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Design considerations of navigation satellite constellation for low Earth orbit

Jaan Praks$^{(1)}$, Zainab Saleem$^{(1)}$, Mayank$^{(1)}$, Kaan Çelikbilek$^{(3)}$, Fabricio Prol$^{(4)}$, Shikha Sharma$^{(1)}$, Heidi Kuusniemi$^{(2)(4)}$,
Luca Ferranti$^{(2)}$, Elena Simona Lohan$^{(3)}$, Christina Pinell$^{(4)}$, Sanna Kaasalainen$^{(4)}$, M. Zahidul H. Bhuiyan$^{(4)}$
(1) Aalto University, Finland
(2) University of Vaasa, Finland
(3) Tampere University, Finland
(4) Finnish Geospatial Research Institute, Finland

Abstract

In this study we provide an overview of feasibility assessment of Low Earth Orbit Position, Timing and Navigation (LEO-PNT) satellite system. We discuss several aspects of such a design, such as signal design, accuracy assessment, satellite constellation design, satellite payload design and satellite platform design. We conclude, that such a system is feasible and provide general parameters for implementation.

1 Introduction

Satellite based position, timing and navigation (PNT) signal is an important component of modern infrastructure which supports terrestrial, aerial and marine services around the globe. Traditionally, the Global Navigation Satellite Systems (GNSS) have utilised the Mid Earth Orbital altitudes where the global coverage can be achieved with only tens of satellites. Unfortunately, as the trade-off for good coverage one faces high ionizing radiation levels at higher orbits and the large free path loss of the signal. These restrictions lead usually to high price of the satellite platform and payload technologies and faint signal, which can be received outdoors in good unobstructed environments. Building of such systems has been feasible only for big public actors. Recently, the rapid decline of Low Earth Orbit (LEO) satellite launch and platform prices has brought up a possibility to construct a small satellite based navigation constellation to LEO [3]. LEO satellites would give significantly stronger signals and have a higher resilience through large numbers of satellites. With stronger signals, it could be possible to provide good service in street canyons, under dense vegetation and perhaps even indoors. Cheaper satellites would also enable shorter replacement cycle and allow quicker technology and service development. Because of these reasons, several actors are currently conducting studies about LEO-PNT feasibility [5]. The Finnish INCUBATE project consortium has recently carried out a comprehensive system study about LEO-PNT system feasibility and proposed possible design and design tools for further development [9, 1]. The design has been covering signal design, signal propagation model, receiver design, satellite constellation design, constellation launch and maintenance design, satellite design and even business model designs. In this presentation we give an overview of the INCUBATE LEO-PNT satellite system design approach and preliminary results.

2 System design optimisation

Designing a GNSS er LEO-PNT system is nontrivial task which requires optimisation of different system parameters which are strongly interdependent. Overall optimisation is usually an iterative process where different design areas are optimised independently and then evaluated as a part of entire system. The key parameters of a GNSS are navigation signal and how the signal sources are distributed spatially, namely the satellite constellation. Both areas have significant restrictions in technical and regulative feasibility. For finding optimal and feasible design parameters, a model of entire system should be made. In order to simplify the task, partial models of strongly interdependent parameters are usually made. In our study we use three broad optimsation tasks, signal optimisation, satellite constellation optimisation and satellite system optimisation. In the following we discuss briefly the key areas of the design and available solutions.

2.1 Navigation signal considerations

The system design has to be started with the signal simulations and signal design which in large parts defines the achievable service accuracy.

2.1.1 Frequency

The choice of the carrier frequency or frequencies will heavily influence and create trade-offs between various link aspects such as the channel path losses (higher at higher frequencies), device/antenna size and antenna spacing in case of antenna arrays (smaller at higher frequencies), available bandwidths (typically higher at higher carrier frequencies) and modulation types (e.g., most modulations are bandwidth dependent and the available bandwidth depends on the chosen carrier frequency). For example, higher frequency bands of operation will translate into smaller an-

