In-orbit demonstration of Precise Point Positioning for real-time on-board high-accuracy orbit estimation of LEO satellites

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ABSTRACT

Satellites in Low Earth Orbit (LEO) are typically equipped with GNSS (Global Navigation Satellite Systems) receivers to obtain real-time positioning, velocity, and timing. Until now, onboard GNSS positioning accuracy in LEO has been limited. Where more accurate state vector estimates are required the raw GNSS data must be post-processed on the ground.

Precise Point Positioning (PPP) is a GNSS positioning technique which allows users to obtain absolute high accuracy positioning. While PPP has been extensively used for precise Earth-based navigation, it has not been used for enhancing the positioning accuracy of satellites in LEO until now.

This paper describes how Fugro has utilised the PPP technique to estimate real-time nominal positioning at sub-decimetre levels of accuracy onboard satellites in LEO. This technology was demonstrated on Loft Orbital's YAM-3 satellite. To the knowledge of the authors, this is the first time that such a level of positioning accuracy has been achieved on-board a LEO satellite in real-time. The system architecture used to deliver PPP-enabling corrections to LEO and the architecture onboard is described. The results from the demonstration are presented and some use cases that benefit from this enhanced onboard position, velocity, and time solution are highlighted.

INTRODUCTION

It is common for satellites in Low Earth Orbit (LEO) to be equipped with a GNSS (Global Navigation Satellite System) receiver to obtain real time positioning, velocity, and timing. This can be an essential part of the onboard guidance, navigation, and control system

(GNC) used for in-orbit operations such as orbit determination, collision avoidance, proximity operations, and other planned mission activities for the satellite. GNSS data is also commonly used to enable and optimise onboard remote sensing payloads, examples include technologies such as radio occultation, synthetic aperture radar (SAR), and RF (radio frequency) geolocation which can sometimes also involve formation flying of several satellites.

Although crucial, until now onboard GNSS positioning accuracy has been limited in comparison to commercial offerings on Earth which can provide centimetre level accuracy, in real time, for a host of professional applications including surveying, precision agriculture, and maritime applications. On Earth, global positioning techniques such as Precise Point Positioning (PPP) are commonly used to allow end users to obtain absolute high accuracy positioning in real-time by utilising precise GNSS orbit and clock corrections, multi-frequency GNSS observation data, and precise observation modelling in the end-user positioning engine. While PPP has been extensively used for precise Earth-based navigation for more than two decades, it has not until now been used for enhancing the positioning accuracy onboard satellites in LEO.

In LEO existing performance ranges from metre level in the best cases, to more typical accuracies that are in the region of tens of metres. Currently where greater state vector accuracy (sub metre) is required raw GNSS data is downlinked for post processing on the ground to obtain a Precise Orbit Determination (POD) solution. Whilst desired levels of accuracy can be obtained in this way, time latency is incurred, and it adds an additional pressure to what is often limited downlink capacity. Improved mission performance can be linked closely to enhanced quality and reduced latency of information to the end user and there is now an emerging trend for satellites to have increased levels of onboard capability and autonomy enabled by edge computing and artificial intelligence. With latency reduction being a key driver of performance Fugro was inspired to leverage its expertise and infrastructure in PPP to develop and demonstrate this technology in orbit (now known as SpaceStar®), to deliver high accuracy GNSS positioning in real time onboard satellites in LEO, also known as precise onboard orbit determination (P2OD).

In conjunction with mission partners Loft Orbital, SpaceStar PPP technology was successfully first demonstrated onboard Loft Orbital's YAM-3 satellite in August 2022. Using the Loft Orbital Software-Defined Payload (SDP), and by reprogramming the onboard Software Defined Radio (SDR) platform inflight sub-decimetre positioning was achieved in real time. To the

knowledge of the authors, this is the first time that such a level of real time positioning accuracy has been achieved onboard a LEO satellite. This state-of-the-art technology allows for the implementation of PPP in LEO with a low SWaP (size, weight, and power) footprint. This technique achieves nominal real-time performance accuracies of positioning at sub-decimetre level and velocity at less than five millimetres per second.

