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Department of Information Engineering

Bachelor Thesis in Computer Engineering

Challenges and Perspectives in Lunar Communication and Navigation Systems for Future Cis-lunar Space Exploration Missions

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Alla mia famiglia.

Abstract

With the increasing interest in lunar exploration and potential for human habitation, the need for accurate and reliable navigation systems on the Moon has become more crucial than ever. The absence of a well-established lunar navigation infrastructure poses significant challenges to future space missions, including safe landing, trajectory planning, and autonomous operations. In this context, the development of a Lunar communication and navigation system (LCNS) capable of providing precise and real-time navigation services is of utmost importance.

This thesis initially presents European space agency (ESA)'s Moonlight mission, and then goes on to describe various proposed implementations of LCNS, considering its technical feasibility, performance, and potential applications. The first stage involves Global navigation satellite system (GNSS)-only technologies and architectures, then moves into the second one where the proposals are GNSS-aided, and finally in the third one, we move on to Lunar-only implementations, thus totally independent of GNSS. Ultimately, the thesis concludes that while significant challenges exist, innovative solutions can ensure the development of robust communication and navigation systems for future cis-lunar space exploration missions.

Sommario

Con il crescente interesse per l'esplorazione della Luna e il suo potenziale abitativo, la necessità di disporre di sistemi di navigazione precisi e affidabili sulla Luna è diventata più che mai cruciale. L'assenza di un'infrastruttura di navigazione lunare ben consolidata pone sfide significative alle future missioni spaziali, tra cui l'atterraggio sicuro, la pianificazione della traiettoria e operazioni autonome. In questo contesto, lo sviluppo di un Sistema di comunicazione e navigazione lunare (LCNS) in grado di fornire servizi di navigazione precisi e in tempo reale è di estrema importanza.

Questa tesi presenta inizialmente la missione Moonlight dell'Agenzia spaziale europea (ESA), per poi descrivere le varie implementazioni proposte di LCNS, considerandone la realizzabilità tecnica, le prestazioni e le potenziali applicazioni. La prima fase coinvolge tecnologie e architetture basate esclusivamente sul Sistema globale di navigazione satellitare (GNSS) (GNSS-only), per poi passare alla seconda fase in cui si discutono proposte che mirano ad integrare il GNSS con altre tecnologie (GNSS-aided), e infine nella terza si passa alle implementazioni Lunar (Lunar-only), quindi totalmente indipendenti dal GNSS. Infine, viene concluso che, sebbene esistano sfide significative, le soluzioni innovative possono garantire lo sviluppo di sistemi di comunicazione e navigazione robusti per le future missioni di esplorazione dello spazio cis-lunare.

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Listing of acronyms

ASI Italian space agency

BGM1 blue ghost mission 1

CF center-finding

CLPS commercial lunar payload services

COTS commercial-off-the-shelf

CP cooperative positioning

CSAC microchip chip scale atomic clock

DOP dilution of precision

DSAC deep space atomic clock

DTE direct-to-Earth

ECOP Earth-GPS continual outage period

EKF extended Kalman filter

ELFO elliptical lunar frozen orbit

ESA European space agency

GEONS Goddard enhanced onboard navigation system

GGMS GEONS ground MATLAB simulator

GNSS global navigation satellite system

GN ground network

GPS global positioning system

HGA high gain antenna

HWIL hardware-in-the-loop

ISECG international space exploration coordination group

ISR inter-spacecraft range

LCI lunar-centered inertial

LCNS lunar communication and navigation system

LEO low Earth orbit

LGCV local geocentric, local vertical

LLO low lunar orbit

LNA low noise amplifier

LNN lunar navigation nodes

LNSS lunar navigation satellite system

LNS lunar navigation system

LuGRE lunar GNSS receiver experiment

MAC microchip micro atomic clock

MC Monte Carlo

MCMF Moon-centered, Moon-fixed

MMS magnetospheric multiscale

NASA national aeronautics and space administration

NRHO near-rectilinear halo orbit

ODTS orbit determination and timing synchronization

OD orbit determination

OpNav optical navigation

PCO projected circular orbit

PDOP positional dilution of precision

PNT position, navigation, and timing

POD precise orbit determination

PVT position, velocity and time

RAFS rubidium atomic frequency standard

RE Earth radius

RF radio frequency

RMS root mean square

SDR software defined radio

SRS Stanford research systems

SSTL Surrey satellite technology ltd

SWaP size, weight, and power

TRN terrain relative navigation

UERE user equivalent range error

USO ultra-stable oscillator

VLBI very long baseline interferometry

VMMO volatile and mineralogy mapping orbiter

1

Introduction

In the vast expanse of space, the Moon stands as a beacon of human curiosity and potential. The necessity for reliable and effective lunar communication and navigation system (LCNS) becomes critical as mankind turns its attention to the Moon with renewed enthusiasm, motivated by the desire to establish a lasting presence and explore its undiscovered territory. Numerous and intricate problems will need to be solved in order to assure the success of navigation, communication, and exploration throughout trips to the Moon.

1.1 BACKGROUND AND MOTIVATION

We now have a much better grasp of space exploration and technology than we had when the first human footprints appeared on the lunar surface. Complex lunar missions are now possible due to developments in satellite technology, communication protocols, and navigation algorithms. These missions, whether they are focused on carrying out scientific study, exploiting resources, or establishing future human settlements, essentially depend on precise navigation and effective communication. To ensure the efficiency and safety of LCNS, certain issues related to the Moon's unusual environment, which is defined by low gravity, vacuum conditions, and extreme temperature swings, must be addressed.

1.2 OBJECTIVES

This thesis' main goal is to thoroughly examine the issues and viewpoints surrounding lunar navigation and communication technologies. By examining the unique features of LCNS, we want to pinpoint the challenges that prevent the creation and use of solid systems and to imagine alternative fixes that may result in more effective and reliable lunar exploration.

The purpose of this thesis is to clarify the difficulties that lunar navigation and communication systems face. For safe and precise lunar operations, navigation includes determining the locations, trajectories, and orientations of spacecraft and landers. The construction of trustworthy connections between lunar stations and Earth-based assets, on the other hand, allows for the interchange of crucial information. This research attempts to offer a comprehensive picture of the interrelated problems within the LCNS domain by tackling the complexities of both communication and navigation.

1.3 OVERVIEW OF SATELLITE NAVIGATION

Modern space exploration relies heavily on satellite navigation, which is crucial for the precise location and navigation of equipment, vehicles, and spacecraft. The United States created and maintains the global positioning system (GPS), which is arguably the most well-known satellite navigation system. It is made up of a constellation of satellites orbiting the Earth and sending out precise signals that are picked up by receivers on the surface of the planet and used to trilaterately determine their locations.

Trilateration includes estimating the time it takes for signals to travel from different satellites to a receiver in order to estimate the distance between the receiver and the satellites. The receiver may establish its precise position in three-dimensional space by intersecting these distance values.

For more details about the position, velocity and time (PVT) computation the interested reader may see [1].

1.4 STRUCTURE OF THE THESIS

The remainder of this thesis is structured as follows:

- **Chapter 2: Moonlight**: This chapter delves into European space agency (ESA)'s Moonlight mission, its goals and plans for the future of moon travel.
- **Chapter 3: GNSS-only**: Here, we explore characteristics and obstacles involved in LCNS proposals based only on global navigation satellite system (GNSS).
- **Chapter 4: GNSS-aided**: In this chapter, we discuss emerging technologies and innovative LCNS solutions that are in part aided by GNSS.
- **Chapter 5: Lunar-only**: Within this chapter we look for technologies that would allow an Earth-independent LCNS and therefore do not refer to GNSS nor GPS.
- **Chapter 6: Conclusion**: The final chapter of the thesis outlines potential future directions in LCNS, considering the evolving landscape of space exploration and technological advancements.

