

LEO-PNT payload architecture and satellite design analysis

Mayank*, Fabricio S. Prol[†], Ville Lundén*, Elena Simona Lohan[‡], Zainab Saleem*, Shikha Sharma*, M. Zahidul H. Bhuiyan[†], Sanna Kaasalainen[†], Heidi Kuusniemi[§], Jaan Praks*

*Department of Electronics and Nanoengineering, Aalto University, 02150 Espoo, Finland

[†]Department of Navigation and Positioning, Finnish Geospatial Research Institute (FGI), National Land Survey of Finland (NLS), 02431 Kirkkonummi, Finland

[‡]Tampere Wireless Research Centre, Tampere University, 33720 Tampere, Finland

[§]School of Technology and Innovation, University of Vaasa, 65101 Vaasa, Finland

Abstract—Low Earth Orbit (LEO) navigation satellite system versatility has the potential to significantly enhance Positioning, Navigation, and Timing (PNT) service reliability. Leveraging an improved geometry due to closer orbital proximity resulting in higher number of visible satellites and reduced free space loss will ensure stronger and more resilient PNT signals. Given the fact that hundreds of satellites are needed for a LEO constellation with a global coverage, the satellites should remain small to maintain a feasible cost of the mission. This work introduces a small satellite LEO-PNT navigation payload concept tailored for LEO constellations. The navigation payload concept is applied to a preliminary satellite design, demonstrating the feasibility of the system. The paper analyzes the performance of a low-cost payload (single-frequency L1-band operation) against a higher cost payload (dual-frequency L1- and L5-band operation), considering short and medium-term clock stability. Other compared parameters include size, mass, overall system cost, and the dependence of the LEO-PNT constellation on existing Global Navigation Satellite Service (GNSS) infrastructure. Isoflux navigation antenna radiation pattern requirements are also analyzed for different LEO altitudes. In addition, this work provides satellite feasibility estimates (power, mass, and link budgets) based on Commercial Off-The-Shelf (COTS) components and subsystems. This work concludes by presenting a performance analysis of a low and high cost small satellite LEO-PNT payload. The analysis shows that the orbital altitude dependent Carrier-to-Noise density ratio (C/No) of a LEO-PNT navigation signal is equal to or better than the C/No of Medium Earth Orbit (MEO) GNSS signals. Hence, this study provides guidance for the development of an efficient and fully operational LEO-PNT satellite system.

Index Terms—LEO-PNT constellation, small satellite, PNT payload

I. INTRODUCTION

Both the private and public sectors have developed capabilities to enhance GNSS. Examples include StarFire (John Deere), TerraStar (NovAtel), and CenterPoint RTX (Trimble). Recently, LEO satellites have demonstrated the capability of

This study is part of the ongoing research within the INdoor Navigation from CUBesAT Technology (INCUBATE) Project, led by the University of Vaasa. The project is funded by the Building the Future - Taking Action programme of the Centennial Foundation of the Federation of Finnish Technology Industries and the Jane and Aatos Erkko Foundation. The copyright notice is: 979-8-3503-5111-8/24/\$31.00 ©2024 European Union

transmitting PNT signals [1]–[8]. Eutelset OneWeb recommends exploring alternatives to GNSS satellite constellations for resilient and future-proof infrastructure [6]. LEO constellations offer the following potential advantages for enhanced navigation signals:

- Increased resistance to jamming when compared to MEO satellite signal at the receiver end.
- Stronger signal reception and higher Carrier-to-Noise ratio (C/No).
- Short channel coherence time reducing tracking errors.
- More precise state variables from atomic clock updates.
- Improved link margins and spectrum availability.

Although no dedicated complete LEO-PNT system exists (as of September 2024), several studies have shown the potential of LEO for demanding PNT applications, such as indoor navigation and autonomous driving [4], [5]. Achieving global coverage from LEO requires more satellites than from higher orbits, in addition to cost-effective integration with MEO GNSS infrastructure [4]. GNSS satellite payloads, such as with Galileo, consist of clock units [9], Navigation Signal Generation Units (NSGUs), Frequency Generation and Management Units (FGMUs), amplifier units, and filters [10]. Galileo satellites weigh over 500 kg with dimensions of 2.9 m × 1.7 m × 1.4 m. Furthermore, they carry large antennas, and require a 1.9 kW power budget. A key question is whether LEO-PNT payloads can achieve similar, or even better performance than existing GNSS payloads. The LEO-PNT navigation payloads would need to adapt to small platform designs, low power consumption, the utilization of COTS components, and potentially multiple frequency transmission. Challenges include distortion from atomic clocks, frequency up-conversion, and power amplification [11].

