Integrity Monitoring and Augmentation of GNSS from Low Earth Orbit Constellations

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BIOGRAPHY

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ABSTRACT

Recent developments in Low Earth Orbit (LEO) satellites are opening new opportunities for navigation services. In this paper, we propose the use of LEO satellites as monitoring stations from space able to provide integrity and augmentation services to GNSS users. In particular, we perform an analysis of potential fault detectability performance improvement using LEO stations compared to an user on Earth. For that, we consider the differences in geometry and the necessary GNSS error models at LEO orbit. The simulation results suggest a potential significant gain in detectability of faults from space using redundancy type monitors.

I. INTRODUCTION

The recent developments in Low Earth Orbit (LEO) technologies are enabling the possibility to enhance existing navigation related services as well as offering new service possibilities (Prol et al., 2022). Both commercial and institutional projects and activities are currently under development or are being studied based on the usage of for instance mega-constellations (e.g., Boeing, OneWeb or Xona, among others) (Menzione and Paonni, 2023; Racelis and Joerger, 2020; Kassas et al., 2024) or dedicated constellations (e.g., ESA LEO PNT or IRIS2) (Ries et al., 2023). These constellations, apart from communication services can either be adapted to provide navigation signal capabilities or are already under design/development for that specific purpose (Curzi et al., 2020). The potential reduced cost of LEO satellite technologies (compared to Medium Earth Orbit (MEO) or ground infrastructure) and its position in space closer to MEO satellites and above most of the atmosphere can uniquely offer new opportunities for future GNSS (Günther, 2018) and to monitor and augment MEO constellations (Yang et al., 2024; Pullen et al., 2023; Catalán et al., 2023; Oezmaden et al., 2024). Augmentation systems are necessary to ensure the integrity of GNSS positioning. Current augmentation systems include Satellite-based Augmentation System (SBAS) (Walter, 2017) based on geosynchronous orbit (GEO) satellites, Ground-based Augmentation Systems (GBAS) (Pervan, 2020) for airport operations, and Aircraft-based Augmentation Systems (ABAS) that provide global integrity service, including, in particular, Advanced Receiver Autonomous Integrity Monitoring (ARAIM) and onboard-sensor augmentation (Garcia Crespillo, 2022). Current

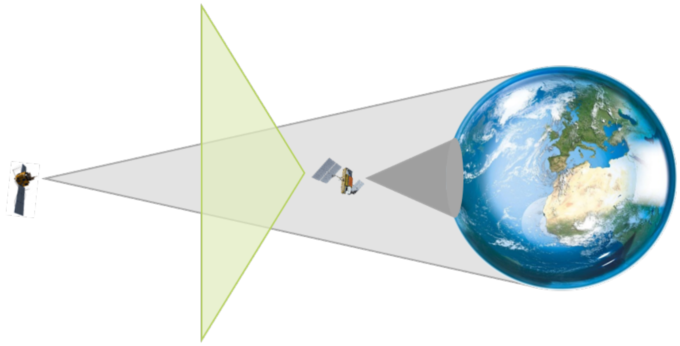


Figure 1: LEO Use Cases

infrastructure-based augmentation like SBAS can ensure the positioning integrity up to CAT I operation with a time to alert (TTA) of 6 seconds and relies on significant ground infrastructure for the monitoring and processing of signals and messages. In parallel, current augmentation systems are only supporting civil aviation application. However, in the last years, more and more existing and emerging transportation applications are requiring a safety (integrity) assessment of their positioning solutions. This includes, for instance, railway signaling and automatic train control (Marais et al., 2017), maritime (EUSPA, 2021) and advanced air mobility (García Crespillo et al., 2024). At the same time, the accuracy and TTA requirements are envisioned to be more stringent compared civil aviation even for CAT III Autoland. This raises the need of the use, adaptation or development of new augmentation systems able to support these new operational scenarios.

