Sub-decimeter orbit estimation for LEO satellites in real time: Demonstration of Precise Point Positioning onboard Norsat-TD

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ABSTRACT

Satellites in Low Earth Orbit (LEO) are commonly equipped with GNSS (Global Navigation Satellite Systems) receivers to obtain real-time positioning, velocity, and time (PVT). Although the highest possible PVT accuracy is obtained by post-processing the raw GNSS data in facilities on the ground, recent advancements in space applications drive the need for precise onboard orbit determination (P2OD) achieving sub-dm level accuracy in real-time with advanced filters, signals from multiple constellations, and PPP (Precise Point Positioning).

SpaceStar® is a GNSS navigation software solution providing real-time onboard high accuracy PVT for satellites in LEO based on the PPP (Precise Point Positioning) technique. PPP is a GNSS augmentation technique which uses orbit and clock corrections to enable users to obtain absolute high accuracy positioning. PPP is used extensively for precise Earth-based navigation and was demonstrated onboard a satellite in LEO in 2022 by Fugro on the Loft Orbital YAM-3 satellite.

This paper discusses how Fugro has continued to develop and utilise the PPP technique to estimate real-time nominal positioning at sub-decimetre levels of accuracy in LEO on the NorSat-TD satellite, launched in May 2023. At the time of writing, SpaceStar® is still active on NorSat-TD, having generated GBs of data and counting. The system architecture used to deliver PPP-enabling corrections to LEO and the architecture onboard is described. The initial results from the demonstration are presented and discussed, followed by a description of future developments that are planned to improve performance going forward.

INTRODUCTION

Satellites operating in Low Earth Orbit (LEO) often rely on GNSS (Global Navigation Satellite System) receivers to obtain real-time data on their position, velocity, and timing. This information is vital for the onboard guidance, navigation, and control systems (GNC), which manage tasks like orbit determination, collision avoidance, and proximity operations. Additionally, GNSS data enables remote sensing applications such as radio occultation, synthetic aperture radar (SAR), and RF (radio frequency) geolocation, which can also involve coordinated maneuvers of multiple satellites.

Historically, the accuracy of GNSS positioning onboard satellites has lagged that of advanced terrestrial systems, which are capable of achieving centimeter-level precision in real-time and is commonly utilised in applications such as surveying, precision agriculture, and maritime navigation and dynamic positioning.

On Earth, Precise Point Positioning (PPP) is a commonly used technique that is used to achieve high-accuracy centimetre level positioning. PPP integrates precise GNSS orbit and clock corrections, multi-frequency GNSS data, and advanced observation modeling. Although PPP has been a staple for precise navigation on Earth for over twenty years, its use for satellite applications in LEO is a recent development.

In LEO, GNSS positioning accuracy typically ranges from a few meters to tens of meters. For missions requiring sub-meter accuracy, raw GNSS data is often transmitted to the ground for post-processing to achieve a Precise Orbit Determination (POD). While effective, this method introduces latency and strains the limited downlink capacity. Enhancing mission performance is closely tied to improving the quality and reducing the latency of information delivered to users. There is a growing trend towards increasing onboard capabilities and autonomy in satellites, driven by advancements in edge computing and artificial intelligence. To address the need for reduced latency, Fugro has utilized its expertise in PPP to develop SpaceStar®®, a technology that provides high-accuracy GNSS positioning in real-time onboard LEO satellites, also known as precise onboard orbit determination (P2OD).

In August 2022, Fugro successfully demonstrated SpaceStar® PPP technology in orbit for the first time onboard Loft Orbital’s YAM3 satellite. In May 2023, a second in-orbit demonstration mission was launched onboard the NorSat-TD satellite, this time running on a GomSpace SDR unit. During the time in orbit, SpaceStar® has successfully been shown to significantly improve stand-alone GNSS accuracy and integrity.

GENERATING AND DELIVERING CORRECTIONS TO LEO

Fugro uses its proprietary ground infrastructure to generate corrections and uses geostationary satellites to deliver them to LEO. This infrastructure is designed to meet the demanding requirements of its terrestrial satellite positioning business which requires a high level of global availability and redundancy. It comprises a worldwide ground network of over 100 reference receiver stations (Figure 1). These stations, equipped with high-precision geodetic hardware, continuously monitor multiple GNSS constellations, including GPS, GLONASS, Galileo, BeiDou, and QZSS.