GENERATING AND DELIVERING CORRECTIONS TO LEO

To generate corrections and to deliver them to LEO Fugro leveraged its existing proprietary ground infrastructure that is designed to meet the demanding requirements of its global satellite positioning business. This infrastructure consists of a ground network of more than 100 globally distributed reference receiver stations (Figure 1) equipped with high-end geodetic hardware which continuously observes GPS, GLONASS, Galileo, BeiDou and QZSS
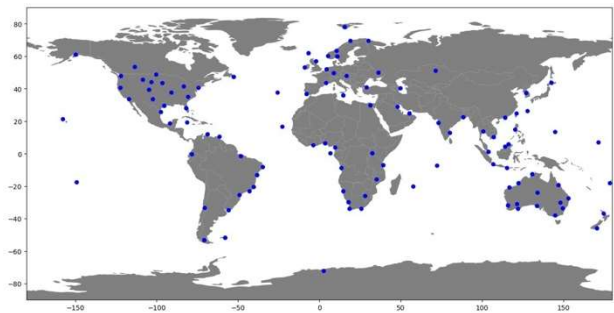

Figure 1: Fugro reference receiver network used for GNSS multi constellation observations for generation of orbit/clock corrections

Raw observation data from the network is available in real-time at Fugro processing facilities where it is used to generate the GNSS orbit and clock corrections at centimetre level. The correction signal is then distributed to users in LEO on L-band via a network of geostationary satellites, as shown in Figure 2.
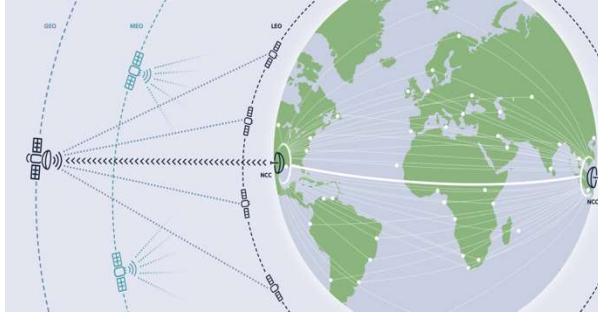
Figure 2: Distribution of corrections on L-band to LEO users via geostationary satellites

ONBOARD ARCHITECTURE

For the YAM-3 satellite (Figure 3) mission, the onboard architecture was one in which the SpaceStar software was integrated onto the Loft Orbital SDR and flown as a payload.
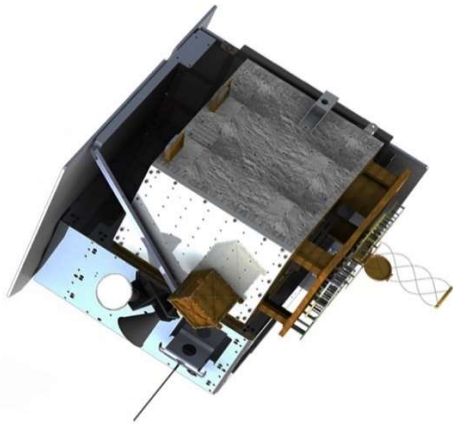

Figure 3: YAM-3 satellite (credit: Loft Orbital)

The SDR provides the RF front end and FPGA resource needed to integrate the proprietary Fugro L-band tracking and demodulator software required for acquisition and decoding of the L-band correction signal that is broadcast from geostationary orbit. Once decoded the correction data is forwarded through to the SpaceStar position engine software which is also integrated within the processing unit of the SDR. The position engine applies the corrections to the raw GNSS measurements that are received from the onboard GNSS receiver to output the high accuracy position, velocity, and time telemetry in real time onboard the satellite, as shown in Figure 4. The SDR is based on a Zynq 7000-series System-on-chip (SoC), including both a capable FPGA (Field Programmable Gate Array) and a powerful ARM processor. For efficiency purposes, L-band tracking has

been implemented in firmware at FPGA level, while the processor runs the PPP engine implemented in software.
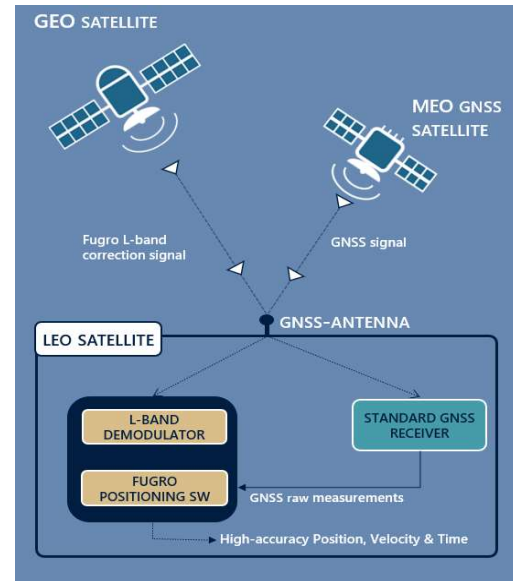

Figure 4: SpaceStar onboard architecture

In the YAM-3 mission, a commercial-off-the-shelf (COTS) receiver and antenna has been used. In particular, the GNSS receiver tracks GPS and GLONASS constellations in dual-frequency L1 and L2. The selected antenna also receives the L-band correction signal, since its carrier-frequency is close to GPS L1. 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.