The use of LEO segment could potentially provide new capabilities for new emerging applications. Potential benefits of GNSS integrity monitoring use cases from satellites in a LEO constellation may include:

- Potential reduction of the Time-To-Alert (compared to e.g., SBAS 6 seconds)
- Reduction of future monitoring costs by lowering the number or stress on ground infrastructure
- Increasing sensitivity in monitoring of certain signal-in-space (SiS) faults
- Potential to extend integrity monitoring of new services like Galileo High Accuracy Service (HAS)

The monitoring from LEO satellites, due to their expected lower cost (compared to MEO satellites) comes with its own new challenges. First, the complexity of the onboard processing has to be significantly reduced compared to ground stations. Current available monitors on ground stations rely on the precise position knowledge of the ground station location to e.g., form geometry-free observables. For LEO satellites, the precise orbit of the LEO needs to be computed since it is not static, and current precise orbit determination (POD) approaches actually rely on the use of GNSS. This inevitably creates a potential correlation between POD and certain monitors which must be properly handled for the design of monitoring approaches. In this sense, this situation resembles to the use of (A)RAIM, where position and time determination is jointly done with fault detection using observables and their redundancy.

In this paper, we first provide an initial architecture for monitoring and alerting functions using LEOs. We comment on some design considerations that may impact the capabilities of this monitoring. We then provide a deeper analysis about the potential redundancy-type monitor that can be considered thanks to on one side, the tracking of multiple MEOs from a single LEO, and on the other side, the advantage of multiple LEO being able to observe a single MEO. Initial simulations and analysis focusing on the level of redundancy in terms of geometric dilution of precision (GDOP) were presented in (Oezmaden et al., 2024), where the impact of different LEO constellations design was studied. In this work, we extend the simulation analysis to provide further insight about the impact of fault detectability in terms of minimum detectable bias depending on GNSS error models and level of Orbit Determination and Time Synchronization (ODTS) of the LEOs. In both cases, we avoid making strong assumptions about specific models or algorithms and focus instead on providing some boundary conditions.

II. INITIAL PROCESSING ARCHITECTURE FOR ALERTING

Different integrity monitoring and augmentation functions and services could potentially be provided by a LEO segment. These could include the integrity functions that are currently in existing augmentation system, which are:

- Alerting: supporting users identifying faulty situations. This is a core function of any integrity monitoring system.
- Augmentation and Corrections: providing users with differential corrections to improve accuracy and integrity.

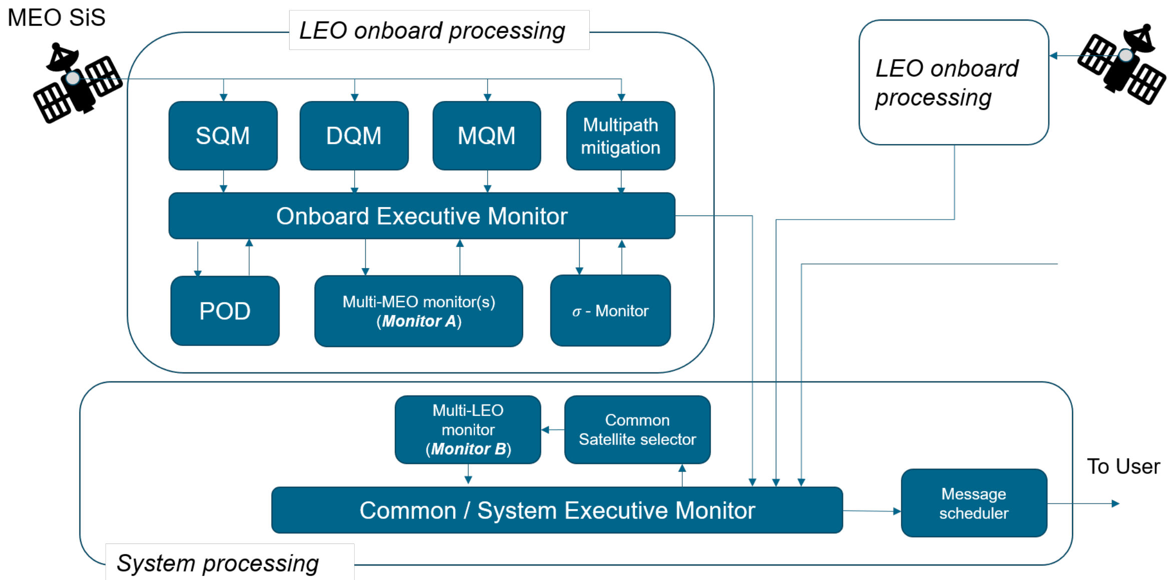


Figure 2: Proposal Processing Architecture for Alerting Service

- Performance monitoring: supporting users to up-to-date information about the current expected errors.