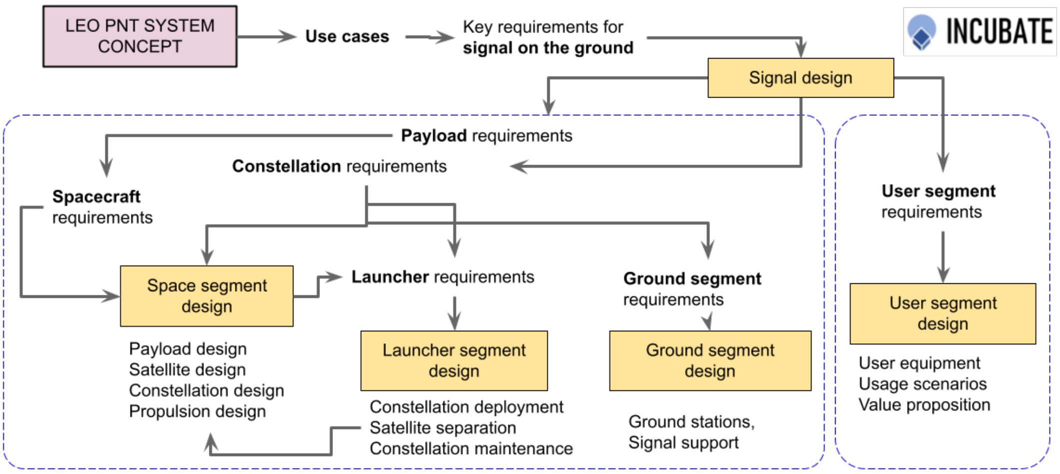

Figure 1. LEO PNT system design process

tenna sizes (which will reduce the satellite/receiver dimensions), but at the same time will increase the path losses as the transmissions will be more attenuated due to the channel and the presence of gases and various atmospheric effects (rain, mist) will bear higher influence on the received signal power than at lower frequency. Another constraint in the frequency choice comes from the International Telecommunication Union (ITU) regulations regarding the use of various frequency bands. The ITU publishes the ITU Radio Regulations (ITU RR) document, in which the frequency band usages from 9kHz to 275 GHz are described. In the document it is determined that the frequency range currently allocated to satellite navigation is L-band, and two portions of 20 MHz bandwidth in S- and C-bands. The L-band is already crowded with GNSS signals. Some LEO satellites are also using K, X, and Ku frequency bands. Our recommendation, taking into account all the above-mentioned constraints is to use moderately high carrier frequencies, above GNSS bands, but below 15 GHz carrier frequency.

2.1.2 Waveform

There are two main classes of modulations in the literature, as emphasized also in [2]: linear modulations and non-linear modulations. The linear modulations have the advantage of a higher spectral efficiency and, typically, more robustness to multipaths and delay errors jitters, while non-linear modulations are typically more robust to Doppler spread and Doppler shifts. For a LEO-PNT system, it is expected that low navigation rates (similar with those in GNSS) are to be enough and therefore the spectral efficiency is not a criterion of importance. As smaller-order modulations need less bandwidth than high-order modulations (both linear and non-linear ones), we recommend the choice of a low-order modulation, such as BPSK, QPSK, GMSK, BFSK, etc. Nevertheless, the exact choice of a suitable modulation needs more investigation especially in terms of robustness to delay-Doppler errors. The modulations can and are typically co-designed with the multiple-access scheme. Most promising multiple-access schemes in the context of LEO are OFDMA and CDMA [2]. Recent works in scenarios with high Doppler spreads have also started to pay attention to an Orthogonal Time-Frequency Space (OTFS) modulation, yet its benefit in the context of a LEO-PNT system is unclear and needs further studies.

3 Navigation solution accuracy

Assessment of navigation solution accuracy is complicated task as it depends on so many interlinked system descriptors. To assess, how the system parameters affect navigation solution accuracy, the system needs to be modelled in sufficient fidelity and also most important environmental factors, for example signal losses and distortions in ionosphere, shall be included in the model. In this project, an end-to-end simulation was developed, which contains most important segments of a satellite-based PNT system, i.e. the space-, ground-, and user-segments all combined [2]. The model allows to calculate statistical distributions of simulated LEO-PNT measurements, such as pseudorange, carrier phases, and Doppler-shift, for various satellite constellation geometries, ionospheric conditions, signal types, frequencies, modulations and encoding. Moreover, the simulation model allows to inject errors to input signal input parameters and study for example, how much satellite clock inaccuracies or satellite position determination errors affect the navigation solution in various conditions. The model uses known and implemented GNSS systems as reference points. As main results, our simulations reveal that LEO systems augmented by classical GNSS can bring improvements in navigation accuracy in comparison to only LEO-based solutions for tens of percents, and provide significant improvement over classic GNSS solutions.

