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Exploring 'New Space' positioning using Low Earth Orbit (LEO) satellites

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Bachelor's thesis to obtain the degree of Bachelor of Science in
Electronics and ICT Engineering Technology

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1 Acknowledgement

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2 Abstract

This bachelor thesis “Exploring ‘New Space’ positioning using low earth orbit (LEO) satellites” consists of two main parts. The first part of this thesis is a comprehensive state of the art study (SOTA) about positioning, navigation and timing (PNT) in LEO. This SOTA study was a collaboration of multiple parties.

Foregoing the simulation, this study is concerned with the latest research and developments on PNT using LEO satellites as well as other contributing factors. Our literature study answers the question: “What are the possible satellite constellations which could be used for positioning?” as well as “What are the signals of opportunity provided by satellite constellations?”. This study also provides the reader with the necessary context of why PNT using LEO satellites is important.

The second part consists of a simulation. This simulation regards localization using pseudoranges. This simulation provides an insight into how pseudoranging works and answers the question: ”What are the differences between LEO satellites and global navigation satellite system (GNSS) when calculating pseudoranges?” and explores the possibilities of localization using LEO satellites.

3 Introduction

GNSS has been dominant since the 90s till today in PNT. Improvements have been made to the design and implementation throughout the years. Recently, however, growing demand has emerged for new PNT solutions. These solutions should solve several shortcomings in the already well-established GNSS. To name a few of these shortcomings: security (spoofing, jamming), multipath propagation, accuracy and energy consumption. Solving these ‘issues’ opens up opportunities for different applications that didn’t seem possible before. For example, autonomous driving requires precise accuracy of 30cm or less. This is not possible using the GNSS that is available currently but may be possible by utilizing LEO satellites. (Janssen et al., 2022)

> **“Recently, however, growing demand has emerged for new PNT solutions. These solutions should solve several shortcomings in the already well-established GNSS. “ ~ (Janssen et al., 2022)**

The first part of this thesis starts with a SOTA study. This study was commissioned by the European Space Agency (ESA). The topic of this thesis regards the signals of opportunity from LEO constellations. Due to the current state of affairs, multiple LEO constellations are being designed, built or are being deployed. The cost of deploying satellites into LEO has declined over the last few decades. Thus making this orbit more accessible for companies to deploy constellations to. (Jones, 2018)

While not all of these constellations were designed for PNT purposes. They could be leveraged for PNT utilizing their respective signal of opportunity. This thesis, therefore, focuses on a technical overview of the main properties of some of the largest LEO constellations providing broadband and narrowband communications.

To further evaluate the potential of LEO satellites for PNT, this thesis explores positioning using pseudoranges. As well as examining the differences in pseudoranging using LEO satellites and pseudoranging using traditional GNSS. Along with delving into the mathematics behind pseudoranging. The simulation will also include visualizing the test environment and localization using the calculated pseudoranges.

4 Method of research in SOTA study

This bachelor thesis was focused on the signals of opportunity and the different constellations that exist or are planned to be implemented in LEO. To research the specifications of satellite constellations Federal Communication Commission (FCC) reports and filings were used. Companies are obligated to send their constellation parameters to the FCC for review. Once they have been approved, they are published for the public to see. These FCC reports contain a description of the orbits as well as communication specifications.

5 Method of simulation

To simulate satellite constellations and study their signals MATLAB Satellite Communications Toolbox was used in addition to MATLAB. This program supplies visualization as well as different functions to calculate the parameters of satellites and links.

To simulate real satellite constellations, tle files were used. These are provided by Celestrak. By using these tle files the positions of the satellites can be simulated and in addition, provide a realistic starting point for the simulation.