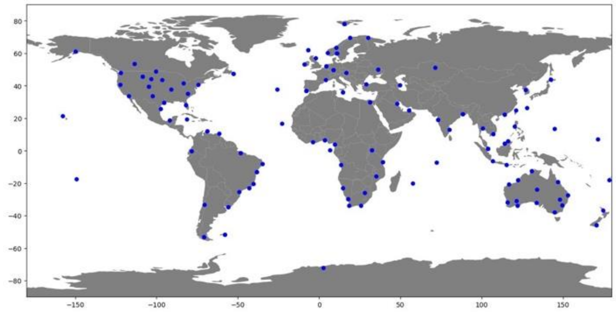

Figure 1: Fugro reference receiver network used for GNSS multi constellation observations for generation of orbit/clock corrections

The raw observation data collected by this network is processed in real-time at Fugro's facilities, where it is used to create GNSS orbit and clock corrections. These corrections are then transmitted to LEO satellites via L-band through a network of geostationary satellites, as depicted in Figure 2.

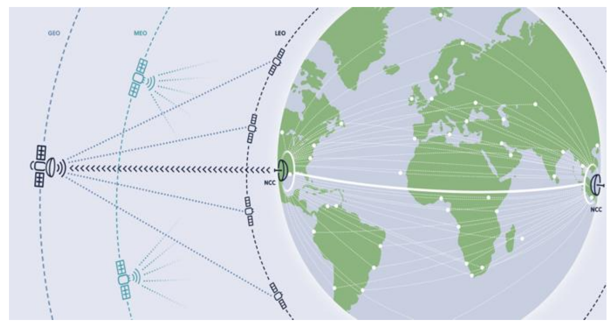

Figure 2: Distribution of corrections on L-band to LEO users via geostationary satellites

ONBOARD ARCHITECTURE

For the NorSat-TD satellite (Figure 3) mission, the onboard architecture was one in which the SpaceStar® software was integrated onto the GomSpace SDR and flown as a payload.

Figure 3: NorSat-TD satellite (credit: Space Flight Laboratory)

The Software-Defined Radio (SDR) serves as the RF front end and provides FPGA resources necessary to integrate Fugro's proprietary L-band tracking and demodulator software. This software is essential for acquiring and decoding the L-band correction signal broadcast from geostationary orbit. Once the correction data is decoded, it is sent to the SpaceStar® position engine software, which is also embedded within the SDR's processing unit. The position engine then applies these corrections to the raw GNSS measurements received from the onboard GNSS receiver, delivering high-accuracy position, velocity, and time telemetry in real-time onboard the satellite, as illustrated in Figure 4. The SDR is built on a Zynq 7000-series System-on-Chip (SoC), featuring both a robust FPGA (Field Programmable Gate Array) and a powerful dual ARM processor. For optimal efficiency, L-band tracking is implemented in firmware at the FPGA level, while the ARM processor runs the PPP engine in software.

In the NorSat-TD mission, a commercial-off-the-shelf (COTS) receiver and antenna has been used. In particular, the GNSS receiver tracks GPS, Galileo and GLONASS constellations in dual-frequency. Separate antennas are used for L-band corrections and the GNSS signal, though a configuration with a single antenna is also possible, as proven during SpaceStar®'s IOD on the YAM-3 satellite. The software integrated in the SDR enables the system to be receiver agnostic so long as the receiver meets the minimum specified requirements of being capable of receiving dual frequency observation data and compatible with more than one of the major GNSS constellations.