4 Satellite constellation considerations

The satellite constellation design is a critical aspect of GNSS design, as it determines the cost and performance of the system, thereby determining the commercial viability of the service to a larger extent. The satellite constellation geometry defines the navigation solution geometry, signal strength, and availability, dictating the number of required satellites and establishing launch requirements. In large parts, a GNSS applications in LEO has not been considered due to the high number of needed satellites and associated building and launching costs, however, recent cost reductions caused by the satellite miniaturization and propulsion technologies allowed LEO-PNT to be a viable option.

4.1 Constellation optimization

As the constellation design directly determines system performance and capabilities, careful optimization of the design is essential. The most critical parameter is the coverage of the satellites. In traditional GNSS, at least 4 signals with good spatial separation are needed to calculate the navigation solution on ground; therefore a minimum of four visible satellites are required everywhere in the service area. The satellite visibility is a function of total number of satellites in the constellation, orbital altitude and orbital plane geometry, but orbital parameters do not describe easily the goodness of the coverage geometry. Therefore, we propose that Geometrical Dilution Of Precision (GDOP) could be used as a measure of positioning performance of the constellation. As a second parameter, C/N_0 could be used to describe the signal quality on the receiver location. These two parameters, together with guaranteed coverage, help define the merit functions for the constellation optimization. While analyzing the problem, it appears in general that higher altitudes allow satisfying coverage conditions with a lower number of satellites in the constellation, and with better GDOP values, but increase the propagation time and the noise of the signals, negatively affecting C/N_0. The secondary trade-off is between cost and both the number of satellites and altitude, which is much more difficult to define rigorously. Naturally, it is more expensive to manufacture and launch more satellites but launch cost per satellite depends on how many satellites can be launched with single rocket to a single orbit. As it is difficult to come up with exact numbers without a dedicated study, it is reasonable to aim to minimize both altitude and total number of satellites. While the number of satellites does not have much effect for C/N_0, higher numbers of satellites result in both higher coverage and better GDOP. An additional trade-off is in LEO region is the increased orbital drag effect in lower orbits and space debris and mitigation policies. A more elaborated overview of the constellation optimization is covered in [9].

4.2 Constellation deployment and maintenance

As discussed earlier, the cost of constellation deployment depends heavily on launch strategy. If multiple satellites can be launched with a single rocket to a single orbit, the launch cost per satellite is significantly reduced. However, a single satellite's capability to separate in orbit or maneuver to a different orbital plane is limited. This capability can be increased by incorporating more capable propulsion or by adopting other approaches leveraging orbital perturbations, but doing so has a substantial influence on cost and time. Therefore, the optimum strategy would be to launch the satellites to near orbital planes in a single, dedicated launch consisting of identical satellites.Replacement satellites will be required for constellation maintenance, necessitating additional launches. One strategy could be to maintain backup satellites in specific orbital planes and transfer the satellites to the correct positions in the constellation using the differential drag method. [6].

5 Satellite technology considerations

A satellite is a vehicle which is designed according to the payload needs and adapted to environmental conditions. Therefore, the most important part of the satellite design is the payload. In LEO-PNT system the payload design is derived from the signal design requirements and the satellite platform is designed according to support the payload in space.

5.1 PNT payload

The PNT payload central element is an atomic clock, supported by clock monitoring and control unit, frequency generation and up-conversion unit and navigation signal generation unit. The power budgets of PNT payload has to be maintained throughout the mission duration since the navigational services are often required uninterrupted. A block level diagram of PNT payload and teh respective process flow can be looked up in further deatil in [7]. The main components of the PNT payload are Clock Monitoring and Control Unit (CMCU), Frequency Generation and Up-conversion Unit (FGUU), Navigation Signal Generation Unit (NSGU). The signal is then further up-converted to navigation service frequencies and is transferred to Solid State Power Amplifier (SSPA) followed by navigation antennas to be radiated out towards the ground terminals and user terminals. In our study we use as a reference a Rubidium frequency standard atomic clock which is controlled and monitored using CMCU. The conceptual design of payload was created from commercially available parts and preliminary power consumption was calculated. Two modes have been considered broadly to identify the two extreme in-orbit payload modes namely safe mode and operational mode. Safe mode has power requirement of 25 W and the operational mode, a maximum of 100 W input power will be required for uninterrupted operations of the system. This is also the mode that is expected to be primary in-orbit mode since the PNT payload will be operation at all times.

5.2 Satellite platform

Taking into account the PNT payload power estimates during the operational mode, we can already assume that the satellite full-filling the payload and other sub-system volume and power requirements will be in the size range of at least 16U CubeSat or dedicated small satellite platform of size 30 - 50 kg. Having the satellite according to CubeSat standards could be cost effective solution in terms of launch and constellation deployment but dedicated platform would allow better to address payload needs. The satellite subsystems are selected based on the identified satellite functions. Some of the main satellite functions are control actuators and correct attitude, antenna and solar panel pointing and communication with ground station [4].