The papers on which this thesis is based are divided into the various chapters as follows:

Table 1.1: Division of academic papers in three phases: GNSS-only, GNSS-aided and Lunar-only

	GNSS-only	GNSS-aided	Lunar-only
[2]	X		
[3]	X		
[4]	X		
[5]		X	
[6]		X	
[7]		X	
[8]			X
[9]			X
[10]			X

2

Moonlight

Figure 2.1: Moonlight logo

The Moonlight initiative, which is a representation of the ESA's vision, aims to promote the development of lunar communication and navigation services that will aid the next generation of institutional and private lunar exploration missions, as well as improving the performance of those missions that are currently being defined [11].

One system for navigation and communication on the Moon would simplify the design, allowing missions to concentrate on their primary tasks. Missions would be lighter since they could rely on this specialized telecommunications and navigation capabilities. This would free up space in the payload for additional research equipment or other items. Missions would be able to land wherever they want with the aid of a precise and dependable service. Rovers might move more quickly across the lunar surface. It may even make it possible for rovers and other equipment to be controlled remotely from Earth [12].

2.1 Moonlight navigation service

In a concept similar to GNSS, the Moonlight project seeks to provide a one-way broadcast radio navigation signal to enable users to calculate its position, velocity, and time. For example, the signals broadcast by the Moonlight satellites will be synchronized among them [11].

Similar to how we now navigate on Earth with Galileo and GPS, such satellites might likewise give navigation information for lunar exploration [13].

Moonlight's goal is to offer the first services in 2026-2028 making use of the major advancements in GNSS satellite technology. To simplify the concept's deployment, current spaceborne GNSS receivers will be reused with the fewest changes possible. This is achieved by implementing GNSS modulations, navigation techniques and technologies [11].

2.2 Preliminary Moonlight system design

A preliminary system design for the Moonlight system is presented in Figure 2.3. The system comprises up to four different segments: lunar space segment, Earth ground segment, lunar user segment and lunar surface segment.

The lunar space segment is comprised of a number of satellites in orbit around the moon. The ground segment required on Earth to support the Moonlight mission is currently being defined. A network of ground stations will be used to establish connections with the spacecraft in order to establish communication linkages with the LCNS satellites. These ground stations will be dispersed all over the Moon surface to maximize visibility to satellites. As the supported data rates must match the services that are being developed to meet the identified user needs, the performance of these links is more crucial to the Moonlight communications services. To close the connection budgets and obtain the necessary data rates, large dishes will be needed.

Two distinct navigation services are envisaged: a one-way navigation signal sim-

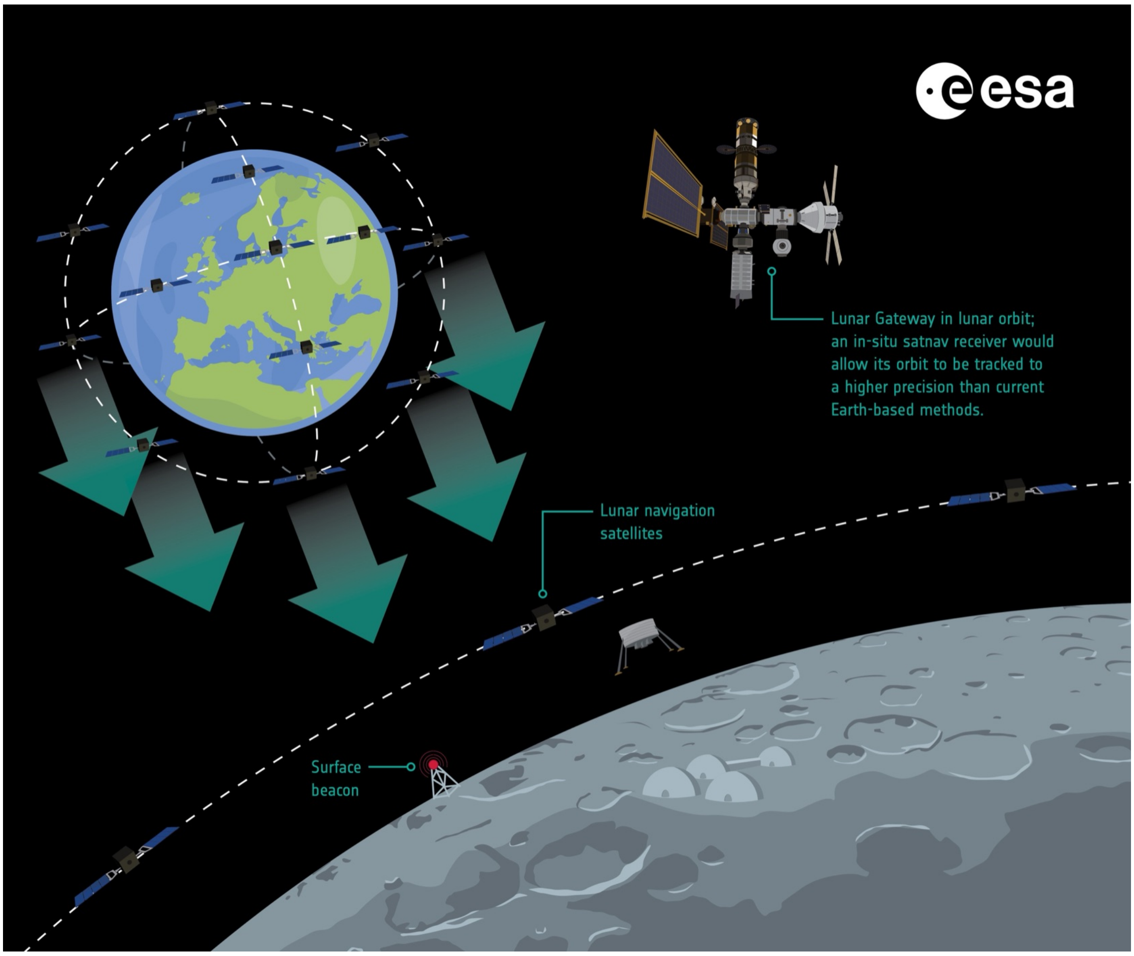


Figure 2.2: Moonlight - Navigation and telecommunications for the Moon [14]

ilar in design to current GNSS signals and a two-way ranging signal which will be part of the communications links rather than being generated within the navigation payload [15].

2.3 ESA strategic roadmap vision

ESA defined three phases to establish a lunar radio navigation service [11]:

- **Phase 1 - Use of high-sensitivity space receivers (2022-2025)**: Based on receiving GNSS signals from the Earth using high sensitivity receivers, on-board dynamic filters, and high gain antennas. Initial support for the

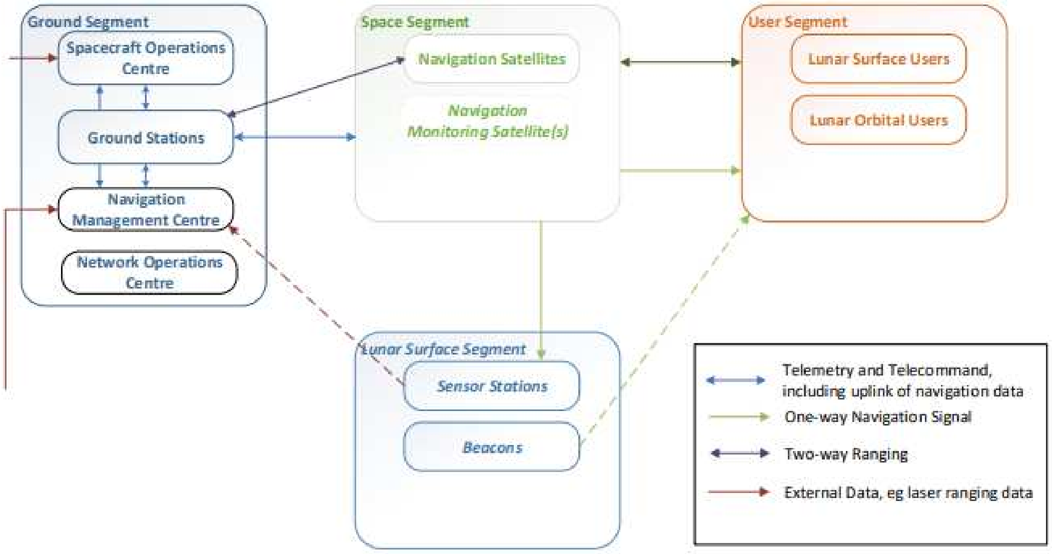


Figure 2.3: Initial Moonlight system design [15]

Earth-Moon transfers and lunar orbit activities should be provided during this phase.