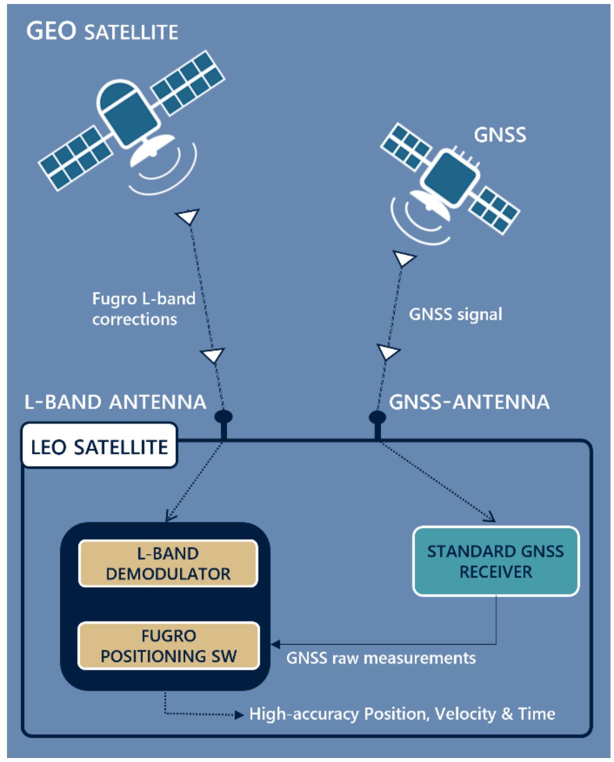

Figure 4: SpaceStar® onboard architecture

IN-ORBIT DEMONSTRATION RESULTS

As of May 2023, SpaceStar® has been enabled in orbit on a frequent basis, resulting in GBs of in orbit data. The real-time computed SpaceStar® solution is compared against precise reference orbits computed on ground in post-processing. The in-orbit demonstration results are discussed in terms of Position, Velocity, Time (PVT) accuracy of SpaceStar®, compared with a standalone GNSS receiver, and validated with independently computed reference orbits by ESA. Furthermore, it is shown how SpaceStar® behaves during L-band and GNSS outages. Lastly, SpaceStar®'s solution integrity is compared with the standalone GNSS receiver.

PVT Accuracy

Figures 5 to 7 depict respectively the position, velocity, and time error during an extended run on November 30, 2024. It demonstrates how SpaceStar® consistently maintains accuracy over the course of multiple orbits. The position error remains around the 10 cm mark, the velocity around the 10 mm level, and the time accuracy is around 1 ns.

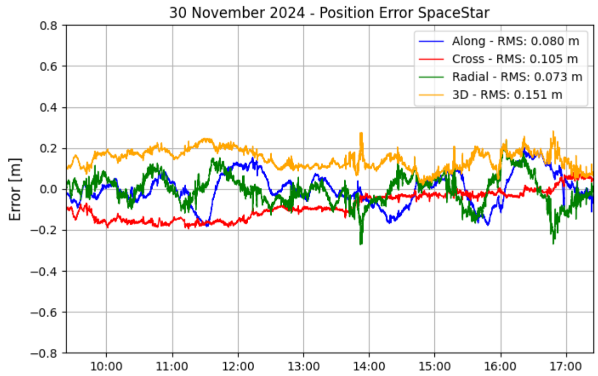

Figure 5: In-orbit position results SpaceStar®

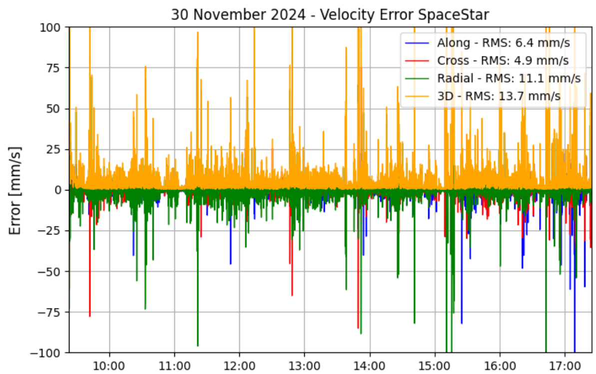

Figure 6: In-orbit velocity results SpaceStar®

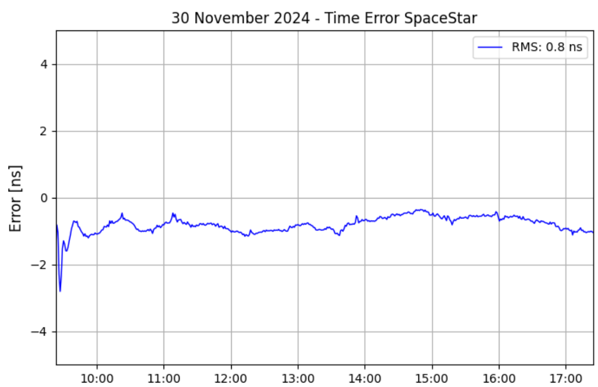

Figure 7: In-orbit time results SpaceStar®

Comparison with Standalone GNSS

While the previous section emphasized the accuracy SpaceStar® achieves, Figures 8 to 10 depict the relative improvement SpaceStar® brings compared to standalone GNSS. As the standalone GNSS receiver outputs positions varying greatly in accuracy, with occasionally spiking over 10 m in error, SpaceStar® is able to consistently achieve sub-decimeter level position errors, thereby improving the standalone solution over an order of magnitude.