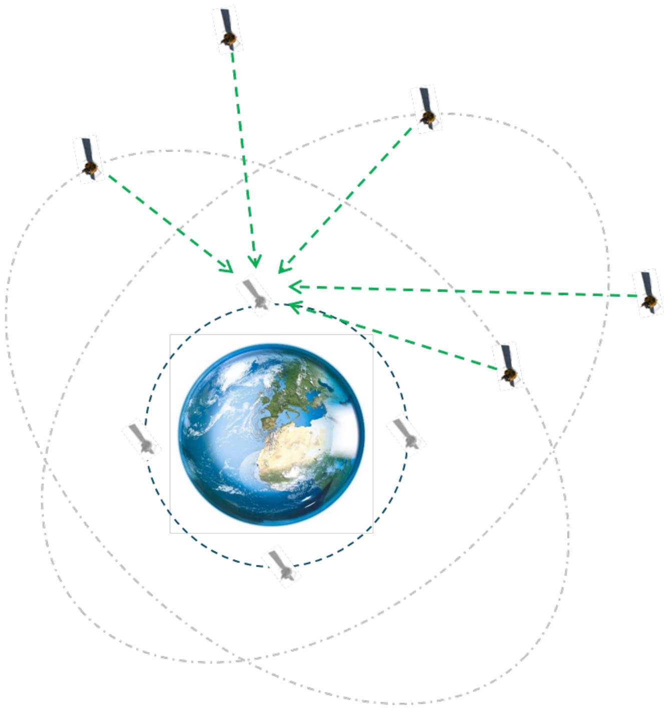
In this work, we focus our analysis and considerations on the potential functions supporting the detection of faults and therefore an alerting system. Leveraging on the experience of current SBAS and GBAS systems (Pervan, 2020), in Figure 2, we propose some potential functions to cover the detection of different type of faults. On the LEO onboard processing side, we could potentially consider a signal quality monitor (SQM), a data quality monitor (DQM), a measurement quality monitor (MQM) and a performance degradation monitor. An additional handling of multipath may be necessary depending on the processing modes. An onboard executive monitor would handle and coordinate the different monitors and flags. Since the position of the LEO satellite is apriori not known, one cannot build a geometry-free type of monitor, therefore we propose as a substitution a redundancy type monitor called *multi-MEO*, which may work in cooperation with the precise orbit deterination (POD) of the LEO satellite. Then, the information from different LEO processing can be combined at system level. On one side, this may be necessary to guarantee the correct observability of faults within the target service area. On the other side, this may also open some posibilities for additional redundancy checks where several LEO are observing the same MEO satellite, here called *multi-LEO* monitor. Please note that the implementation of some of these monitors may depend at the end on different factors like:

- the computational power available on each LEO
- the availability of (optical) inter-satellite links
- the amount of support from ground infrastructure
- the LEO constellation design, altitude and number of satellites

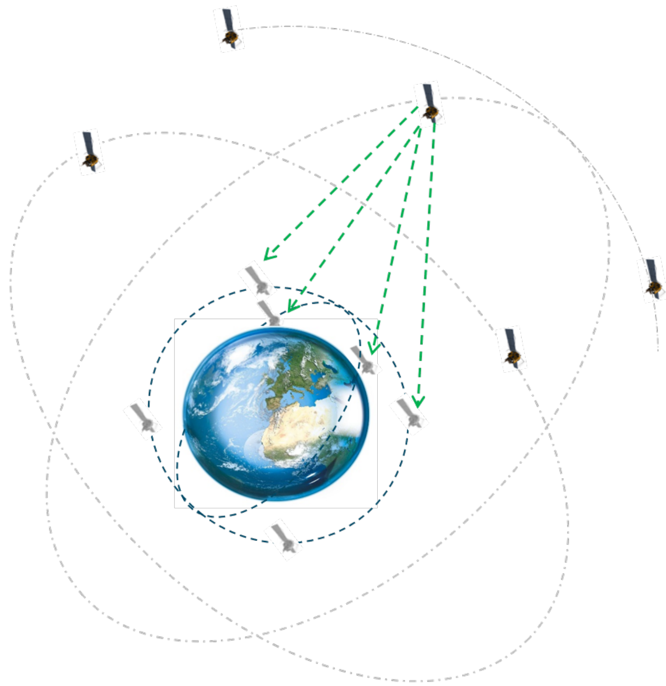
In this work, we will mainly focus on the potential benefits of the multi-MEO redundancy monitor assuming any processing is possible from the system engineering point of view. The system limitations and restrictions must be properly considered in the future.