IN-ORBIT DEMONSTRATION RESULTS

For in-orbit demonstration of LEO PPP, SpaceStar was enabled on board YAM-3 in August 2022 for the first time. Figures 5 and 6 show respectively the position and velocity accuracy of standalone GNSS without corrections (blue) and PPP (red). Both solutions have been compared against a reference precise orbit computed in the ground in post-processing. It can be nicely observed how the PPP-enabled position accuracy converges to sub-decimeter level after the first 10-15 minutes of convergence time, and the PPP-enabled velocity has significant less noise than standalone GNSS-based velocity.
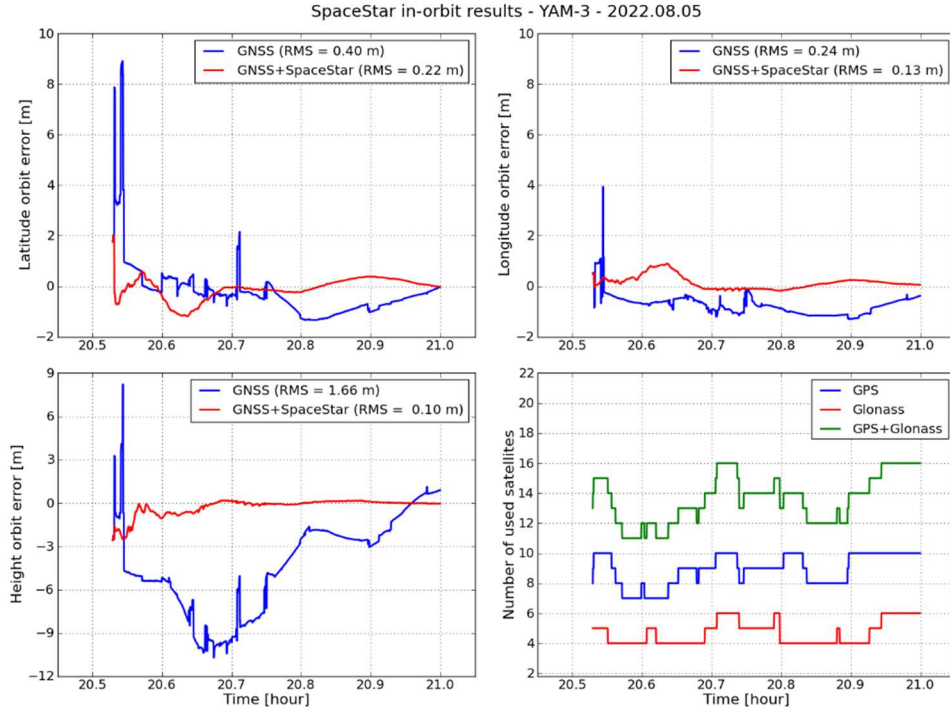
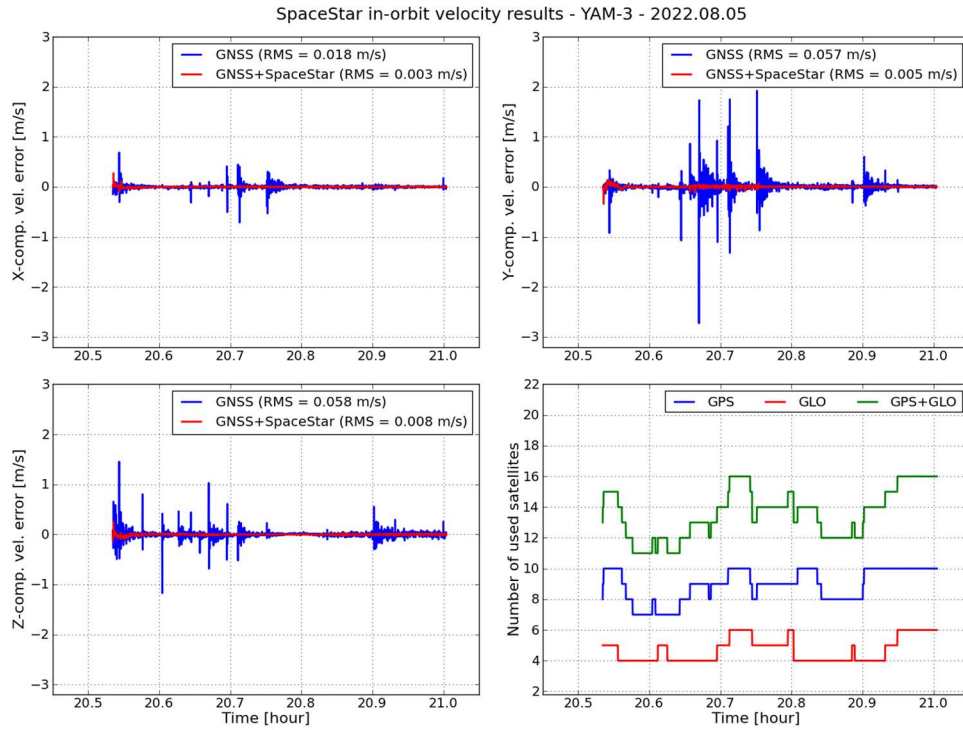**Figure 5: In-orbit positioning results for SpaceStar on-board YAM-3**