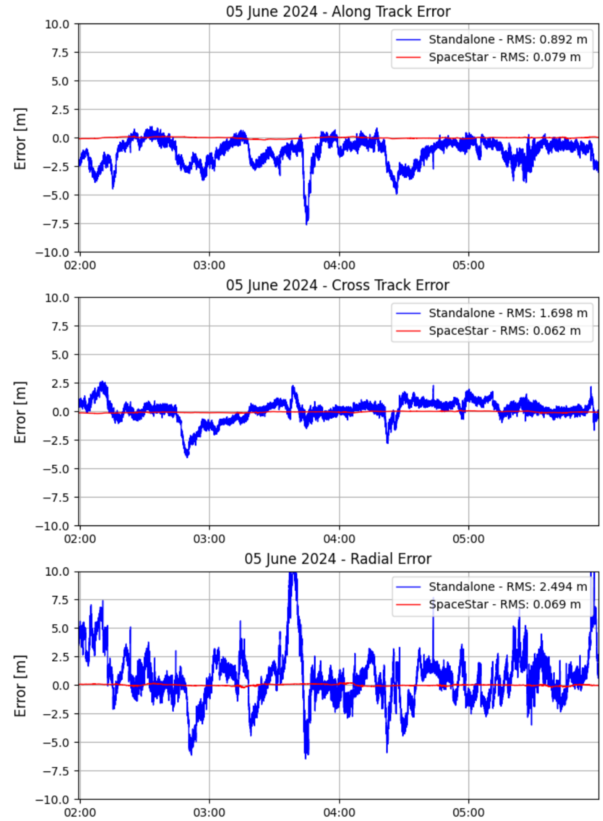

Figure 8: Position comparison SpaceStar® and Standalone GNSS

In terms of velocity error, standalone GNSS has a significantly higher number of outliers and is noisier relative to SpaceStar®. However, where SpaceStar® brings more improvement is in the timing solution. SpaceStar®'s time output yields RMS values of nanosecond level, while the GNSS receiver's time accuracy is at tens of nanoseconds and looks considerably more inconsistent compared to SpaceStar®.