Despite limited research in this field, some companies have introduced LEO-PNT payloads for small satellites, with some missions [12], [13] even testing these in orbit. Development effort has been put into COTS GNSS receiver designs [14], PNT payloads based on Software-Defined Radio (SDR) technology [15], chip-scale atomic clocks [16], inertial measurement units [17], and optical PNT payloads [18]. Previous studies have

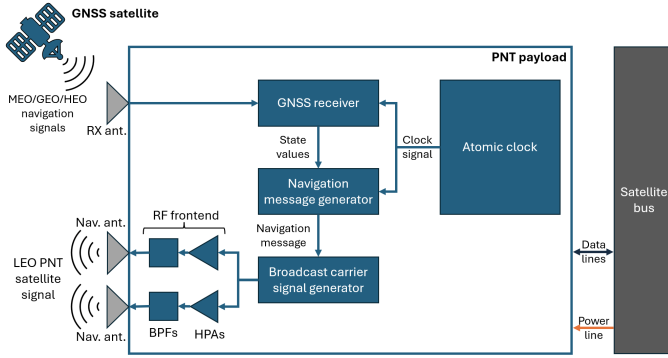


Fig. 1. LEO-PNT payload architecture.

covered challenges, opportunities [4], signal processing [19], constellation optimization, and signal generation analysis [20] for LEO-PNT services.

This work presents a minimalistic small satellite LEO-PNT payload architecture that can be customized to different Size, Weight, and Power (SWaP) requirements depending on the mission scenarios and applications. The desired navigation signal frequency band depends on the specific application of the LEO-PNT system [25]. The proposed payload can be adapted to operate across these different frequency bands. An isoflux antenna, another key component for PNT services, has been explored for wide beam-angle necessary for LEO satellites. This paper compares two payload designs offering functionalities of single-frequency and multi-frequency navigation signals.

The structure of this paper is as follows: Section II presents a block level diagram of both proposed LEO-PNT payloads. Section III develops further on the payload design to perform the feasibility analysis of LEO-PNT payloads and the required satellite link, mass and power budgets. Section IV analyses the results of the comparison between the two payloads and discusses the payload time stability and signal strength, as well as the effects of orbital altitude on the PNT performance. Finally, Section V presents the conclusions of the work.

This work focuses on the component-level architecture of the LEO-PNT payload and satellite design. A parallel publication, which will be presented at the IAC 2024 conference, will cover the module-level architecture of the LEO-PNT payload. The work presented here is a further development on the first iteration of the LEO-PNT payload design featured at the IAC 2024 conference.

II. LEO-PNT PAYLOAD ARCHITECTURE

Figure 1 shows the block level architecture diagram of the LEO-PNT payload architecture proposed in this work. The payloads are specifically designed to meet the size, mass, and volume constraints of a 6 U and 12 U small satellite platform for low SWaP and high SWaP PNT systems, respectively. The payloads are capable of simultaneously transmitting navigation signals and receiving GNSS signals, ensuring uninterrupted and accurate PNT services.

In the payloads, GNSS signals are received by a GNSS module to extract the current orbit position, velocity and timing of the LEO satellite. The atomic clock keeps the GNSS timing aligned to enhance the signal accuracy. The navigation message generator utilizes received GNSS state variables to generate navigation messages. The carrier signal is generated by the on-board atomic clock in the signal generator and combined with the navigation message. The frequency generator produces the carrier frequency at L-band, after which the signal is forwarded to the transmission module where it passes through High Power Amplifiers (HPAs) and Band Pass Filters (BPFs) before finally reaching the navigation antennas.