5.3 Payload antenna

The satellite should probably have three different antennas, namely: S-band (TT&C), C-band (integrity messages and payload command) and X-band antenna (offering navigational services). The PNT payload antenna is required to have Isoflux radiation pattern with a half power beam-width (HPBW) of 20° to 30°. Considering a conservative gain value of antenna to be 8 dBi the link margin of above 3dB is achieved. This kind of radiation pattern is mandatory to ensure homogeneous power distribution for navigational services. This kind of radiation pattern can be achived by combining different antennas such as helix, patch or a combination of both. Further investigation is already underway to estimate the expected radiation pattern, gain, size of antenna and satellite interface for the system [8].

6 Conclusions

Our assessment shows, that a LEO-PNT system is feasible to built with current small satellite technology and it could be deployed to LEO. The provided service quality would be comparable with existing GNSS or in some aspects even better. The system could have for example approximately 300 satellites in 10 orbital planes at 825 km altitude in Walker-delta configuration. A single satellite could be in 20 to 50 kg class small satellite with 100 W orbital average power capability. A very crude estimate about the possible price of this kind of system could be in the order of magnitude of 500 million euros.

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References

[1] Ruben Morales Ferre, Jaan Praks, Gonzalo Seco-Granados, and Elena Simona Lohan. “A Feasibility Study for Signal-in-Space Design for LEO-PNT Solutions with Miniaturized Satellites”. In: *IEEE Journal on Miniaturization for Air and Space Systems* (2022).

[2] Fabricio S Prol, R Morales Ferre, Zainab Saleem, Petri Välisuo, Cristina Pinell, Elena-Simona Lohan, Mahmoud Elsanhoury, Mohammed Elmusrati, Saiful Islam, Kaan Çelikbilek, et al. “Position, Navigation, and Timing (PNT) Through Low Earth Orbit (LEO) Satellites: A Survey on Current Status, Challenges, and Opportunities”. In: *IEEE Access* (2022).

[3] Min Li, Tianhe Xu, Meiqian Guan, Fan Gao, and Nan Jiang. “LEO-constellation-augmented multi-GNSS real-time PPP for rapid re-convergence in harsh environments”. In: *GPS Solutions* 26.1 (Dec. 2021), p. 29. ISSN: 1521-1886. DOI: `10.1007/s10291-021-01217-9`.

[4] Oltjon Kodheli, Eva Lagunas, N. Maturo, Shree Krishna Sharma, Bhavani Shankar Mysore, J. Montoya, J.C. Merlano Duncan, Danilo Spano, Symeon Chatzinotas, Steven Kisseleff, Jorge Querol, Lei Lei, Thang Vu, and George Goussetis. *Satellite Communications in the New Space Era: A Survey and Future Challenges*. Feb. 2020.

[5] H. S. Cobb G. Gutt M. O’Connor T. G. R. Reid T. Walter Lawrence D. and D. Whelan. *Innovation: Navigation from LEO*. June 2017.

[6] Hannu Leppinen. “Deploying a single-launch nanosatellite constellation to several orbital planes using drag maneuvers”. In: *Acta Astronautica* 121 (Dec. 2015). DOI: `10.1016/j.actaastro.2015.12.036`.

[7] Dirk Felbach, Francis Soualle, Lars Stopfkuchen, and Alexander Zenzinger. “Clock monitoring and control units for navigation satellites”. In: *2010 IEEE International Frequency Control Symposium*. 2010, pp. 474–479. DOI: `10.1109/FREQ.2010.5556283`.

[8] Paulo Valle, A. Netti, Marcello Zolesi, R. Mizzoni, Mauro Bandinelli, and R. Guidi. “Efficient dual-band planar array suitable to GALILEO”. In: vol. 626. Dec. 2006, pp. 1 –7. DOI: `10.1109/EUCAP.2006.4584868`.

[9] Kaan Çelikbilek, Zainab Saleem, Ruben Morales Ferre, Jaan Praks, and Elena Simona Lohan. “Survey on Optimization Methods for LEO-Satellite-Based Networks with Applications in Future Autonomous Transportation”. In: *Sensors* 22.4 (), p. 1421. ISSN: 1424-8220. DOI: `10.3390/s22041421`.