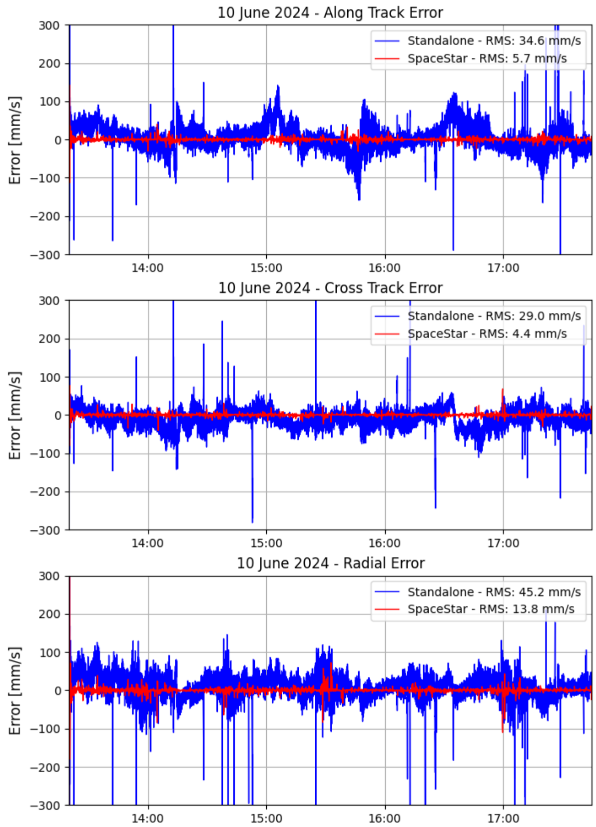

Figure 9: Velocity comparison SpaceStar® and Standalone GNSS

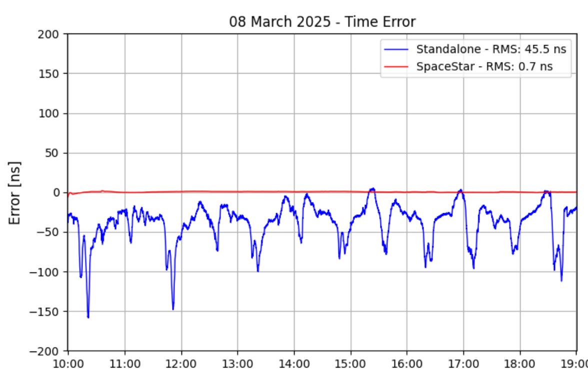

Figure 10: Time comparison SpaceStar® and Standalone GNSS

External Validation

As an additional method of validation of the accuracy, Fugro has cooperated with ESA to provide independent reference orbits. The results and comparison of those reference orbits are displayed in Figures 11 to 13. It is observed that the error of SpaceStar® relative to the two reference orbits is similar, meaning the two independently computed reference orbits align very well.

This is further visualized in Figure 10, where the difference between the two orbits is shown to be a few centimeters, thereby validating SpaceStar®'s results.