- **Phase 2 - LCNS (2025-2035)**: Transmitting extra range signals from the Moon's orbit and surface to improve Phase 1. This phase ought to enable a significant decrease in the geometric dilution of precision (DOP) and an increase in service accessibility, which would result in improved lunar orbit navigation and initial landing/surface position, navigation, and timing (PNT) services (for instance, on the Moon's South Pole).

- **Phase 3 - Full lunar PNT system (2035-onwards)**: This Phase is expected to offer PNT services throughout the whole Moon's surface and improve positioning availability and precision at the lunar South Pole. Phase 2 might be supplemented with more lunar orbiting satellites and Moon surface beacons to achieve this. Increased autonomy may result from this phase's ability to provide integrity services for safety-critical applications.

2.4 THE LUNAR PATHFINDER NAVIGATION EXPERIMENT

A lunar communication relay satellite named Lunar Pathfinder will be launched by Surrey satellite technology ltd (SSTL) and ESA in order to provide communication services to lunar missions. In order to show the acquisition of GNSS signals in lunar orbit and the capability of computing the orbit state vector of the satellite in real-time on board, the satellite will be equipped with a high-sensitivity GNSS spaceborne receiver. Numerous articles have examined the idea of lunar GNSS, and it has been demonstrated (particularly during flight testing as part of the national aeronautics and space administration (NASA) magnetospheric multiscale (MMS) project [16]) that it is still possible to acquire and track GNSS signals despite the signals' extreme received low power.

The GNSS experiment in Lunar Pathfinder consists in a GNSS receiver developed by SpacePNT and a GNSS antenna; this may become a key technology for the lunar orbit determination of Phase 2 LCNS satellites [11].

2.5 ORBIT DETERMINATION AND TIMING SYNCHRONIZATION

How precisely the ephemeris and on-board time of the LCNS satellites can be computed will directly affect the precision of the navigation solution that the Moonlight service can offer to users. Novel methods will be needed to give the inputs needed for the orbit determination and timing synchronization (ODTS) process because it is likely there will not be any monitoring stations on the lunar surface, at least during the early deployment of the LCNS system. To achieve the ODTS accuracy standards while minimizing the load on the system and the mission expenses, the ideal combination of inputs must be determined.

There are several different ranging methods: Radiometric Ranging, Earth GNSS Measurements, Cross-links, External Data Sources. Their description can be found in [15].

2.6 Navigation performances of a lunar lander using a minimum LCNS configuration of 4 lunar orbiting satellites

The LCNS constellation considered here consists of 4 satellites in elliptical lunar frozen orbit (ELFO) in 2 orbital planes: this serves as an example constellation to show the potential results achievable in a realistic lunar landing trajectory. A GNSS spaceborne receiver with similar features to the one that will fly in Lunar Pathfinder in 2024 is used on board to carry out the ODTS processing.

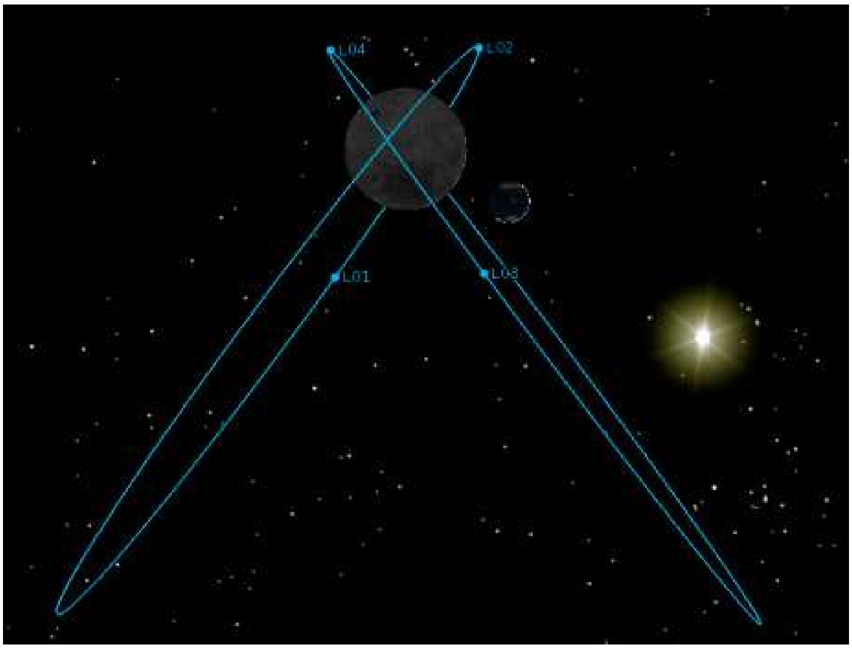


Figure 2.4: 4 satellites in 2 planes ELFO constellation [11]

A satellite equipped with a GNSS receiver could achieve roughly 41m 3D root mean square (RMS) in ELFO orbits. The orbit and clock errors taken into account are 50m 1-σ for each orbit component and 50m 1-σ for the clock [11]. Because a future system may use many ODTS approaches simultaneously, such as direct-to-Earth (DTE) radiometric readings, laser ranging, inter-satellite communication, etc., it is crucial to note that these values are rather conservative. Despite having just 4 satellites and a significant orbital and clock inaccuracy, it is possible to attain 47m 3-σ and 27m 3-σ horizontal precision for single epoch and multi-epoch approaches respectively. The 90m 3-σ results fall well within the parameters specified in the worldwide exploration roadmap.

The findings in this contribution confirmed that the Moonlight navigation service could be a game-changer for lunar exploration. They showed that it is possible to achieve outstanding performances, outperforming current state-of-the-art landing technologies, using a very basic GNSS spaceborne receiver (very small size, weight, and power (SWaP)).

3

GNSS-only

This chapter focuses on LCNS technologies that depend entirely on GNSS for PNT on the Moon.

In order to enable efficiency and speedy deployment, there has recently been an increase in interest in using a SmallSat platform for the upcoming lunar navigation satellite system (LNSS). The onboard clock and the orbit type are two design decisions for the SmallSat-based LNSS that have not yet been decided.

Designing an LNSS has particular difficulties in comparison to the conventional Earth-GPS due to [2]:

- the onboard clock's limited SWaP, which also restricts timing stability
- the scarcity of lunar ground monitoring stations
- increased orbital perturbations in lunar environment

To tackle these issues, two main solutions have been proposed and will be presented throughout this chapter: a LNSS with time-transfer from Earth-GPS, the use of GNSS receivers such as lunar GNSS receiver experiment (LuGRE) and Navimoon.

3.1 LNSS with time-transfer from Earth-GPS

Given these difficulties in creating a PNT constellation for the lunar environment, one possibility is to make use of the Earth's current legacy GNSS, such as GPS, which has higher-grade atomic clocks and a vast ground monitoring network.