A. Atomic-clock module

The atomic clock is the central piece of the functionality of the LEO-PNT payload. This module is responsible for the time management and signal accuracy across various modules of the payload. This atomic clock can be realized using different technologies based on caesium, rubidium (Rubidium Atomic Frequency Standards, RAFSs), hydrogen (Passive Hydrogen Masers, PHMs), or crystal oscillators. While PHMs offers the best medium-term stability (around 10^{-14} s inaccuracy over 10^4 s), they present high power consumption and mass. In contrast, crystal oscillators or caesium atomic clocks are lightweight and consume little power. They also present high short-term (1 s to 10 s) stability but poor medium-term stability (100 s to 10^4 s). However, medium-term to long-term stability can be ensured by disciplining the on-board atomic clock using GNSS signals as a reference to maintain its time stability. Furthermore, various steering techniques can be employed to compensate for frequency off-set of the atomic clock [26]. Over a long term, such methods could also improve the reliability and accuracy of the low cost atomic clocks. Therefore, even crystal oscillators and cesium atomic clocks remain an attractive option for small satellite PNT payload applications.

B. GNSS receiver module

The GNSS receiver is responsible for LEO satellite orbit determination and time synchronization with the MEO GNSS satellites in real-time. The module extracts the navigation state variables (such as satellite position, velocity, and acceleration) from the GNSS signal. The GNSS receivers are highly impacted by the algorithm used to determine the state variables. Thus, an effective solution for small LEO-PNT satellites could be provided through a combination of a GNSS receiver with well-optimized SWaP, multi-constellation and multi-frequency capabilities, and an advanced state determination algorithm.

C. Signal generator module

The atomic clock generates signals at a stable frequency of 10 MHz, which can be directly used by the navigation message generation unit to produce the navigation message. A navigation message contains the satellite state variables (position, velocity and time) and their co-variances (uncertainties) along

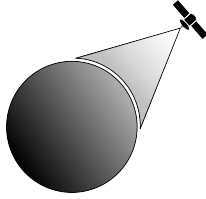


Fig. 2. Isoflux radiation pattern presents higher gain towards the edges of the pattern when illuminating the Earth.

with a time stamp and a time bias value. This information is bundled with Pseudo-Random Noise (PRN).

Various technologies such as Graphical Processing Units (GPUs) for high throughput tasks, Central Processing Units (CPUs) for general purpose processing or Field Programmable Gate Arrays (FPGAs) for customized, power efficient, and real-time processing can be utilized for navigation message generation. For frequency up-conversion, technologies such as oscillators, signal generators, or frequency synthesizers can be used.

D. Transmission module

The transmission module consists of the Radio Frequency (RF) front end that contains HPAs and BPFs. The superimposed carrier and navigation signals received from the up-converter are then amplified in the transmission module using the HPAs. Amplifiers based on silicon, Laterally Diffused Metal-Oxide Semiconductors (LDMOSs), Gallium Nitride (GaN), or Gallium Arsenide (GaAs) can offer a transmission output power of 30 dBm at L-band. A BPF is introduced to the transmission chain to reduce the power level of various harmonics produced by the HPAs. The amplifiers are the most power intensive components in the RF chain.

E. Isoflux antenna

For PNT services, a constant signal power throughout the coverage area is critical. To achieve this, an isoflux radiation pattern is achieved for navigation antennas. The obtained isoflux radiation pattern is rotational symmetric along the nadir direction and presents higher gain further away from nadir, as illustrated in Fig. 2. This type of radiation pattern compensates for higher free space path loss of the signals in off-nadir directions, ideally enabling constant signal power everywhere within the coverage area. An orbital altitude of 800 km has been assumed with isoflux radiation pattern offering a 0 dBi gain in the nadir direction. The isoflux field-of-view needed for maximum ground coverage for satellites in different orbits is presented in Fig. 3. A field-of-view of close to 125° would enable full global coverage with minimum constellation size from the assumed 800 km orbit.