6 Results of SOTA study

A constellation can be defined as a set of spacecraft that share characteristics like the number of satellites, orbits, design and service provided. Hundreds of LEO constellations are fully operational, being deployed in orbit, or being prepared to launch soon (Kulu, 2022). LEO is already a very popular orbit for constellations as shown in Figure 1. These projects tend to be susceptible to frequent changes in parameters such as the number of satellites, frequencies, and altitudes. Most of them are purposed for a specific application, e.g. Earth Observation (EO), IoT sensor data communication, M2M communication, and providing 5G or Internet from space. While their primary goal can remain the same, the signals used for communication purposes can be leveraged for PNT purposes as a secondary goal.

Some of the largest and most interesting LEO constellations can be found in Table 1, along with their most recent characteristics at the time of writing. Previously Iridium was the largest constellation consisting of around 70 elements. Nowadays SpaceX's Starlink constellation has the most elements in LEO (Bassa et al., 2022).

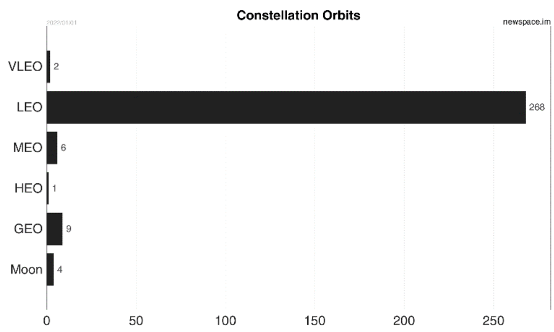

Figure 1: Orbits of small constellations (Kulu, 2022)

Not all constellations are worth researching for PNT purposes. Earth Observation (EO) constellations, emission monitoring constellations and other observational satellites do not offer much potential utility regarding this subject. Examples of these constellations include but are not limited to Iceye, RapidEye, Spire, and Capella Space.

Table 1: Overview of the main properties of some of the largest LEO constellations providing broadband and narrowband communications. Data is according to referenced sources.

Name	Operator	Constellation design	Number of satellites	Frequency bands used for communication	Intended services
Iridium NEXT	Iridium Communications Inc.	Altitude: 780 km Inclination: 86.4° (Herbert J. Kramer, 2022)(Hindin & Murphy, 2016)	66 (+ 6 in-orbit spares + 6 hanger spares)	L-band user (1616-1626.5 MHz) K-band Satellite-to-Satellite (22.18- 22.38 GHz)GW downlink (19.4-19.6 GHz) Ka-band GW uplink (29.1-29.3GHz)	Internet access, satellite telephony
OneWeb	OneWeb and Airbus	Market access grant Altitude: 1200 km Inclination: 87.9° Phase 1 Altitude: 1200 km Inclination: 55°, 87.9° In several orbital planes Phase 2 Altitude: 1200 km Inclination: 40°, 55°, 87.9° In several orbital planes (ONEWEB, 2016) (Weimer et al., 2021)	Market access grant 720 Phase 1 716 Phase 2 6 372 Total number of elements 7 808	Ka-Band GW uplink (27.5-29.1GHz, 29.1-29.5GHz*, 29.5-30GHz) Ku-Band GW downlink (17.8-18.6GHz, 18.8-19.3GHz, 19.3-19.7GHz*, 19.7-20.2GHz*) User uplink (12.75-13.25GHz*, 14-14.5GHz) User downlink (10.7-12.7GHz) *(FCC authorization not yet requested)	Internet access
Starlink	SpaceX	Starlink generation 1 Phase 1 Altitude: 540 – 570 km Inclination: 53° - 97.6° In several orbital planes Phase 2 Altitude: 335.9 -345.6 km Inclination: 42° - 53° In several orbital planes (Del Portillo et al., 2018)(Albulet, 2017)(Albulet, 2020)	Phase 1 4 408 Phase 2 7 518 Total number of elements 11 926	Ku-band User (10.7-14.5 GHz) V-band downlink user/ GW (37.5-42.5GHz) Uplink user/GW (47.2-50.2, 50.4-52.4GHz) TT&C downlink (37.5-37.75GHz) TT&C uplink (47.2-47.45GHz) Ka-band GW (17.8-30 GHz)	Internet access
Project Kuiper	Amazon	Constellation consists of Kuiper-V system and Kuiper-Ka system Altitude: 590 - 650km Inclination: 33° - 80° In several orbital planes (Kaufman, 2021)	7 774	V-Band GW downlink (37-5-42GHz,42-42.5GHz*) GW uplink(47.2-50.2GHz,50.4-51.4GHz) Ku and V-Band User downlink (10.7-12.7GHz,37.5-42GHz,42-42.5GHz*) User uplink (12.75-13.25GHz,14-14.5GHz,47.2-50.2GHz,50.4-51.4Ghz) V-Band TT&C downlink & Beacon (40.0-40.1GHz) TT&C uplink (47.2-47.3GHz) *Non-U.S. only	Internet access