III. REDUNDANCY-BASED MONITORS

In terms of the observability between LEO and MEO satellites, one could consider two scenarios: The situation where individual LEO satellites are able to receive measurements from multiple MEO satellites and the scenario where multiple LEO satellites are receiving measurement from the same MEO satellite. These two scenarios, depicted in Figure 3, lead to some considerations of possible monitors based on the redundancy and the meaning to guarantee the service provision within the service area.



(a) Multi-MEO Scenario



(b) Multi-LEO Scenario

Figure 3: Redundancy Scenarios for LEO-MEO Analysis

1. Multi-MEO

The LEO satellites are moving (in contrast to a ground station) and their position must be therefore computed in order to have observability of GNSS measurement errors in the range domain. The joint estimation of position, time and fault detection is what (A)RAIM methods are designed for. We set therefore to investigate the potential benefit and performance improvement of performing RAIM-type fault detection from the LEO orbit.

LEO position and time synchronization to GPS and Galileo is apriori unknown, which can be represented as the unknown parameters $\mathbf{x}$:

$$\mathbf{x} = \begin{bmatrix} x & y & z & b_u^E & b_u^G \end{bmatrix}^T, \tag{1}$$

where x, y, z are the position coordinates and b_u^E, b_u^G, the clock bias for Galileo and GPS respectively. An estimate of $\mathbf{x}$ can be computed at every epoch as:

$$\hat{\mathbf{x}} = \mathbf{S}\mathbf{z}, \tag{2}$$

where $\mathbf{S} = (\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}\mathbf{H}^T\mathbf{R}^{-1}$ with $\mathbf{R}$ being the covariance matrix of measurements $\mathbf{z}$ (typically code measurements) and $\mathbf{H}$ is the geometry matrix. The term $\mathbf{DOP} = (\mathbf{H}^T\mathbf{R}^{-1}\mathbf{H})^{-1}$ is known as the dilution of precision matrix. A full geometry factor is the Geometric DOP (GDOP), which can be computed as $GDOP = \text{trace}\{\mathbf{DOP}\}$. Assuming single simultaneous fault, a suitable test statistic can be formed based on the residuals of the position-time estimator as:

$$q = \mathbf{z}^T(\mathbf{I} - \mathbf{HS})^T\mathbf{R}^{-1}(\mathbf{I} - \mathbf{HS})\mathbf{z}, \tag{3}$$

which follows a central χ^2 distribution in the fault-free case. In the case of a fault, q follows a non-central χ^2 distribution with λ centrality parameter. The detection performance of q can be evaluated in the single simultaneous fault situation by means of the minimum detectable bias, which is the minimum bias that would cause the test to trigger for a certain probability of fault alarm and misdetection (Hewitson and Wang, 2006; Grosch et al., 2017). The minimum detectable bias for satellite i can be

Table 1: Table of simulation parameters and their values used for the results unless specified otherwise

Parameter	Used value
Initial time	2024-02-18 00:00 UTC
End time	2024-03-19 00:00 UTC
Simulation rate	60 s
Orbit propagator	Two-body Keplerian
Satellite Constellations	GPS, Galileo, and LEO
GPS Almanac File	MAAST almgps24+3.txt
Galileo Almanac File	MAAST almgalileo.txt

computed as:

$$MDB_i = \frac{\lambda_0}{\sqrt{\alpha_i^T(\mathbf{I}-\mathbf{HS})^T\mathbf{R}^{-1}(\mathbf{I}-\mathbf{HS})\alpha_i}}, \tag{4}$$

where α_i is a vector with zeros except for the row corresponding to satellite i. For a given epoch, as a performance metric, it is normally taken the *maximum* MDB among all the visible satellites. Note that the MDB depends both on the geometry situation (through $\mathbf{H}$) and on the measurements error models (through $\mathbf{R}$). In Section V, these metrics will be evaluated for different simulation conditions.