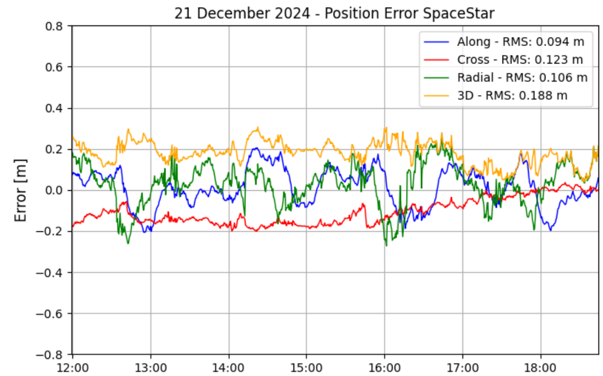

Figure 11: Position error SpaceStar® using ESA reference orbits

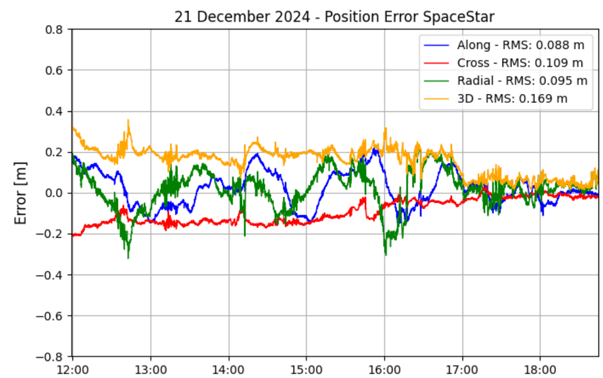

Figure 12: Position error SpaceStar® using Fugro reference orbits

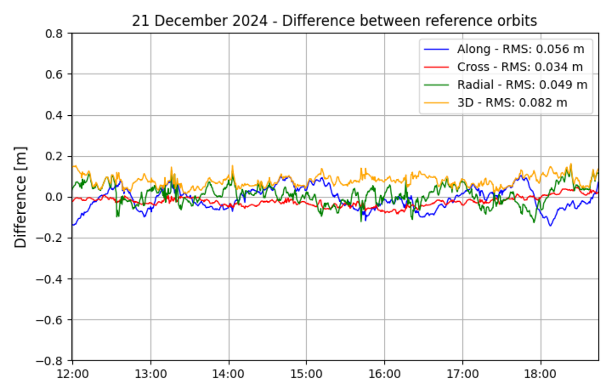

Figure 13: Difference between ESA and Fugro reference orbits

L-Band Outages

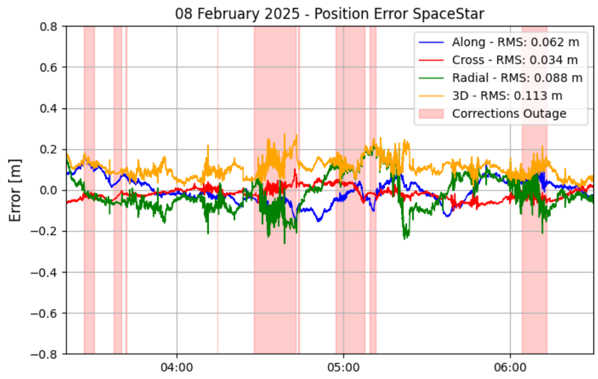

Figure 14: SpaceStar® performance in presence of L-band outages

Depending on location and attitude of the satellite, L-band outages are inevitably present in LEO. SpaceStar®'s navigation software has been designed in such a way that is able to coast on 'old' corrections without significant performance degradation, as is visualized in Figure 14, where the red shading indicates periods of correction outages. It is observed that the solution degradation is minimal, and the accuracy is maintained.

GNSS Outages

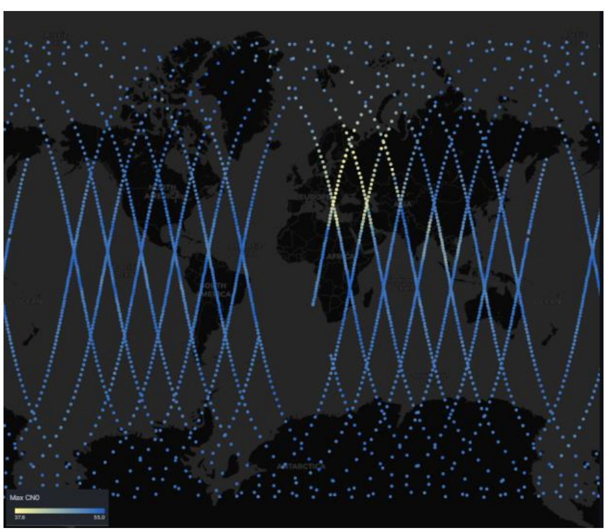

Figure 15: Overlay of GNSS Max CN0

The increasing occurrence of jamming activities on Earth is also noticeable in Space. Figure 15 shows a world overlay of the maximum CN0 of tracked GNSS signals, where blue and yellow respectively indicate high and low CN0. The lower CN0 locations coincide with known jamming activities, specifically in Eastern Europe. Because of this, GNSS outages occur frequently when passing over these areas. Since the working principle of SpaceStar® is to enhance GNSS measurements, SpaceStar® is unable to compute a solution when these observations are not present. This is shown in Figure 16, where such a GNSS outage occurs at 07:00 hrs. Once GNSS measurements resume, it is able to converge within approximately 20-30 minutes to sub-decimeter level.

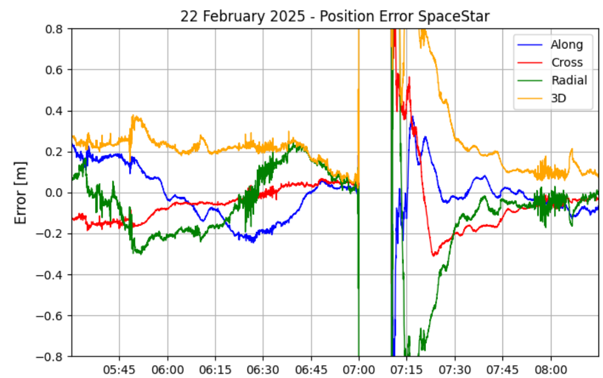

Figure 16: SpaceStar® reconvergence after GNSS outage

Solution Integrity

Next to accuracy, another benefit of SpaceStar® is its enhanced integrity relative to standalone GNSS. An example is depicted in Figure 17, where the position error distribution of both SpaceStar® and the GNSS receiver itself is displayed. The standalone GNSS has outliers in the order of thousands of kilometers, SpaceStar® rejects those faulty measurements and does not output a solution at those times. The outliers of SpaceStar® are mainly due to reconvergence periods after experiencing GNSS outages above Eastern Europe, as explained in the previous section.