III. LEO-PNT SATELLITE DESIGN

Based on the architecture depicted in Fig. 1, different variations of the payloads are possible. Table I shows the weight and power comparison of two proposed LEO-PNT payload designs with low and high SWaP. The high-SWaP

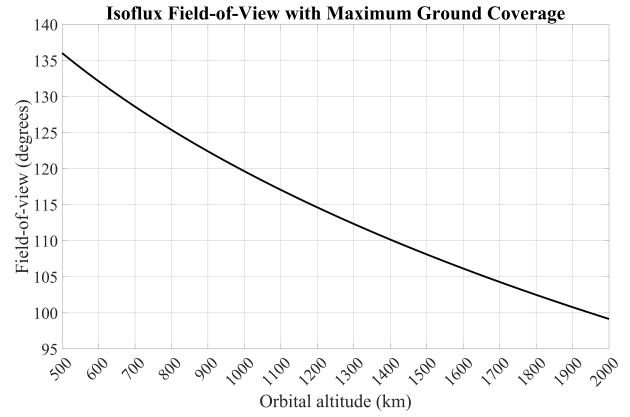


Fig. 3. Isoflux antenna field-of-view that provides maximum ground coverage depends on the orbital altitude. With narrower isoflux beams the ground coverage would decrease, whereas wider beams would present spillover loss because part of the power would be radiated past the Earth.

payload contains a more sophisticated GNSS receiver that can provide in-orbit position and velocity data with down to sub-millimeter accuracy while the low-SWaP PNT payload relies on a GNSS receiver that delivers this information at sub-meter accuracy. Additionally, the high-SWaP payload has multiple power amplifiers for dual frequency navigation signal operations while the low SWaP payload is capable of only single frequency operation and therefore needs only one amplifier. The amplifiers in the transmission module add significantly to the power and mass budget of the payloads, especially for the high-SWaP option.

TABLE I
COMPARISON OF HIGH AND LOW SWaP PAYLOAD MODULES.

	Instruments		Weight (g)		Power (W)	
	Low	High	Low	High	Low	High
Atomic clock	CSAC ^a	Oscillator or RAFS ^b	0.35	700	0.12	18
GNSS module and antenna	AsteRx-m3 Pro + ant.	AsteRx-m3 Pro + ant.	100	100	1	1
SGAU ^c	GPU or freq. synthesizer	FPGA or multi-octave RF upconv.	2	418	10	28
Transmission	RF-Lambda HPA	RF-Lambda HPA	204	306	18	36
Nav. antenna	Isoflux array	Isoflux array	350	700	-	-
Total:			656	2224	29	81

^achip scale atomic clock, ^brubidium atomic frequency standard, ^csignal generation and up-converter

A. Satellite subsystem selection

Based on the requirements imposed by the two LEO-PNT payload options, two satellite platform designs with high and

low SWaP characteristics have been presented. In addition to the core PNT payload, other key subsystems of a spacecraft considered in the satellite design are compiled in Table II.

TABLE II
SATELLITE SUBSYSTEM SELECTION FOR THE LOW AND HIGH SWaP PNT PAYLOAD CASES.

Satellite Sub-system	Low SWaP	High SWaP
PNT Payload	Low SWaP PNT Payload	High SWaP PNT Payload
EPS + battery	COLOSSUS PCDU 2(12 U)	COLOSSUS PCD (L1A)
COM	XLink-S SDR	XLink-S SDR
ADCS	Gen 1 closed loop ADCS (3-axis) CW500	Gen 1 closed loop ADCS (3-axis) CW5000
Propulsion	ThrustMe I2T5	ThrustMe NPT30-I2 1U
OBC	NanoMind-Z7000	NanoMind-Z7000

B. Link margin

The link margin estimates for the low (L1-band only) and high (both L1- and L5-band) SWaP satellite designs are presented in Table III. An orbital altitude of 800 km and L-band navigation signals are assumed. The navigation signal can be detected at -30 dB link margin by implementing a suitable filter matching technique. Therefore, the obtained link margin is sufficient for signal reception on-ground

TABLE III
LINK MARGIN ESTIMATES FOR THE NAVIGATION SIGNALS.

Frequency	TX power (W)	Band-width (MHz)	TX ant. gain (dBi)	RX ant. gain (dBi)	Link margin (dB)
L1-band (1575.42 MHz)	18	10	0	0	-19
L5-band (1176.45 MHz)	18	10	0	0	-23

C. Power budget

Based on the component and subsystem selection in Table II, the power budget of the satellite with the payload operational is estimated (with 10% margin) to be 60 W and 200 W for the low SWaP and high SWaP satellite, respectively. The power budget is the main driver of the satellite size, since the solar panels and batteries must be sized to be able to support the power consumption of the subsystems. Assuming a 10% maximum depth of depletion of the batteries and requiring a positive power budget at the End of Life (EoL) of the satellite, 180 and 480 solar cells are needed for the low and high SWaP spacecraft, respectively. The batteries are estimated to maintain an EoL power capacity of 336 W h and 415 W h for low and high SWaP systems, respectively.