2. Multi-LEO

Compared to the classical application of (A)RAIM, the LEO satellite is not the final user. LEO satellites are in principle using the redundancy check to detect faults early so that this information can be transmitted to users on Earth. The problem is that a single LEO satellite is only able to observe the projection of a certain fault on its line-of-sight between the LEO and the affected MEO. This means that a certain conspicuous fault may not be observable from a certain LEO while affecting users in some location on Earth. The combination of the information and monitoring between different LEOs about the same MEO satellite is therefore essential to guarantee a complete service area.

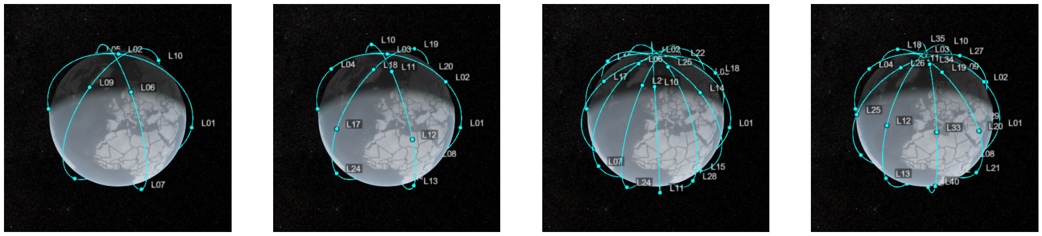
IV. CONSTELLATION SIMULATIONS AND SETUP

To generate the satellite constellations used in this paper, we used an in-house simulator under the name LEONAS (LEO Navigation System Simulator), which wraps the base functions of the MATLAB Satellite Communications Toolbox, Stanford's MAAST (Jan et al., 2009), and provides an extra set of utility functions. LEONAS is able to propagate orbits using different set of engines and is able to execute a visiblity analysis between the agents in the simulation, be it between satellites or between a ground user and a satellite. All satellite constellations are loaded by parsing YUMA almanac files from a configuration file describing different scenarios utilizing different constellations. LEO constellations are defined as Walker delta constellations, and their almanacs are generated on the fly. The two GNSS constellations, namely GPS and Galileo, are loaded from their respective MAAST YUMA almanacs, which in turn are based on MOPS RTCA (2001). In this paper we use the 24+3 configuration for GPS and a 30 satellite configuration for Galileo. Figure 4 visualizes a selection of LEO constellations studied in this paper, whereas Table 1 lists all relevant simulation configuration parameters and their used value. The results of LEONAS are written to disk and saved in MATLABs MAT-File format version 7.3. This allows compatibility with HDF, a widely accepted data encapsulation format in the scientific community. A log file containing list of events of the simulator is saved alongside results. The log file contains a header including metadata such as the version of LEONAS which produced the results, thus enabling the reproducibility of the research data.

V. ANALYSIS AND RESULTS

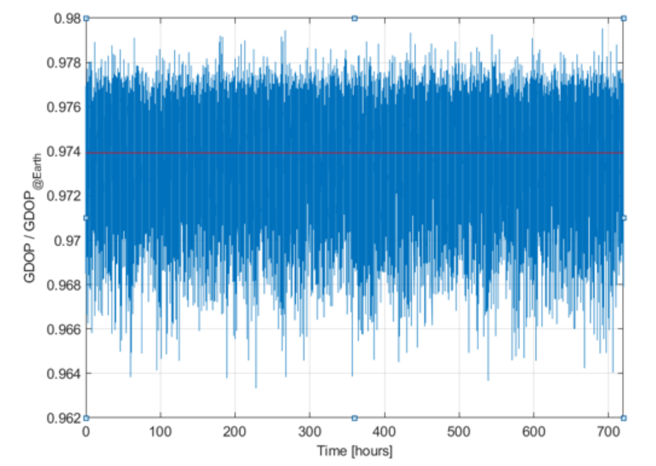
Based on the different constellation simulations presented in Section IV, this section's main purpose is to evaluate the benefit of performing multi-MEO monitor from LEO orbit compared to an user on Earth. The analysis are separated into:

- the potential gain in geometry
- the potential improvement with respect to the necessary error models to be considered for GNSS measurements
- the improvement in terms of MDB
- the sensitivity to potential LEO ODTS

