PhD Thesis Description

1. Title

DEVELOPMENT AND ANALYSIS OF SIGNAL PROCESSING ALGORITHMS FOR ESA LEO PNT SYSTEM

2. Supervisors

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3. Description

3.1. Context

The interest in Low Earth Orbit (LEO) mega constellation systems providing either high data-rate communications (high-speed internet) or Position Navigation and Timming (PNT) services, which is commonly referred to as LEO PNT, has grown in the last years with a significant acceleration of the research and development of such systems [1]. To provide some examples, China is planning on deploying 3 LEO mega constellation systems; Geospace which is a commercial system providing PNT services for autonomous vehicles, CentiSpace which is an hybrid commercial and governmental system proving augmentation to Beidou (Precise Point Positioning and integrity) and Satnet which is a commercial system providing high-speed internet services [2]. US is planning on deploying, is deploying or has deployed several LEO mega constellation systems, Blackjack which is a governmental system for researching LEO constellations capacities, XONA Space System which is a commercial system proving PNT services, TrustPoint which is a commercial system providing PNT services, Satelles which is a commercial system proving PNT services using the IRIDIUM constellation, and Starlink which is a commercial system providing high-speed internet services [2]. Finally, Europe is preparing two projects, LEO PNT (which follows the ELCANO project funded by ESA on a system study on potential LEO-PNT capabilities for potential future space-based PNT infrastructures [1]) and IRIS2 which is funded by the European Commission and is designed to tackle a wide variety of services, from high-speed internet to even PNT [2].

The advantages to use LEO mega constellation for PNT services are quite numerous and the driving force of the constant interest growth in these systems [1]. First of all, the increase of satellites in view, even in constrained environments such as urban canyons, increase the DOP (Dilution of Precision) of the navigation solution with the consequence increase on the final accuracy performance. Moreover, the fast change in the LEO satellites position makes the propagation channel to vary very fast and, for example, it makes obstructed Line-Of-Sight (LOS) signals to become unobstructed in a relative short of amount of time in comparison with MEO GNSS signals. Second, LEO satellites being closer to Earth have low Free Space Losses (FSL) in comparison to MEO GNSS satellites; for example a LEO satellite have about 20dB less of FSL at the 600km (Edge-of-Coverage). Third, the improved link budget can allow for the use of non-typical RNSS frequency bands to provide more specifically targeted PNT services, such as Ka/Ku frequency bands for high precision PNT services due to the large available bandwidth which can be offered to the navigation signal, and such as UHF frequency band to obtain deep signal penetration for indoor, canopy or urban canyons positioning. Fourth, the high dynamics of the LEO satellites increase the importance of Doppler frequency/speed measurements and thus the overall quality of the PVT (position velocity Time) solution; indeed, the first operational global positioning system, TRANSIT, was based only on Doppler positioning with LEO Satellites; moreover, the high dynamics of the satellite will also change the correlation time of the signal distortions, such as the ionosphere, and will allow reduced convergence time for high-accuracy GNSS positioning. Fifth, the high number of LEO satellites expected in a mega constellation and the proximity of the satellites allow for two-way PNT signals enhancing their timing and ranging capabilities. Finally, LEO PNT systems can be less complex than GNSS due to the reuse of GNSS services (LEO satellites can determine its position and time synchronization from GNSS) with the consequent reduction of Size, Weight and Power consumption of the satellite payload.

3.2. Objective(s)

The goal of this thesis is to conduct the analysis of LEO mega constellations focusing on the first stages of the receiver, the Radio-Frequency Front End (RFFE) block and mainly the signal processing block, by proposing acquisition and tracking algorithms specifically adapted to LEO PNT signals, by providing theoretical thresholds and by providing mathematical models of at least the noise component distorting the code delay and phase delay pseudorange measurements associated to the developed acquisition and tracking algorithms. The outputs of this PhD, mainly the code delay and phase delay pseudorange error models could be used for further LEO PNT analysis focused on PVT performance.

3.3. Work Plan

The proposed thesis will focus on the LEO PNT being currently developed by ESA and its different proposed signals.

The first phase of the thesis will consists in selecting 2 or 3 signal candidates depending on the targeted applications. Indeed, as previously said, depending on the frequency band, the targeted services vary; UHF band targets indoor or urban positioning, L, S or C bands target typical GNSS PNT services and Ka/Ku band targets PPP services. Therefore, in this PhD thesis, the analyzed signals will depend on the needs of CNES and the needs of the cofunding partner, Thales Alenia Space, after a first high-level analysis of all the proposed signals in the ESA LEO PNT ICD. For example, one typical band (e.g. L band) and one experimental band (Ka band) could be selected.