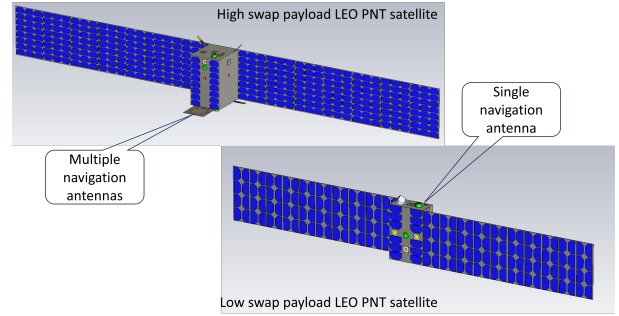


Fig. 4. LEO-PNT Satellite CAD.

D. Mass budget

Given the mass calculated for the PNT payload in Table I, subsystem selected in Table II, and structure mass (including the solar panel mass) of a 6 U (single frequency, low-SWaP) and a 12 U (dual frequency, high-SWaP) CubeSat, the mass of single frequency and dual frequency LEO navigation satellite is 15.39 kg and 30.15 kg, respectively.

E. Satellite CAD model

A rendering of LEO-PNT satellites with both low and high SWaP is shown in Fig. 4. The model depicts the arrangement of different external systems, the deployable solar panels, positioning of antennas and the placement of other sensors. The design adheres to three constraints: Firstly, the solar panels are pointing towards the sun, ensuring optimal power generation. Secondly, the antennas are constantly directed towards the ground, enabling efficient communication. Thirdly, the propulsion system is aligned towards the velocity vector, enabling satellite maneuverability by adjusting orbital speed.

F. Constellation estimates

Constellation design estimates were made for the proposed LEO-PNT satellite as shown in Fig. 5. The antenna beamwidth of 120° at 800 km altitude results in a footprint with 3490 km diameter. A minimum of four visible satellites at all global locations with 20% footprint overlap was assumed.

According to the analysis, a Walker-Star constellation with 8 orbital planes at an inclination of 56° with 40 satellites each will give a constellation with global coverage (except polar regions) sufficient for navigation services (at least four satellites constantly visible at all locations). LEO constellation at clearly lower orbital altitudes than 800 km would require a multi-layer design to achieve global coverage, that is, they would require satellites with varying orbital altitudes as well as different orbital plane inclinations. For altitudes higher than 800 km, global coverage can be achieved with a similar constellation design as for 800 km orbits, but with fewer satellites. Changes in orbital altitude should also be reflected in the navigation antenna beamwidth as shown in Fig. 3.

IV. PAYLOAD PERFORMANCE ANALYSIS

The performance of the payloads with low and high SWaP is compared primarily based on the clock stability and C/No.

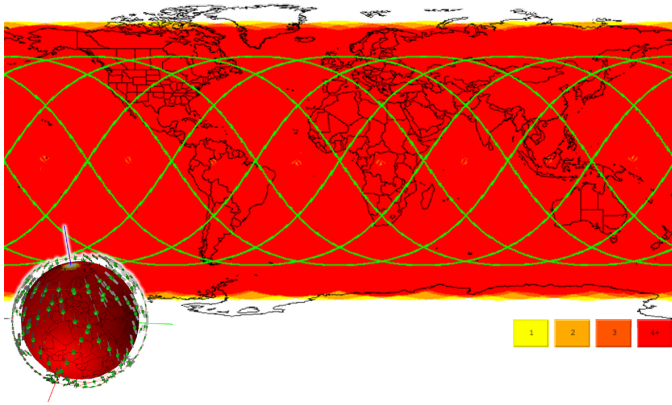


Fig. 5. LEO-PNT walker star constellation simulations. Here the legends 1, 2, 3, and 4+ represent the number of visible satellites.