In this paragraph we follow a work that focuses on GPS, but the topic can be generalized to GNSS. The Earth-GPS signal is significantly weaker at lunar distances of approximately 385000 km, and the Earth-GPS satellites headed toward Earth are generally obscured by the Earth as well as the Moon. This restricts the Earth-GPS signal availability at lunar distances to only come from the limited, clear portions of the main lobe and the side lobes of the Earth-GPS broadcast antenna. However, NASA's MMS utilized these significantly weakened and sporadic Earth-GPS signals to effectively estimate location in space, proving the feasibility of using Earth-GPS at lunar distances [2]. In particular, the authors propose to combine the intermittently available Earth-GPS signals in their suggested time-transfer architecture's timing filter to reduce the cost and SWaP demands of the onboard clocks. This architecture is shown in Figure 3.1.

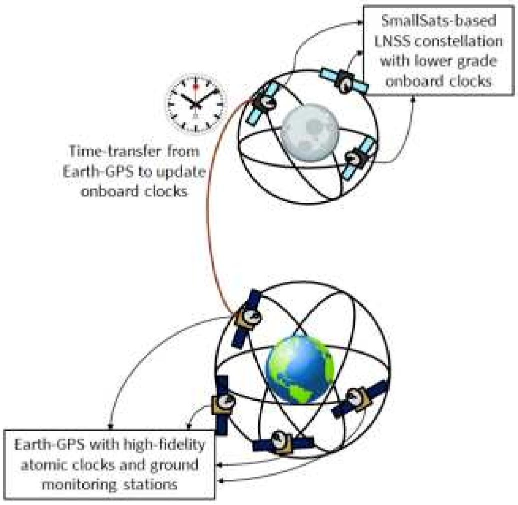


Figure 3.1: Architecture of the proposed time-transfer from Earth-GPS, which uses intermittently available Earth-GPS signals to correct the lower-grade clocks onboard the LNSS satellite [2]

After performing numerous simulations to examine the trade-off between different choices of the onboard clock (microchip chip scale atomic clock (CSAC), microchip micro atomic clock (MAC), Stanford research systems (SRS) PRS-10, Excelitas rubidium atomic frequency standard (RAFS) and NASA's deep space atomic clock (DSAC)) and the orbit types, i.e., ELFO, near-rectilinear halo orbit (NRHO), low lunar orbit (LLO) and projected circular orbit (PCO), the lunar user equivalent range error (UERE), which describes the ranging precision of signals broadcast from an LNSS satellite, was evaluated.

Given its high altitude and fewer occultations from Earth and the Moon, a NRHO was found to have the shortest maximum Earth-GPS continual outage period (ECOP) of only 420 s. Even with lower Earth-GPS measurement update rates with sampling periods of up to 30 min, a low lunar UERE of 30 m may be achieved using low-SWaP onboard clocks (such as CSAC, SRS PRS-10).

In conclusion, lower-SWaP onboard clocks and easier-to-maintain lunar orbit types can be chosen over the others to still achieve a desired lunar UERE across the entire LNSS constellation.

3.2 Lunar GNSS receivers

The accuracy and latency of conventional PVT determination methods can occasionally limit the accomplishments that can be made throughout the course of future lunar missions. The use of Earth GNSS signals for autonomous real-time navigation in the cis-lunar space has been thoroughly investigated to overcome this problem [3].

3.2.1 The LuGRE

The LuGRE payload is a partnership between NASA and Italian space agency (ASI) on the Firefly blue ghost mission 1 (BGM1), which aims to demonstrate GNSS-based location, navigation, and timing at the Moon. A low-noise amplifier, a radio frequency (RF) filter, a high-gain L-band patch antenna, and a weak-signal GNSS receiver make up the LuGRE payload. The receiver will follow the Galileo E1 and E5a signals in addition to the GPS L1 C/A and L5 signals, delivering the pseudorange, carrier phase, and Doppler data to the ground. Additionally, Kalman filters and least-squares point solutions will be used to compute navigational solutions aboard [4].

In order to achieve its ultimate objective of proving GNSS-based PNT at the Moon, LuGRE has three objectives [4]:

- 1. Receiving GNSS signals at the Moon is objective No. 1; return information and describe the GNSS signal environment on the moon.
- 2. Using GNSS data gathered at the Moon, demonstrate navigation and time estimation.
- 3. Make use of the data gathered to aid in the creation of GNSS receivers specifically designed for lunar usage.

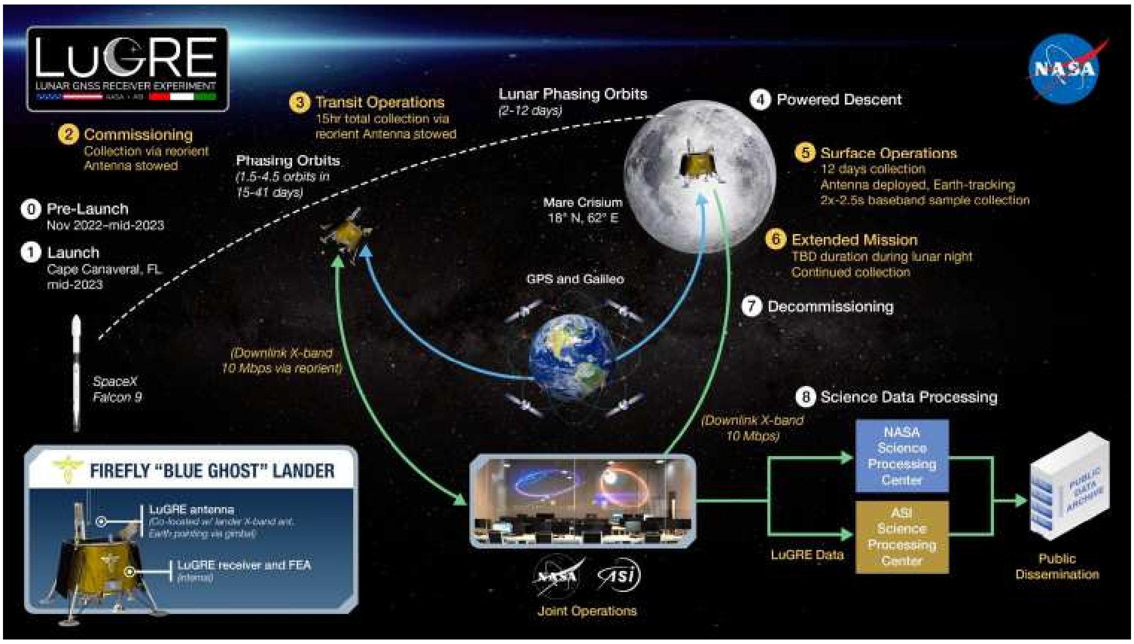


Figure 3.2: LuGRE concept of operations overview [4]

Figure 3.2 shows the LuGRE mission concept of operations and its nine unique stages.

The modern, high-altitude GNSS receiver and high-gain, Earth-pointing L-band antenna that make up the LuGRE payload are designed to capture and characterize GNSS signals both in the cislunar environment and on the lunar surface.

