Analysis of Moon Navigation Considering Earth GNSS Signals and LCNS Constellation

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***Abstract*—Lunar missions are increasing with the objective of establishing a sustainable human presence. This paper studies the feasibility of using weak Earth GNSS signals and a potential Lunar GNSS constellation for Moon navigation, focusing on the receiver C/N0 and proposing different alternatives for LGNSS constellation design.**

***Keywords*—GNSS, LCNS, GPS, Galileo, LMS, LinkBudget**

I. Introduction

More than 50 years after the Apollo program, we are entering a "second Space Race," seeking to not only return humans to the Moon, but also to establish a sustainable human presence. With signicant increases expected in crewed and robotic activities, future lunar missions will require reliable and precise Position, Navigation, and Timing (PNT) services everywhere on the Moon.

NASA recently introduced a concept called Cislunar Autonomous Positioning System (CAPS), with the objective of providing autonomous navigation services in cislunar space. CAPS would use inter-satellite link range and range-rate measurements between cooperating satellites to provide absolute inertial and relative positioning. [1]

The European Space Agency Lunar Communication and Navigation Service (LCNS) is aimed to provide communication and navigation services for a wide range of institutional and commercial Moon missions. The idea is to use the most recent GNSS satellite technology to implement a one-way broadcast solution, while keeping the possibility to supply an additional two-way navigation service. The current idea is to have 5 satellites, orbiting in Elliptical Lunar Frozen Orbits (ELFOs), distributed in 3 different planes. [1]

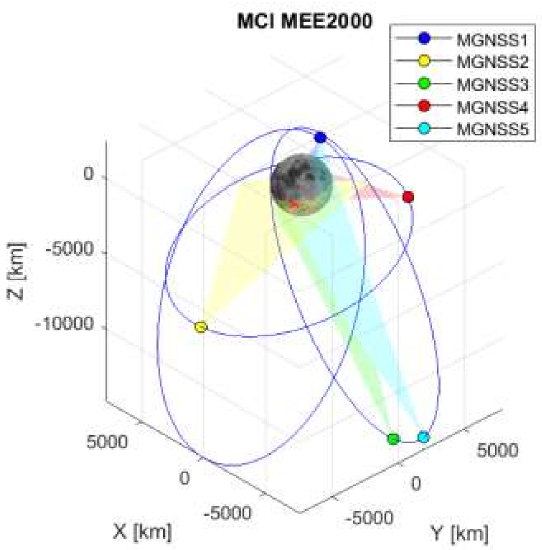

Fig. 1. LCNS satellites [1]

Referring to LCNS, currently only three out of the five LCNS satellites are utilized, in order to target the horizontal positioning of a lunar rover in the proximity of the South Pole [1]. A formal horizontal precision in the order of tens of meters is achieved when the horizontal dilution of precision is around or below 10 and three LCNS satellites are in view [2]. In another studio, the estimation performed is kinematic, which implies that the navigation solution is competitive only when good visibility and DOP are achievable and the navigation error quickly diverges from the best achievable value of around 30 meters [3].

This paper will try to analyze Earth GNSS and potential LCNS signals, focusing on signal in space and receiver acquisition and demodulation of the signal. In addition, Earth and Moon scenarios will be compared to analyze the feasibility of the designing of LCNS.

This paper is structured as follows: after this introduction, Earth GNSS and LCNS signal scenario will be studied and some simulations will be done in order to see the feasibility of this solution. Finally, resulting conclusions will be analyzed.

II. Earth GNSS Signals

When mentioning Earth GNSS signals in other studios, only two constellations where considered: NASA's GPS and ESA's Galileo.

A. GPS

Global Positioning System or GPS is a United States space-based radionavigation system that helps pinpoint a three-dimensional position to about a meter of accuracy and provide nano-second precise time anywhere on Earth. GPS is comprised of three different parts, but in this studio the only one needed in the space segment [4].