Figure 6: In-orbit velocity results for SpaceStar on-board YAM-3

APPLICATIONS FOR HIGH ACCURACY POSITIONING

As well as the incremental improvement of existing applications that suffer from latency, real time high accuracy precise onboard orbit determination (P2OD) has the potential to unlock areas of radical innovation in nascent fields such as in-orbit servicing and manufacturing (IOSM) where post processing and its associated latency is not an option. A selection of use cases for this technology have been highlighted.

RF remote sensing

Techniques such as such as synthetic aperture radar (SAR), radio-occultation, reflectometry, and RF geolocation can all require precise orbit determination which necessitates the use of ground-based post processing. Whilst this form of precise orbit determination can satisfy the accuracy requirement for producing information products for some end users, it does this with an inherent level of built-in latency. For some end users this is not of concern, however there are other users, concerned predominantly with rapidly changing events, where latency is undesirable and directly diminishes the value of the information gathered. For some remote sensing and spectrum monitoring applications formation flying techniques are utilized which can also benefit from precise real time positioning.

Thruster calibration

Thruster calibration and precise orbital maneuvers have the potential to be enabled more efficiently by using this technology. Direct measurements of delta-v can be observed onboard in real time to levels of accuracy of less than five millimeters per second. This precise maneuvering capability potentially enables better in-orbit characterization of on-board thrusters, leading to more efficient fuel usage which can lead to longer mission life.

Collision avoidance

Collision avoidance and fleet management in LEO has become an important topic as the risk of conjunctions rise due to increasingly congested orbits that are shared with other active satellites as well as space debris. Highly accurate real time positioning onboard the satellite has the potential to enable and improve the safety of autonomous satellite collision avoidance systems, reducing false alerts and unnecessary avoidance manoeuvres.

Rendezvous and proximity operations

A key feature of emerging in-orbit servicing and manufacturing (IOSM) applications can be enabled significantly through precise onboard orbit determination. In close approach and docking application it can help to enable approaching spacecraft to safely achieve a desired relative position, alignment, and velocity during target approaches, which in conjunction with other onboard sensors can help to reduce the risk of collision.

Inter satellite laser link (ISLL)

ISLL requires that during initial acquisition the transmitting satellite should locate the position of the receiving satellite before the laser beam can be pointed towards it. Typically, this is done through traditional RF communications, this could be enhanced and made more efficient with use of this technology. Precise on-board position and time can also help in facilitating ground-to-space laser-based communications, both in signal acquisition and increased bandwidth thanks to less uncertainty of the LEO orbit and better time synchronization.

LEO-PNT

LEO-PNT systems will require accurate onboard Orbit Determination and Time Synchronization (ODTS). It is anticipated that LEO PPP solutions will play a role in providing a viable solution to this challenge that is both effective and commercially viable.

SUMMARY AND CONCLUSIONS

While PPP has been extensively used in ground application over several decades, its novel use in LEO can enhance existing applications as well as open new mission opportunities where existing in-orbit position, velocity and/or time are a limiting factor.

Fugro is delivering now the first PPP service with global coverage to facilitate real-time P2OD. The technology has been demonstrated for the first time in Loft Orbital's YAM-3 mission using a COTS GNSS receiver/antenna and a flexible SDR platform. The initial in-orbit results confirm the expected accuracy of position better than 10 centimeters and velocity better than 5 millimeters/second.

References

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