Fig. 6 compares the time stability of the two payload designs. The low-SWaP payload utilizes a CSAC, which offers a short-term time stability of 3×10^{-10} s and a medium-term stability of 1×10^{-11} s. In contrast, the high-SWaP payload includes a crystal oscillator with a short-term stability of 5×10^{-13} s and an RAFS providing medium-term stability of 6×10^{-14} s. The time stability will reduce below 1 ns for the low SWaP payload and it will thus require a GNSS signal update every 100 min (1 orbit time period) while the high SWaP payload will maintain time stability below 1 ns for at least 24 hours. This indicates that the low-SWaP payload has reduced autonomy and increased dependency on GNSS signals compared to the high-SWaP payload.

Fig. 7 compares the C/No of L-band frequencies (L1 = 1575.42 MHz and L5 = 1176.45 MHz). The lower L1 frequency demonstrates better signal strength due to reduced free space loss. A typical GNSS signal has a C/No of 45 dB-Hz [22] at 30° elevation. In both L1- and L5-frequencies, the C/No remains between 45 dB-Hz and 52 dB-Hz across different LEO altitudes elevation angles below 30° . Thus, the proposed LEO-PNT payload is able to provide C/No equal to or higher than typical GNSS signals due to reduced free space loss. Utilising higher gain isoflux navigation antennas for the LEO-PNT satellites could further improve the C/No of the LEO-PNT signals. This increased signal strength could enhance the resilience of LEO-PNT signals against spoofing and jamming when compared to typical MEO GNSS signals. However, the increased antenna gain could require narrower antenna beams and, hence, more satellites.

V. CONCLUSION

This work introduces two LEO-PNT payload architectures with low and high SWaP requirements. In addition, the work investigates the satellite platform designs required to support these payloads. The high-SWaP payload, due to its combination of oscillator and RAFS, offers better time stability than the low-SWaP payload. The analysis presented in this work shows that a resilient PNT signal is possible from small satellite payload offering a minimum C/No of 42 dB-Hz to

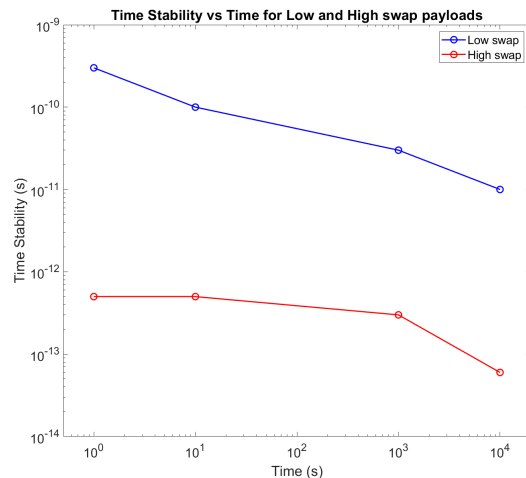


Fig. 6. Low- and high-SWaP clock stability comparison.

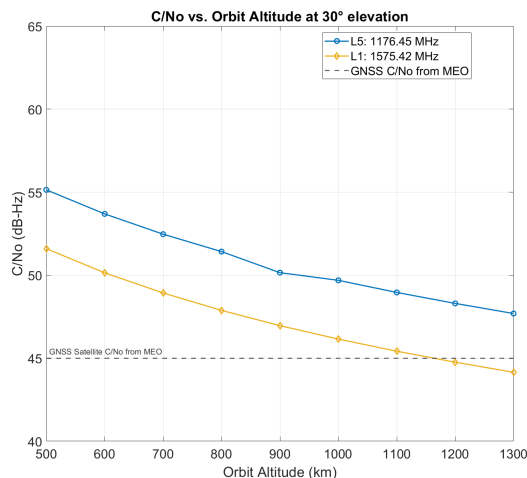


Fig. 7. Carrier-to-Noise ratio (C/No) on the L1 (1575.42 MHz) and L5 (1176.45 MHz) bands at different orbital altitudes based on the free space path loss model. Assuming an ideal isoflux antenna pattern, the elevation angle of the signal does not affect C/No.

52 dB-Hz in LEO. Hence, the proposed LEO-PNT system can offer significantly higher C/No than a typical GNSS signal that reaches 35 dB-Hz to 45 dB-Hz C/No at a 20° elevation angle.