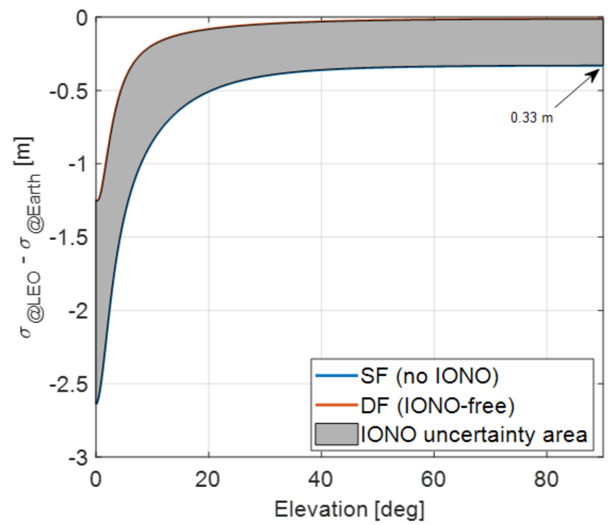


(a) 88°: 12/3/1 **(b)** 88°: 24/3/1 **(c)** 88°: 28/7/1 **(d)** 88°: 40/5/1

Figure 4: A selection of LEO Walker delta constellations simulated in this paper. Walker notation $i : t/p/f$, where i denotes inclination, t total number of satellites, p number of orbital planes, f phasing factor.



(a) GDOP gain between LEO and user on Earth (LEO constellation 88:24/3/1)



(b) Reduction of error budget for GNSS pseudorange received at LEO orbit

Figure 5: GDOP and Error Model Evaluation

1. Impact of Geometry

The first analysis consists on the evaluation of the potential beneficial situation at LEO orbit compared to an user on Earth. The virtual user on land is assumed to be at 100 meters of altitude and projected below the LEO satellite. For the case of the Walker 88:24/3/1 LEO constellation, Figure 5a shows the evolution of the gain between the GDOP at LEO satellite and the user on Earth, assuming 5 degrees elevation mask. The median gain is found to be 2.6%. Although the improvement may not seem large, one should note that GDOP is a multiplicative factor for position determination and will therefore contribute to the overall improvement in detectability.

2. Impact of Error Models

LEO satellites are much closer to GNSS satellites compared to an user on Earth. Thanks to its unique position in space, the GNSS signals are less affected by atmospheric errors (see illustratively in Figure 6. In particular, a receiver in a LEO satellite won't experience any tropospheric error. Depending on the actual altitude of the LEO satellite some residual ionospheric error will be present in GNSS measurements. Although some work in Imad et al. (2024); Kim and Kim (2020) have proposed a modeling approach of ionospheric error for LEO satellites, it is still open how much the residual ionopheric error could be compensated, removed or if a reliable bound for it is possible to be derived. Here, instead of making any assumption about the potential residual ionospheric error, we investigate the boundary conditions. On one side, the case that all the ionospheric error can be removed or compensated for, which would allow for single frequency measurement evaluation. And on the other side, the situation that ionospheric error must be fully modeled similarly to land users, which would correspond to performing dual frequency *iono-free* combinations (with its associated increase in noise). The potential reduction in pseudorange error model standard deviation considering no tropospheric error and the two boundary conditions for ionospheric error can be seen in Figure 5b between a LEO receiver and an user on Earth.