7 Results of simulation

7.1 Visualization of the test environment

The setup of the test environment includes four LEO satellites from the company Space X. The snapshot was made on the 20th of April 2022 at 9:20:18 UTC. These four satellites were chosen because they were in clear sight from Campus Groenenborger at the University of Antwerp.

The visualization and the links between the receiver and satellites are visible in Figure 2 LEO satellite simulation scenario.

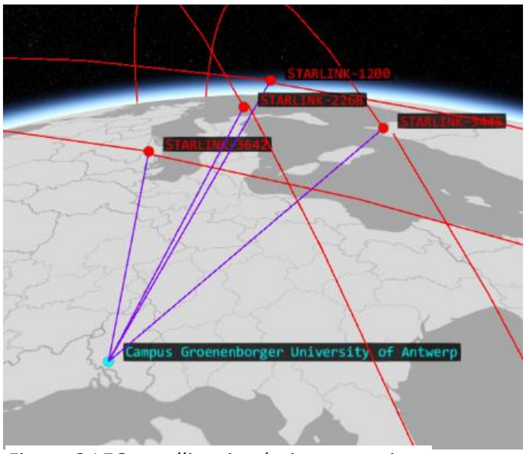

Figure 2 LEO satellite simulation scenario

7.2 Comparison of pseudoranges of GNSS and LEO

A pseudorange is the approximate distance between satellite and receiver. This distance can be calculated with the coordinates of the receiver and the coordinates of the satellite. To calculate the pseudorange this thesis explores two techniques. The first technique incorporates no other variables besides the coordinates of the receiver and the satellite. The second technique also incorporates the rotation of the earth. The rotation of the earth needs to be incorporated into the calculation to account for the travel time of the signal. See the annexe for a full description of these calculations: “Calculating pseudoranges utilizing satellite and receiver coordinates”, (Van Uytsel, 2022a).

To compare both methods of calculating pseudoranges, four GNSS satellites were used in combination with four LEO satellites to assess the difference between both constellation types. Furthermore, the MATLAB pseudorange function was slightly altered to print the error between both calculation techniques. Visible in Figure 3 Comparison of GPS and LEO satellites error calculating pseudorange by not taking the rotation of the earth into accountshows the difference between not taking the rotation of the earth into account when calculating the pseudorange of a satellite and taking the rotation of the earth into account. This is noticeably larger in Galileo satellites (GSAT) than the Starlink satellites. This is due to the longer distance the signal has to travel from the Galileo satellites to the receiver. The signal of LEO satellites experiences a shorter travel time and therefore the earth’s rotation doesn’t affect the pseudorange by much. To summarise this experiment, the calculations between both constellations can be done the same way. However, there is a big difference in simplifying these calculations. For GNSS satellites not incorporating the rotation of the earth into the calculations, results in a significant error. For LEO satellites not incorporating the rotation of the earth results in a small error. To read the full description of the experiment see annexe: “Comparison of pseudoranges between LEO and GPS satellites”, (Van Uytsel, 2022b)