In addition to the LEO-PNT payloads, supporting satellite platform designs were outlined. For these satellite platforms, mass, link, and power budgets were estimated for both the low and high SWaP options. The work shows, that the electrical, mechanical, and RF requirements of the LEO-PNT payloads can be met with low cost 6U/12U small satellite platforms. Moreover, LEO-PNT signals can offer better C/No than MEO GNSS signals, offering thus higher resilience. To achieve this, higher gain navigation antennas are necessary for LEO satellites to improve C/No, and results show that the required isoflux navigation antenna for L-band could be designed to fit in a small satellite form factor. Therefore, the work shows that

a LEO navigation service based on small satellites is viable.

In future work, the hardware of the proposed navigation payloads could be manufactured based on the subsystems identified in this work. The manufactured hardware would allow validating the analysis presented in this work, as well characterizing the performance of the payloads.

REFERENCES

- [1] Dai, Liwen, Chen, Yiqun, Lie, Adhika, Zeitzew, Michael, Zhang, Yuki, "StarFire™ SF3: Worldwide Centimeter-Accurate Real Time GNSS Positioning," Proceedings of the 29th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2016), Portland, Oregon, September 2016, pp. 3295-3320.
- [2] Sheridan, Kevin, Alves, Paul, Masterson, Sara, Busser, Jennifer, Sad-eque, Zafer, Gakne, Paul, Verlaine, Melachroinos, Stavros, Martin, Robert, "TerraStar X: Precise Point Positioning with Fast Convergence and Integrity," Proceedings of the 32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019), Miami, Florida, September 2019, pp. 1916-1943. <https://doi.org/10.33012/2019.17092>
- [3] Zhang, Feipeng & Brandl, Markus & Chen, Xiaoming & Drescher, Ralf & Glocker, Markus & Landau, Herbert & Leandro, Rodrigo & Nitschke, Markus & Salazar, Dagoberto & Weinbach, Ulrich. (2013). Trimble CenterPoint RTX – A First Study on Supporting Galileo.
- [4] F. S. Prol et al., "Position, Navigation, and Timing (PNT) Through Low Earth Orbit (LEO) Satellites: A Survey on Current Status, Challenges, and Opportunities," in *IEEE Access*, vol. 10, pp. 83971-84002, 2022, doi: 10.1109/ACCESS.2022.3194050.
- [5] F. S. Prol, S. Kaasalainen, E. S. Lohan, M. Z. H. Bhuiyan, J. Praks and H. Kuusniemi, "Simulations using LEO-PNT systems: A Brief Survey," 2023 IEEE/ION Position, Location and Navigation Symposium (PLANS), Monterey, CA, USA, 2023, pp. 381-387, doi: 10.1109/PLANS53410.2023.10140118.
- [6] R. Faragher and M. Ziebart, OneWeb LEO-PNT: Progress or Risky Gamble? 28 September 2020, <https://insidegnss.com/oneweb-leo-pnt-progress-or-risky-gamble/>, (Accessed 03.07.24).
- [7] T. Janssen, A. Koppert, R. Berkvens and M. Weyn, "A Survey on IoT Positioning Leveraging LPWAN, GNSS, and LEO-PNT," in *IEEE Internet of Things Journal*, vol. 10, no. 13, pp. 11135-11159, 1 July 2023, doi: 10.1109/JIOT.2023.3243207.
- [8] R. Morales Ferre, J. Praks, G. Seco-Granados and E. S. 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*, vol. 3, no. 4, pp. 171-183, Dec. 2022, doi: 10.1109/JMASS.2022.3206023.
- [9] D. Felbach, D. Heimbuerger, P. Herre and P. Rastetter, "Galileo payload 10.23 MHz master clock generation with a clock monitoring and control unit (CMCU)," IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum, 2003. Proceedings of the 2003, Tampa, FL, USA, 2003, pp. 583-586, doi: 10.1109/FREQ.2003.1275156.