The second phase of the thesis will consists in analyzing in-depth the identified signal of the first phase. The following tasks will be conducted and constitute the research core of the PhD thesis:

- The main analysis will be focus on the identification of optimal/advanced acquisition and tracking algorithms specially tailored to the LEO constellation specifications as well as the ESA LEO PNT individual signals. For example, the high dynamics of LEO satellites make the Doppler frequency non-linear during the typical coherent integration time values of GNSS signals (from 1ms to 20ms) and thus alternative solutions, such as the Doppler frequency prediction from user position and satellite ephemerides, must be searched for. Moreover, due to the higher number of LEO satellites in a mega constellation (> 300 satellites) with respect to the number of GNSS satellites of a typical constellation (~30 satellites), the on-board clocks are of lower quality with the consequent increase on the clock phase noise jitter. In addition, specific signal structures may be used such as Chirp-Spread-Spectrum (CSS) waveforms [1] or 2-way PNT signals; such structures will require non-traditional signal processing techniques.
- Theoretical thresholds, minimum C/N_0 necessary to obtain the desired performance of a process, will be derived for the proposed acquisition and tracking algorithms.
- Mathematical models for nominal, and potentially abnormal, code delay and phase delay pesudorange measurements errors associated to the proposed advanced acquisition and tracking algorithms will be derived. The derived mathematical models will depend on the available information but at least the AWGN distortion will be provided.
- Radio Frequency (RF) compatibility between LEO PNT signals and existing MEO GNSS signals or other signals in the selected frequency band will be computed; existing RF computation

methodologies will be reviewed in order to determine its applicability to LEO PNT signals [3][4].
- Innovative 2-way ranging signal will be analyzed, specific signal processing methods will be proposed and theoretical thresholds will be derived.

Other secondary tasks which could be of interest during the PhD work but for which the decision on addressing them will be evaluated during the development of the PhD are:

- If sufficient information about the ESA LEO PNT constellation is known, link budgets may be computed as complement to the theoretical thresholds to verify whether the desired performance can be achieved [3].
- Authentication from a signal processing point of view, such as the implementation of secured PRN codes (chip level authentication), may be evaluated and their implementation impact on nominal LEO PNT signals will be quantified and compared to alternative signals not implementing the authentication features.
- Eventually, signal design propositions could be made.

Practical analysis to validate theoretical developed results will be conducted through simulated IQ samples or through the exploitation of collected IQ samples from broadcasting satellites (if available).

Finally, although the in-depth analysis of other LEO PNT systems such as XONA or CentiSpace are not planned in this PhD thesis, if an opportunity arises and the ICD contents are made public or known, a similar signal processing analysis could be made in order to compare the performance of the different systems. Irrespective of the appearance of this opportunity, a bibliographic analysis will be continuously conducted to identify other LEO PNT system performance and to compare them to the signal processing performance of the derived ESA LEO PNT system.

3.4. Keywords

Signal processing, LEO PNT, navigation, acquisition, tracking, RF compatibility

3.5. References

[1] L. Ries et al., "LEO-PNT for Augmenting Europe's Space-based PNT Capabilities," 2023 IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, CA, USA, 2023, pp. 329-337, doi: 10.1109/PLANS53410.2023.10139999.

[2] Sébastien Trilles, TAS "De la Terre à la Lune : les challenges des futurs systèmes de navigation", Les Rendez-vous aéro de l'innovation 2023 « Systèmes de communication et de navigation par satellites », ISAE-SUPAERO/ENAC

[3] Radio Technical Commission for Aeronautics (2022) DO 235C - Assessment of Radio Frequency Interference Relevant to the GNSS L1 Frequency Band

[4] Recommendation ITU-R M.1831-1, A coordination methodology for radionavigation-satellite service inter-system interference estimation, 09/2015

4. Doctoral School

EDMITT

5. Research Unit

TéSA (working place shared with ENAC/SIGNAV group)

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6. Proposed Funding

- CNES (Half funding, 1st preselection phase succeeded, final phase needs an identified candidate)
- Thales Alenia Space (private company, half funding, confirmed)
- Other back-up options: ENAC