The Qascom QN400 GNSS Receiver serves as the brain of the payload. This tradition, together with the use of commercial and/or pre-qualified components, lowers mission risk overall and development. The payload itself weighs less than 5 kg and uses a maximum operating power of 14W. The high level payload architecture is shown in Figure 3.3 [4]:

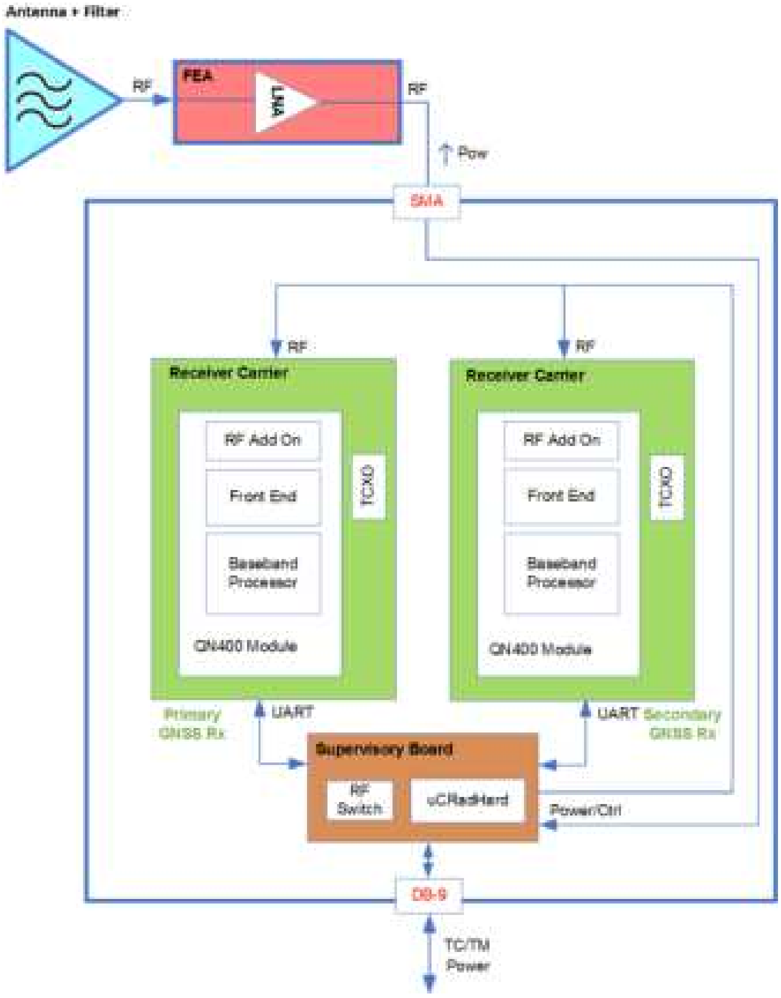


Figure 3.3: LuGRE payload high level architecture [4]

After operating for at least 15 hours during the Earth-Moon transit phase and in lunar orbit, the payload will track GNSS signals over the next 12 Earth days on the lunar surface. An average of 4 GNSS signals were visible throughout the mission, according to a preliminary review of the LuGRE activities, even on the lunar surface. An extended Kalman filter can analyze pseudorange data and converge within the allotted time during the transit operations phases, according to analysis of the transit phase [4].

3.2.2 NaviMoon

The test version of a unique satellite navigation receiver has been delivered for integration testing on the Lunar Pathfinder spacecraft. The NaviMoon receiver is designed to perform the farthest ever positioning fix from Earth, employing signals that will be millions of times fainter than those used by our smartphones or cars [17].

As part of the NAVISP program, SpacePNT created NaviMoon, an ultra-high sensitivity GNSS receiver that can track and acquire Galileo and GPS signals down to 15 dB Hz and combine the corresponding measurements with a high-fidelity dynamics model to produce previously unheard-of navigation performance (100 m RMS positioning accuracy). Embarked on SSTL's Lunar Pathfinder, NaviMoon is the key component of Phase 1 in ESA's lunar PNT implementation roadmap. NaviMoon is built to function for at least three years in lunar orbit despite being implemented on a cheap, commercial-off-the-shelf (COTS)-based hardware platform. It is also prepared to be developed into a fully space-qualified product to assist operations in lunar missions.

NaviMoon is a dual constellation (GPS + Galileo) and dual frequency (E1/L1 + L5/E5a) GNSS receiver that offers the host platform autonomous real-time PVT solutions. Because NaviMoon is primarily COTS-based, it allows for tremendous cost reductions while maintaining extremely high availability. This outcome was made possible by a highly modular architecture that is based on three pillars [3]:

- a high-performance local oscillator;
- an optimized architecture with fast digital signal processing implemented in hardware and acquisition/tracking control and navigation functions implemented in software;
- a specific microcontroller for managing, protecting, and monitoring external interfaces.

The acquisition engine is based on cutting-edge algorithms. The extended Kalman filter (EKF) architecture is used by the navigation engine to combine GNSS readings with a high-precision dynamics model in the best possible way.

The external low noise amplifier (LNA), which is just as essential to the receiving chain as the GNSS receiver, has been engineered to give high gain (> 25 dB), good interference rejection (> 60 dB), and noise figures as low as 1.4 dB, all in a relatively small enclosure.

The first hardware-in-the-loop (HWIL) test results, addressing mainly the acquisition and tracking capabilities are very encouraging, and demonstrate the capabilities of the core of the NaviMoon receiver [3].

4

GNSS-aided

In this chapter, various GNSS-aided solutions for a LCNS are presented. More in detail, we will consider solutions such as GNSS-cooperative positioning (CP) and the lunar relay satellite system, explaining their characteristics and why they could be a very useful technique.

4.1 GNSS-CP

4.1.1 Description and characteristics

The GNSS-CP solution would make use of the presence of GNSS receivers and communication links, in order to improve the performance of spacecraft navigation while implementing a non-invasive approach. As a result, the navigation sub-system's size, weight, and power would be reduced [6].

By utilizing the assistance of one or more other GNSS users who are connected to the same network, a GNSS user can improve their positioning performance. The basic idea of the proposed scheme is to obtain a relative distance measurement between GNSS users by exchanging information on their respective pseudoranges measured with respect to the trackable GNSS satellites. The estimation of the PVT solution then makes use of this relative distance [6]. In order to determine their baseline vector, a user with limited GNSS visibility can communicate raw GNSS measurements with another user (auxiliary agent) across a communication channel.

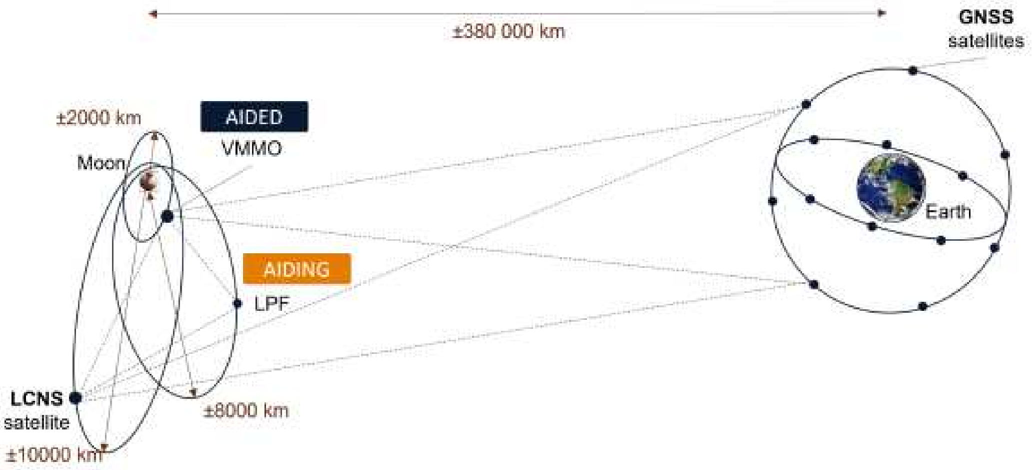


Figure 4.1: Representation of inter-spacecraft range (ISR) between lunar missions spacecrafts (Pathfinder and VMMO) exploiting current GNSS and future LCNS satellites [5]

Figure 4.1 shows a realistic lunar scenario, expected to be in space in 2024, discussed in [5]. Given its favorable conditions for GNSS visibility, the Lunar Pathfinder in its ELFO acts as the aiding agent, with the volatile and mineralogy mapping orbiter (VMMO) in its low lunar orbit acting as the aided agent. The GPS and Earth-GNSS Galileo constellations, as well as one LCNS satellite, provide navigational signals to both spacecraft. S-band data linkages between the two missions are furthermore accessible. The agent-to-agent distance between the VMMO and the Lunar Pathfinder is calculated using an algorithm, and the correctness of the baseline estimation is assessed. The increase in positioning accuracy is assessed in a second phase once integration of this inter-agent distance and the GNSS measurements obtained by VMMO have been completed.