- [10] G. Burbidge, T. Watson and T. Forward, "Development of the Galileo In-Orbit Validation (IOV) Payload," 2007 IET Seminar on Global Navigation Satellite Systems, Portsmouth, 2007, pp. 27-42, doi: 10.1049/ic:20070509.
- [11] Rebeyrol, Emilie & Macabiau, Christophe & Julien, Olivier & Issler, Jean-Luc & Ries, Lionel & Boucheret, Marie-Laure & Bousquet, Michel. (2006). Signal distortions at GNSS payload level.
- [12] Ma, Lin & You, Zheng & Liu, Tianyi & Shi, Shuai. (2016). Coupled integration of CSAC, MIMU, and GNSS for improved PNT performance. *Sensors*. 16. 682. 10.3390/s16050682.
- [13] Khatri Y; Aboaf A; Dowd D; Flood C; Dixon H; Axelrad P, CSAC Flight Experiment to Characterize On-Orbit Performance, AIAA/USU Conference on Small Satellites Conference, 1st August 2020.
- [14] NovAtel, "OEM719 Specifications," [Online]. Available: https://docs.novatel.com/OEM7/Content/Technical_Specs_Receiver/OEM719_Specifications.htm. [Accessed: 03-Jul-2024].
- [15] Symlink, "High-End GNSS SDR payload", Datasheet: <https://www.symlinks.com/en/spatial/charge-utile-gnss-de-haute-performance>, (Accessed 03.07.24).
- [16] K. Aheieva et al., "CubeSat mission for ionosphere mapping and weather forecasting using chip-scale atomic clock," 2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL), Singapore, 2017, pp. 761-766, doi: 10.1109/PIERS-FALL.2017.8293237.
- [17] Mudarris, Mudarris & Basirung, Muhammad & Sumariyanto, Iris. (2022). ROCKET LOAD TEST BASED ON INERTIAL MEASUREMENT UNIT SENSOR IN SUPPORTING NATIONAL AIR DEFENSE. *Jurnal Pertahanan: Media Informasi ttg Kajian & Strategi Pertahanan yang Mengedepankan Identity, Nasionalism & Integrity*. 8. 1. 10.33172/jp.v8i1.1496.
- [18] J. DeLange, S. Frick, J. Runnels, D. Gebre-Egziabher and K. Hedstrom, "Sensor for small satellite relative PNT in deep-space," 2016 IEEE/ION Position, Location and Navigation Symposium (PLANS), Savannah, GA, USA, 2016, pp. 955-963, doi: 10.1109/PLANS.2016.7479794.
- [19] Nicola, Mario & Falco, Gianluca & Ferre, Ruben & Lohan, Elena Simona & Fuente, Alberto & Falletti, Emanuela. (2020). Collaborative Solutions for Interference Management in GNSS-Based Aircraft Navigation. *Sensors*. 20. 4085. 10.3390/s20154085.
- [20] R. Morales Ferre, J. Praks, G. Seco-Granados and E. S. 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*, vol. 3, no. 4, pp. 171-183, Dec. 2022, doi: 10.1109/JMASS.2022.3206023.
- [21] Adilov, Nodir & Alexander, Peter & Cunningham, Brendan & Albertson, Nikolas. (2024). An Analysis of Launch Cost Reductions for Low Earth Orbit Satellites (accepted for publication, *Economics Bulletin*, 2022). *Economics Bulletin*.
- [22] Tian, Yijun & Sui, Lifeng & Xiao, Guorui & Dongqing, Zhao & Tian, Yuan. (2019). Analysis of Galileo/BDS/GPS signals and RTK performance. *GPS Solutions*. 23. 10.1007/s10291-019-0831-5.
- [23] Jennifer E. Donaldson, Joel J.K. Parker, Michael C. Moreau, Dolan E. Highsmith and Philip D. Martzen NAVIGATION: Journal of the Institute of Navigation June 2020, 67 (2) 411-438; DOI: <https://doi.org/10.1002/navi.361>
- [24] A. Montesano et al., "Galileo System Navigation Antenna for Global Positioning," The Second European Conference on Antennas and Propagation, EuCAP 2007, Edinburgh, 2007, pp. 1-6, doi: 10.1049/ic.2007.1441.
- [25] Eissfeller, Bernd & Pany, Thomas & Dötterböck, Dominik & Förstner, Roger. (2024). A Comparative Study of LEO-PNT Systems and Concepts. 758-782. 10.33012/2024.19646.
- [26] Wu, Yiwei & Gong, H. & Zhu, Xiangwei & Liu, W.-X & Ou, Ge. (2016). Twice atomic clock steering algorithm and its application in forming a GNSS time reference. 44. 1742-1750. 10.3969/j.issn.0372-2112.2016.07.032.