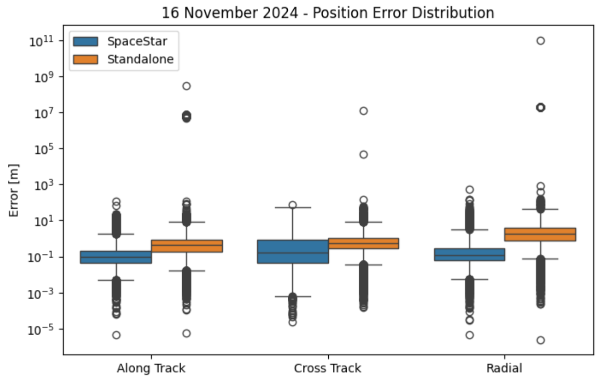

Figure 17: Error distribution SpaceStar® and Standalone GNSS

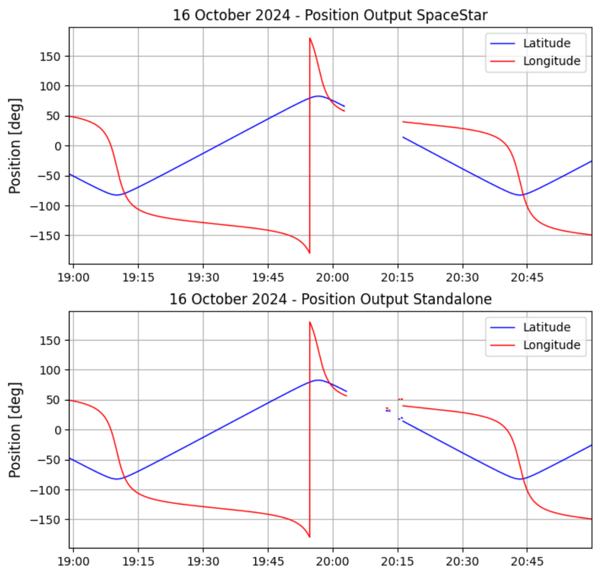

Figure 18: Position output difference in presence of spoofing signals

What was also found in orbit is that the standalone GNSS receiver was subject to spoofing activities on ground. This is noticed when plotting the position output, in terms of latitude and longitude, over time (Figure 18). From about 20:03 hrs until 20:16 hrs the GNSS signals are too weak to produce a solution. However, in that same period, around 20:12 hrs, the GNSS receiver gets spoofed, where the position remains locked to specific coordinates (31.7°N, 36.0°E) which coincide with the location of Queen Alia International Airport in Jordan (See Figure 19). During the date of the event, there have been known spoofing activities at that location. SpaceStar®'s real-time quality checks reject those GNSS measurements, which indicates its robustness against spoofing.

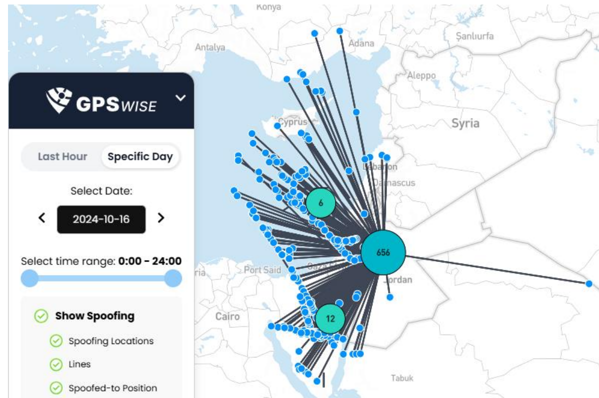

Figure 19: Spoofing activity on 16-10-2024 (https://spoofing.skai-data-services.com/)

SUMMARY AND CONCLUSIONS

Although Precise Point Positioning (PPP) has been widely utilized in ground applications for many years, its innovative application in Low Earth Orbit (LEO) can improve existing applications and create new mission opportunities where current in-orbit position, velocity, and time constraints are limiting factors.

Fugro introduces the first globally covered PPP service to enable real-time Position, Velocity, and Time (PVT) determination. This technology has been thoroughly demonstrated and tested on NorSat-TD using a COTS GNSS receiver/antenna and GomSpace Software-Defined Radio (SDR) platform. SpaceStar®'s PPP performance achieves typical errors of 10 cm, significantly surpassing the accuracy of standalone receiver outputs. Additionally, it has demonstrated enhanced PVT solution integrity compared to the standalone GNSS receiver. Moreover, the potential inclusion of navigation message authentication (NMA) in SpaceStar®'s services will be evaluated to further enhance PVT integrity.

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DISCLAIMER

The views expressed herein are solely those of the authors and do not necessarily reflect the official views of the European Space Agency

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