In fact, combining GNSS data with inter-agent base vector estimations enhances the geographical distribution of resources that supports the evaluation of navigational solutions. This method's non-invasive approach is its key benefit over other GNSS augmentation options in the context of lunar missions.

4.1.2 Advantages of GNSS-CP technique

Because it would loosen the requirements for the creation of specialized lunar navigation systems, this technique would be an excellent fit for Moon exploration given the large number of missions anticipated in the coming years [5]. The findings in [6] have demonstrated that GNSS-CP can actually bring significant value to this new space era, despite the many differences between terrestrial applications and space applications, including faster dynamics, lower GNSS signal power level, and worsened geometry. Particularly, it has been demonstrated that the geometrical circumstances involved in computing the user's position are significantly improved by using nearby spacecraft as additional navigation aids in addition to Earth GNSS and future LCNS.

The two major advantages of the proposed technique lie in that:

- it is non-invasive, which is particularly desirable in space to make missions light and allow them to concentrate on their essential operations,
- the fact that the cooperative users do not need to be in line-of-sight to help one another.

4.2 Lunar relay satellite system

4.2.1 Description and characteristics

To handle communication and navigational needs and guarantee resilience for the range of prospective robotic and human exploration missions to the Moon, a system of lunar relay satellites has been proposed in [7]. To enable the system to deliver in-situ navigation services to missions in the lunar and cis-lunar environment, the relays are designed to estimate self position and time knowledge onboard. The navigational performance of the relay itself has a significant impact on the precision and quality of those services.

To assess the lunar relay navigation performance, a series of orbit determination (OD) Monte Carlo (MC) simulations are run using lunar gravity modeling and a variety of onboard clocks and measurement types including weak-signal GNSS, ground network (GN) pseudorange and Doppler, and optical navigation (OpNav) center-finding (CF). The estimated trajectories produced by these lunar relay MC simulations, along with the associated errors, and transmitted navigation reference signal parameters, are used to evaluate the expected navigation performance of a user on a descent trajectory to the lunar surface.

The scenario involves a lander system that uses one-way range and Doppler measurements from reference signals sent by the lunar relay for onboard navigation.

The Goddard enhanced onboard navigation system (GEONS) flight software is used to propagate the trajectory and covariance, simulate and process measurements, and perform state and covariance updates. GEONS ground MATLAB simulator (GGMS) utilizes a truth spacecraft, which is taken from the truth trajectory or propagated from an initial state, and an estimated spacecraft whose state is updated at each measurement update using the EKF.

The errors reported by the GGMS are given by the difference between the estimated and truth spacecraft trajectories [7].

4.2.2 Weak-signal GPS tracking

Although it was initially intended for use on Earth and in low Earth orbit (LEO), GPS-based space navigation is now applicable to users at considerably greater altitudes. Missions like MMS have shown that weak signal GPS monitoring is effective at distances up to 29.34 Earth radius (RE), or 50% of lunar distance. Although the LuGRE mission will soon use GPS data at the Moon, the GGMS models are not yet informed by mission data utilizing GPS at lunar distances. This is why the GGMS extends GPS modeling to lunar distances by including MMS flight data to predict how the GPS signal degrades based on distance [7].

4.2.3 Findings on navigation performance

The study conducted in [7] found that the choice of onboard clock and measurement observables used on a potential lunar relay has a large impact on the spacecraft state and clock errors and the accuracy of measurements provided to users.

The ultra-stable oscillator (USO) clock inaccuracies can increase significantly, especially during GN and GPS measurements outages, even if the spacecraft state errors are only 2-3 times larger utilizing an onboard USO instead of RAFS. It has been demonstrated that including OpNav CF measurements during GPS outages is enough to retain spacecraft state information using both the RAFS and USO clocks, but it is insufficient to estimate clock error.

It has also been demonstrated that precision navigation performance can be achieved even during measurement outages using a mix of GPS and OpNav CF observables with a RAFS clock.

Additionally, it was shown that, as predicted, the relay state and clock errors have a direct effect on the navigation for a lunar lander using lunar navigation nodes (LNN) (spacecraft providing navigation services in lunar orbit) reference signal pseudorange and Doppler measurements.

The choice of the relay onboard clock was proven to have a significant degrading effect when used as the single measurement observable, however when paired with terrain relative navigation (TRN) and GN measurements, the LNN reference signal measurements significantly increase descent performance regardless of the relay onboard clock.

A RAFS type clock is recommended for the relay in order to optimize its potential as a supplement and alternative to TRN measurements, although a relay with a USO clock could still produce relevant measurements [7].

5

Lunar-only

Within this chapter we look for technologies that would allow an Earth-independent LCNS and therefore do not refer to GNSS, such as GPS.

A worldwide navigation and communication system for the Moon is still lacking despite the multitude of missions that are being planned. Because of this, each mission is now designing its own unique solution for DTE communication and/or data relay transmission and Earth-ranging based navigation; this duplication is intrinsically wasteful and results in complicated and expensive solutions for each mission.

Utilizing a shared navigation and communications system would simplify the design of individual missions, make their payload lighter, allow for the carriage of more scientific equipment, and increase the cost-effectiveness of each mission [18].

Despite being a crucial technology, GNSS signals from the Earth constellations can only reach the near-side of the Moon or, more generally, the regions in cislunar space that are not blocked by the Moon.

Additionally, Earth GNSS signals by themselves are insufficient due to the precision and availability needed to enable autonomous landing and rover navigation. The existing navigation strategy for these missions depends on a variety of sensors and communication with Earth operating teams, which restricts the autonomy of the on-board systems and invariably introduces delay for even the simplest movement between nearby places. Then, a specialised lunar navigation system might considerably enhance present methods. This would improve user position accuracy globally, enable moon navigation in regions without DTE visibility, and increase service accessibility in general [8].

5.1 PNT requirements

There are numerous sources that provide different recommendations and suggestions for PNT requirements for an eventual lunar PNT system. The international space exploration coordination group (ISECG) has recommended that a 3-σ positioning requirement of 90 m for precision landing and 0.4 m absolute and relative positioning requirement for in-space timing and navigation autonomy be achieved. The strict requirements for absolute and relative positioning are the intended final state for an extensive PNT system, but they now require space-certified clocks that are 10-100 times more accurate than what is currently possible [19]. Whereas a NASA report suggests a number of positioning specifications, all within 3-σ, including surface operations within 30 m, precision landing within 100 m (10 m less stringent than that by ISECG), 10 m for surface rendezvous, 100 m and 10 cm/s velocity error for any lunar constellations, and 50 km and 2 cm/s velocity error for users performing station keeping close to libration points, like the L2 Lagrange point [19].

The PNT performance requirements used in section 5.3 are:

- 1 kilometer 1-σ in position, and
- 1 microsecond 1-σ in time.

These are the same as those employed by the ARTEMIS mission, and they are probably sufficient for many applications involving space domain awareness [9].

5.2 Lunar PNT beacon

The lunar augmentations systems proposed by Schönfeldt et al. [8] include additional satellites in lunar orbits and static ranging beacons on the lunar surface.

In order to attain adequate South Pole coverage, ELFOs are of great interest and have been the focus of various prior internal ESA studies. Due to their excellent stability and low station holding requirements, frozen orbits are ideal for lunar radio navigation systems.

Satellites orbiting the moon provide placement on a greater volume, although ranging beacons are the most direct method for location in a specific area. One significant benefit of employing a beacon over satellites is that the position of the beacon only has to be established seldom, whereas satellites in lunar orbits require continual precise orbit determination (POD).

