | United States National Geodetic Survey PPP Online Positioning User Service |
| NRCAN CSRS PPP: | Natural Resources Canada Canadian Spatial Reference System PPP service |
| OBU | On-board Unit |
| OS-NMA: | Galileo's Open Service Navigation Message Authentication |
| OSR: | Observation State Representation |
| PPK | Post Processed Kinematic |
| PPP: | Precise Point Positioning |
| RTK: | Real Time Kinematic |
| RTT: | Round Trip Time |
| SiP: | System in Package |
| SSR: | Space State Representation |
| SPEAR: | Satellite Positioning Engine for Accurate and Real time navigation |
| SPP: | Single Point Positioning |
| ROK1: | GNSS geodetic antenna located at Rokubun's HQ roof |
| UWB: | Ultra Wide Band |
| VRS: | Virtual Reference Station |