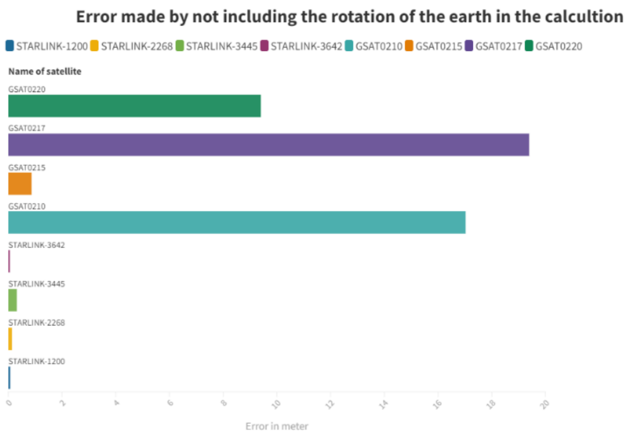

Figure 3 Comparison of GPS and LEO satellites error calculating pseudorange by not taking the rotation of the earth into account, bar graph

7.3 Localization using pseudoranges

Localization using pseudoranges has been standard practice for GNSS. To calculate this a least-squares positioning algorithm is used. To determine the position of the receiver an initial prediction is made from an initial location. In a GNSS context, the centre of the earth is chosen as the initial location.

After this calculations are made iteratively. Start from an initial estimation, analyse how far this estimation is from the target, check if the estimation is close enough to the target to stop and if that isn't the case, repeat the process. An additional check is made each iteration to verify that the algorithm is still converging. If the algorithm wouldn't be converging the calculated position would get progressively worse and stray further and further from the actual location. Therefore, the algorithm would stop if this is the case. (Groves, 2013)

By using this algorithm and taking as starting point the centre of the earth, the following error between the actual location and the calculated location was obtained:

```
Error X-axis: 40 498 032 meters
Error Y-axis: 2 902 469 meters
Error Z-axis: 49 394 725 meters
```

This error is very big. To improve this localization function, a different initial location was chosen. In this simulation, an initial position closer to the real position was chosen but this location still had a large enough offset from the real receiver location. This was done to verify if the algorithm was able to find a better estimation. The offsets were chosen in a 10 to 100km range. When employed this way, the algorithm functions and an accurate localisation is obtained. To read the full description of the experiment see annexe: "Localization for LEO satellites using pseudoranges" (Van Uytsel, 2022c)

```
Error X-axis: 24 meters
Error Y-axis: 5 meters
Error Z-axis: 3 meters
```

8 Conclusion

LEO is becoming a very popular and crowded orbit. Companies are competing for their piece of market share in this 'new space' economy. Broadband constellations from tech companies like SpaceX with Starlink and Amazon with Project Kuiper do not incorporate any features for PNT services. Nevertheless, these constellations could be leveraged for these purposes. This could be done by using the signal of opportunity and analysing this signal. A dedicated LEO constellation for PNT is being researched and designed by companies such as Xona space and could be tested in the near future. (Janssen et al., 2022)

Furthermore, localization can be done by using pseudoranges. These pseudorange calculations can be simplified for LEO satellites. This thesis shows that the error between the calculation taking the earth's rotation into account and the calculation not taking the rotation into account is minimal for LEO satellites. However, for GNSS satellites this isn't the case. Therefore incorporating the rotation of the earth into the pseudorange calculations of LEO satellites is a step that doesn't add much value and may be left out in certain applications for a performance gain.

Using pseudoranges for localization can be done by using a least-squares localization algorithm starting from the centre of the earth. This method is used in GNSS and provides good results. For LEO satellites, however, this isn't the case. Starting the algorithm from the centre of the earth results in a divergence of the iterative algorithm. To counter this problem, this thesis shows that choosing a starting position in the vicinity of the receiver results in accurate localization and convergence of the algorithm.

9 Resources

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