The lunar navigation system might be supported by the beacon in transmitting range signals timed to the primary lunar navigation system (LNS) orbiters. It could also serve as a reference point for LNS orbiters, enable local differential lunar surface navigation services, and give lunar users access to Earth GNSS navigation data to make it easier for them to use Earth GNSS signals. Finally, the beacon could serve as a co-location point for various selenodetic methods, including transmitters compatible with very long baseline interferometry (VLBI) and laser retroreflectors, and Earth GNSS receivers, all of which might open up new and intriguing scientific possibilities.

Based on findings in [8], it seems sensible and realistic to gradually deploy a lunar navigation system, which would allow the weight of GNSS satellites in the final PNT solution to be continuously decreased as the size of the lunar constellation is expanded. While a GNSS-only solution (such as phase 1 of the lunar navigation roadmap 2.3) can satisfy the PNT requirements for users of lunar orbit and Earth-to-moon transfers, this is insufficient for users of lunar landing and lunar surface operations, where additional ranging ”augmentations” are deemed necessary.

This can be accomplished when concentrating on the South Pole, which is the target of many missions scheduled for this decade, by combining the GNSS constellation with a straightforward lunar constellation of three satellites and the use of a lunar surface beacon (such as phase 2 of the lunar navigation roadmap 2.3). This may offer good positional dilution of precision (PDOP) values as well as excellent availability. Subsequently, this phase 2 system might be gradually updated with more lunar orbital range satellites, chosen to enhance the service accessibility at the other lunar latitudes (such as phase 3 of the lunar navigation roadmap 2.3).

If the landing and surface operations are carried out during specific times when there are enough ranging sources available, it has been demonstrated that a practical phase 3 intermediate solution consisting of four ELFO-South satellites and an additional ranging source located on the Gateway station could already provide a potential autonomous lunar navigation system from the South Pole up to the lunar equator.

The possible setup outlined might provide a full, autonomous moon PNT surface service with excellent PNT solutions being accessible 40% to 100% of the time thanks to 12 lunar orbital ranging sources. With this potential architecture, PNT availabilities would be more than 80% for all lunar surface locations if local ranging beacons were added at the expected landing sites [8].

5.3 LIGHTHOUSES

Another PNT architecture proposal is the one presented by Mitch et al. [9], which offers practical performance at a SWaP level that is appropriate for most spacecraft and is independent of the GPS.

The first key trade examines several alternatives for a space-based augmentation of the ground transmitter system while taking into account the loss of precision that a user spacecraft will encounter in cislunar space. The second trade takes into account how to serve the volume surrounding each ground transmitter as well as the volume of cislunar space that the architecture must service. The third trade takes into account how the network's ground transmitters are coordinated to maximize user performance. These trades create a foundational set of criteria that characterize the design.

The architecture has three primary building blocks: Lighthouses, Sextants, and Sub Sats. In this architecture, the lighthouses serve as the main source of radio navigation signals. There would be many lighthouses (ten to sixty) scattered all over the planet, with a variety of different geometries. These stations have transmitters oriented in the direction of their intended Cislunar operating zones, and they might even sweep their signals through the Cislunar volume like a classical lighthouse. The Sextant satellites add their own signal to the Lighthouse signal laydown. The main advantage of the Sextants satellites is that they can be located far farther away from the Earth and even at cislunar distances like L-points than the Earth-based Lighthouses. The Sub Sats, or Submarine Satellites, are the end users of the PNT information. The need for autonomous functioning without transmissions sets them apart from conventional Cislunar spacecraft.

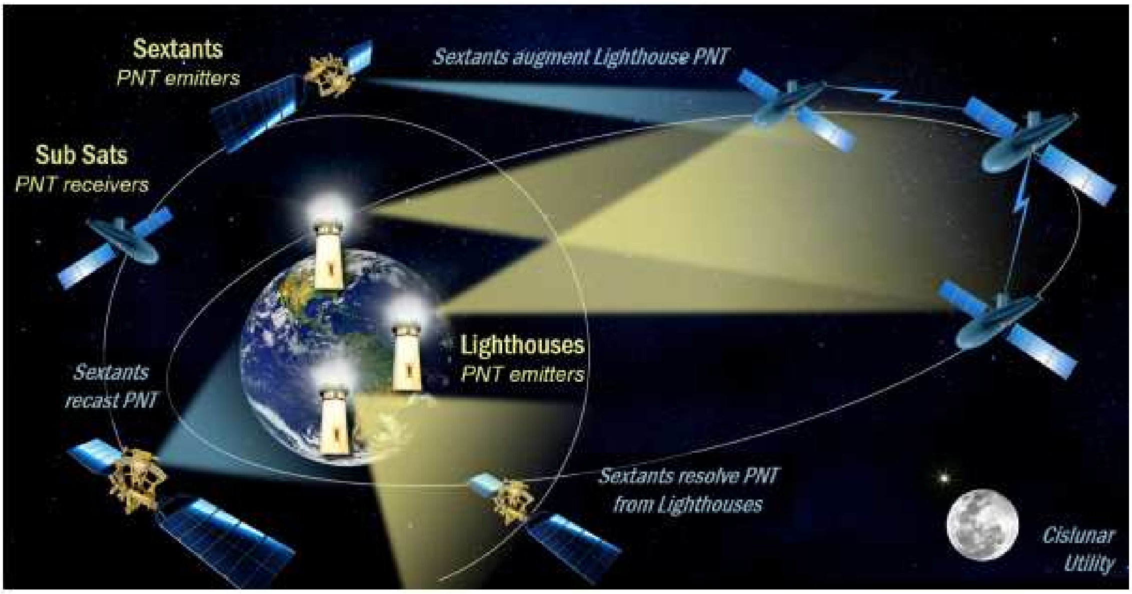


Figure 5.1: Lighthouses architecture operational view [9]

A DOP study was carried out for the Cislunar plane and the Cislunar PNT service volume. It was demonstrated that even a single satellite orbiting distant from Earth, such Earth-Moon L4 or L5, provides a significant performance boost. By taking into account techniques to time-multiplex the coverage of the Cislunar volume, it was possible to lower the overall resources used by each Lighthouse. This led to the conclusion that any time-multiplexing technique would require coordination of all Lighthouses to achieve a meaningful improvement in the user satellite's navigation performance; otherwise, the oscillator drift of the user satellite would impair the navigation performance.

It was then discovered that if the mission is able to filter its PNT signals for several hours or a day, several of the missions could meet the theoretical Cislunar PNT requirements of 1 km 1-σ in location and 1 us 1-σ in time, as discussed in 5.1. A single satellite enhancing the Lighthouses design enhances the performance sufficiently to satisfy these far more demanding requirements for missions that need faster convergence and/or better accuracy, such as 100 m 1-σ over a day or 1 km 1-σ over tens of minutes [9].

5.4 Stellar Navigation

In order to travel through lunar space, a further proposal was made by Critchley-Marrows et al. [10], which investigates the idea of a stellar-based positioning system that uses stars as GNSS beacons. Their research shows how a star and Moon sensor might achieve the majority of requirements for lunar missions, which demand accuracies at a 100-1000 m margin. The proposed technology might potentially assist and serve as a supplement to the currently planned RF-based lunar navigation infrastructure.

During and after Apollo, ideas for estimating a position and orbit using stars emerged.