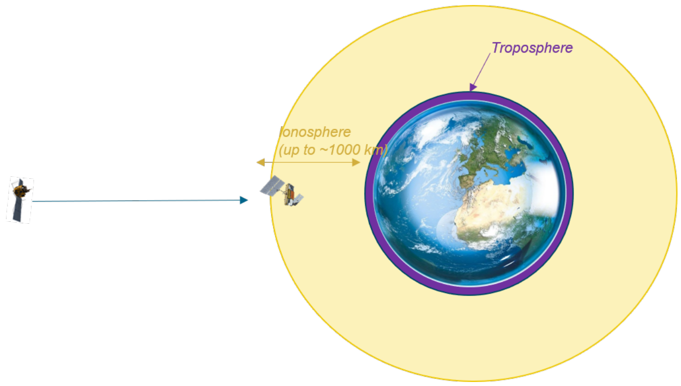
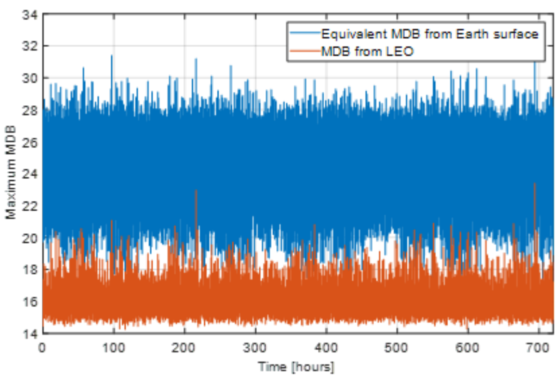
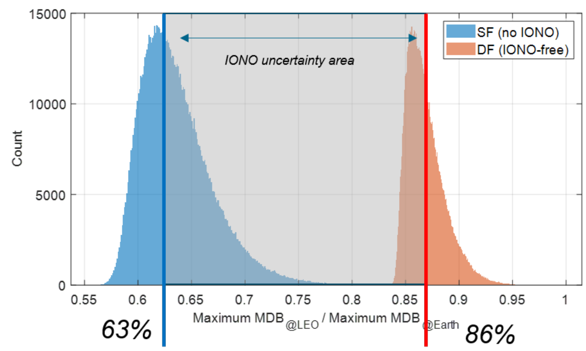


Figure 6: Illustration of LEO satellite above atmosphere



(a) Maximum Minimum Detectable Bias (MDB)



(b) MDB distribution

Figure 7: Minimum Detectable Bias Analysis (LEO constellation 88:24/3/1)

3. Minimum Detectable Bias

The combined effect of geometry (GDOP) and different error models at LEO orbit can be seen in terms of the maximum minimum detectable bias from Equation 4 over time in Figure 7a. The distribution of the MDB gain between LEO and Earth receiver for the two boundary ionospheric conditions is shown in Figure 7b. A median reduction in the MDB between 14% and 37% have been obtained.

4. Impact of POD and ODTS

Up to now, we have considered the situation that the monitor needs to fully compute jointly position and time of the LEO at every epoch independently. This means that if N satellites are visible, only $N-5$ degrees of freedom are available for the test statistic. However, satellite orbits are highly predictive and there exists different methods to obtain accurate POD over time. Additionally, onboard clocks may also be able to be predicted over short time spans. Furthermore, Kalman filter algorithms may be used which leverage on estimation over time. In this situation, position and time may not be fully unknown at the LEO satellite and more degrees of freedom may be available for detection. In fact, in Crespillo et al. (2017) it was shown that the degrees of freedom are modulated depending on the level of predicted information available for testing over sequential estimators. In order not to make strong assumptions about the possible POD or ODTS algorithms and their performance, we make again a boundary study with the following situations: position and time are unknown, position is fully known, time desynchronization is fully known, both position and time are fully known. The results of the distribution of MDBs for these 4 situations is depicted in Figure 8. This analysis gives an idea of the range of MDB improvement due to more sofisticated onboard algorithms.

VI. CONCLUSIONS

The new developments of LEO technologies offer interesting opportunities for the development of new augmentation systems based on a LEO segment to support the improvement of integrity monitoring performance in terms of time to alert, fault

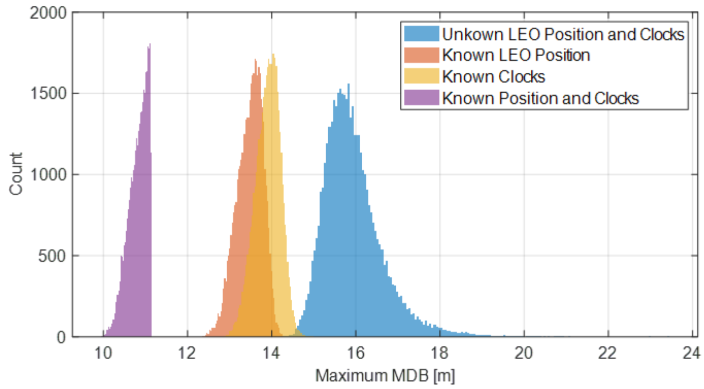


Figure 8: Boundary Analysis of Multi-MEO MDB depending on ODTS knowledge

detection sensitivity and integrity monitoring of high accuracy services. This work provides important insights about the fault detection design and potential performance improvement for redundant monitor onboard LEO satellites.

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