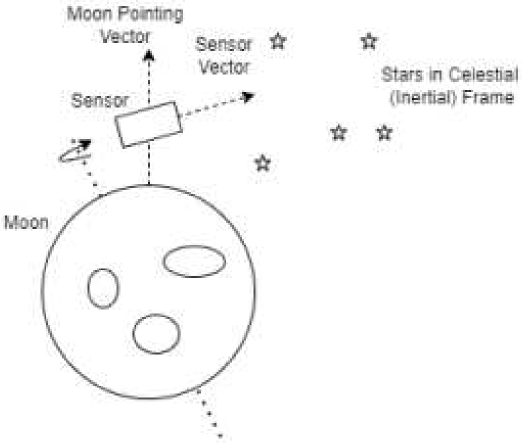


Figure 5.2: Navigation sensor illustrating the Moon-pointing and sensor vector [10]

The navigation system for the Moon using stellar sources would rely on two core components, the star sensor and the Moon sensor. The two parts are complementary to one another. The star sensor calculates star positions from a known celestial frame, which is inertial from the perspective of the lunar user. It is thought to be an acceptable assumption to take the origin in a lunar-centered inertial (LCI) frame for the level of fidelity required of the navigation system for astrometric missions that determine star locations. However, this coordinate system does not know the location of the Earth's core because stars can only be represented by unit vectors. This is taken into consideration by the Moon sensor, which establishes the Moon's local position in relation to the sensor array. This frame is known as the local geocentric, local vertical (LGCV). The horizon, gravitational field, or the Sun/Earth positions could be used because this system needs to determine the location of the lunar surface body [10].

5.4.1 Potential navigation performance

The potential accuracy of the lunar camera would be primarily affected by the ability to discern the Moon from the blackness of space and the precision to which the lunar geometrical shape might be measured. To determine a position, the Moon sensor analyzes what is known as the Moon-pointing vector. The Moon-centered, Moon-fixed (MCMF) frame may then be used to determine the known position in terms of a longitude and latitude.

The results for varying the pointing accuracy are illustrated in Figure 5.3. The performance is achieved at the 30 m level with a precision of pointing at 0.01°, assuming the star sensor accuracy to be 0.01°, which is typical to most star systems. Twenty stars, distributed randomly across the image plane, make up the field of view. Figure 5.4 provides a summary of the findings while also changing the star tracker field of view.

By taking measurements of the surrounding factors, such as the gravitational field or lunar limb/horizon, the moon's pointing vector is created. In order to evaluate if it is feasible to attain the requisite pointing precision of 0.01°, models are created and examined to consider each of these strategies. By doing this, it will draw attention to the sensor's usefulness for lunar users. To simplify integration to current and future lunar systems, parameters characteristic of COTS components are considered.

After a series of examinations on celestial, flat horizon and gravity sensors, it was found that the system's expected accuracy satisfies user needs in the majority of mission phases, from transfer orbit to surface operations. Accuracies in the decameter range may be achieved by the sensor suite. The system may also serve to support and supplement the planned lunar infrastructure for navigation [10].

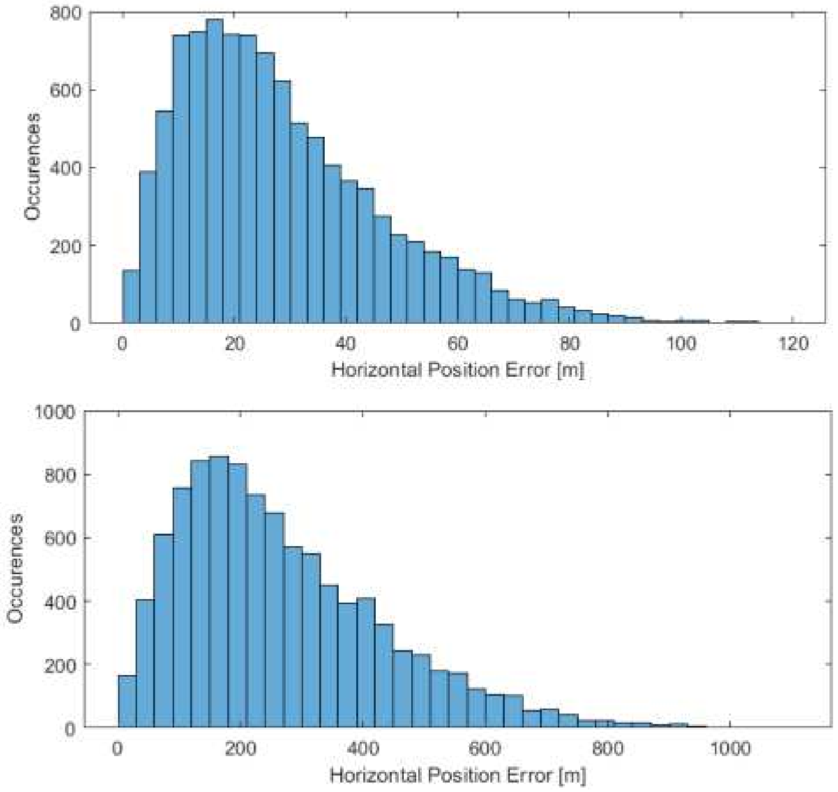
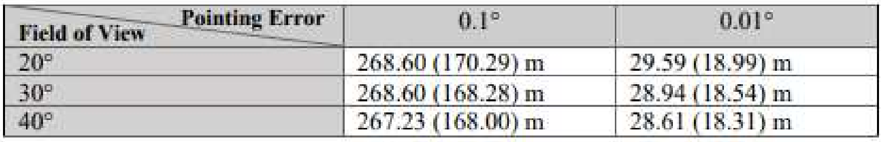


Figure 5.3: Horizontal position error with varying pointing error σ_q (0.01° on the top and 0.1° on the bottom). The FOV is set to 40° [10]



Pointing Error Field of View	0.1°	0.01°
20°	268.60 (170.29) m	29.59 (18.99) m
30°	268.60 (168.28) m	28.94 (18.54) m
40°	267.23 (168.00) m	28.61 (18.31) m

Figure 5.4: Estimated horizontal accuracies of the star tracker and Moon pointing assembly, according to star tracker field of view and Moon pointing error. The performances are reported as the mean (standard deviation) of the error [10]

6

Conclusion

In conclusion, this thesis has provided a comprehensive examination of the perspectives and challenges of the LCNS. Through the analysis of existing research and the exploration of potential future advancements, it has become evident that LCNS is a critical component for the successful exploration and colonization of the Moon. The results emphasized the significance of dependable and effective communication and navigation skills to support diverse lunar operations and facilitate lunar missions.

The study found that to guarantee the LCNS's maximum performance, a number of significant challenges must be solved. Developing adaptive and resilient communication protocols that can withstand the harsh lunar environment is one of these challenges, as is creating reliable and redundant communication links, mitigating signal propagation problems brought on by the lunar terrain, addressing potential signal interference, and so on. The precision and effectiveness of navigation systems on the Moon will also need to be improved, and this will need advancements in autonomous navigation methods and lunar mapping algorithms.

Even though LCNS technology and research have advanced significantly, there are still a number of potential areas that have not yet been thoroughly investigated. These areas could offer promising opportunities that might have a big influence on lunar exploration and colonization efforts:

- Quantum communication for lunar missions: examining the possibility for ultra-secure and quick data transport between lunar bases and Earth via quantum communication. Lunar communication might undergo a revolution thanks to the use of quantum entanglement principles, which would provide unmatched security and transmission rates [20].

- Optical communication for lunar navigation: investigating the use of optical communication for data transfer on the Moon. Optical links could offer higher data rates and lower power consumption compared to traditional radio frequency-based communication [21].
- Deep learning-based navigation: investigating how to improve lunar navigation systems using deep learning techniques. For lunar rovers and landers, combining machine learning and computer vision techniques may enhance accurate localization and real-time obstacle avoidance [22].

These fields of study have the potential to transform the capabilities of lunar communication and navigation, bringing in a new era of lunar exploration and opening the door for future projects like resource extraction, lunar habitats, and eventually human settlement on the Moon. Collaboration between scientists, engineers, and space agencies from all around the world will be necessary to meet these obstacles and investigate the unexplored potential of space.

In conclusion, LCNS has a bright future, and the success of lunar missions will surely be greatly influenced by tackling the aforementioned undiscovered issues. Continued advancements in LCNS research and development will be essential for realizing the full promise of lunar exploration and laying the foundations for a new age of space travel as mankind sets its eyes on the Moon and beyond.

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