GPS is composed by a constellation of at least 24 US government satellites distributed in six orbital planes inclined 55° from the equator in a Medium Earth Orbit (MEO) at about 20,200 kilometers (12,550 miles) and circling the Earth every 12 hours. GPS signals can be transmitted on 3 different bands [4]:

- GPS L1 Band (Navigation Service): 1575.42 MHz with a bandwidth of 15.345 MHz
- GPS L2 Band (Commercial Service): 1227.6 MHz with a bandwidth of 11 MHz
- GPS L5 Band (Modern Services): 1176.45 MHz with a bandwidth of 12.5 MHz

For our study we will only consider L1 Band (Navigation Service). The L1 signals are transmitted with enough power to ensure the minimum received signal power level of -158.5 dBW [4]. If we apply a margin of 7 dB, then:

$$p_{rx,EGNSS-GPS} > -158.5\ dB \tag{1}$$

Spread spectrum techniques are applied to L1 signal, which is modulated with a QPSK constellation. The resulting signal follows the equation [7]:

$$s_{L1}(t) = \sqrt{2P_x}D(t)x(t)\cos(2\pi f_{L1}t + \theta_{L1}) + \sqrt{2P_y}D(t)y(t)\sin(2\pi f_{L1}t + \theta_{L1}) \quad (2)$$

where P_x, P_y are powers of different signal components, D(t), x(t) and y(t) are D code, C/A code and P code of satellite respectively, f_{L1} is the frequency of carrier wave, and θ_{L1} is the initial phase.

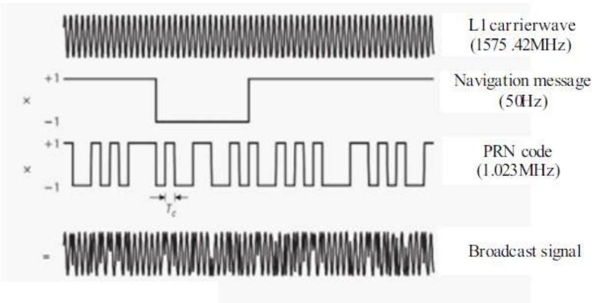

Fig. 2. The spread spectrum and modulation for GPS L1 signal [7]

B. Galileo

Galileo is Europe's own global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. Currently providing Initial Services, Galileo is interoperable with GPS and Glonass, the US and Russian global satellite navigation systems. By offering dual frequencies as standard, Galileo is set to deliver real-time positioning accuracy down to the metre range [5].

The current Galileo system consists of 26 satellites in all. All but two of these are positioned in three circular Medium Earth Orbit (MEO) planes at 23,222 km altitude above the Earth, and at an inclination of the orbital planes of 56 degrees to the equator. The remaining pair were placed in incorrect orbits by a Soyuz launcher error and are currently employed for search and rescue but not as operational members of the constellation. Galileo signals can be transmitted on 3 different bands [5]:

- Galileo E1 Band (Open Service): 1575.42 MHz with a bandwidth of 24.552 MHz
- Galileo E5 Band: 1191.795 MHz with a bandwidth of 51.15 MHz
- Galileo E5a Band (Aeronautics Service): 1176.45 MHz with a bandwidth of 20.46 MHz
- Galileo E5b Band (Safety of Life Service): 1270.14 MHz with a bandwidth of 20.46 MHz
- Galileo E6 Band (Commercial Service): 1278.75 MHz with a bandwidth of 40.92 MHz

The transmitted signals are Right-Hand Circularly Polarised (RHCP)

For our study we will only consider E1 band (Open Service). It is divided in two signals, E1b which contains the data and E1c which is a pilot. It is modulated with CBOC modulation, a particular case of the CBCS Modulation. The CBCS modulation (Composite Binary Coded Symbols) is the result of superposing BOC(1,1) and a BCS (Binary Coded Symbol) waveform with the same chip rate [6].

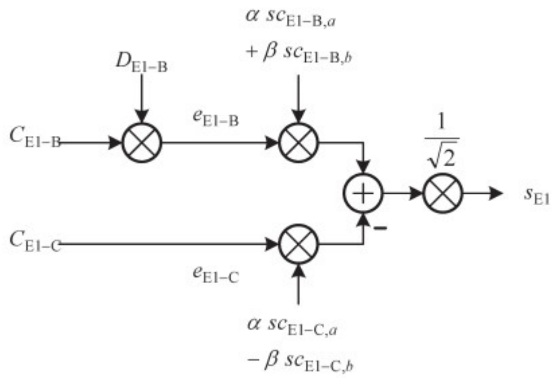

Fig. 3. Modulation Scheme for the E1 CBOC Signal [6]

The E1-B/C composite signal is then generated according to the following equation [6]:

$$s_{E1}(t) = \frac{1}{\sqrt{2}}\Big(\alpha sc_{E1-B,a}(t) + \beta sc_{E1-B,b}(t)\Big) - e_{E1-c}(t)(\alpha sc_{Ei-c,a}(t) + \beta sc_{E1-C,b}(t))) \quad (3)$$

$$\text{with } sc_x(t) = sgn(\sin\big(2\pi R_{s,x}t\big))$$

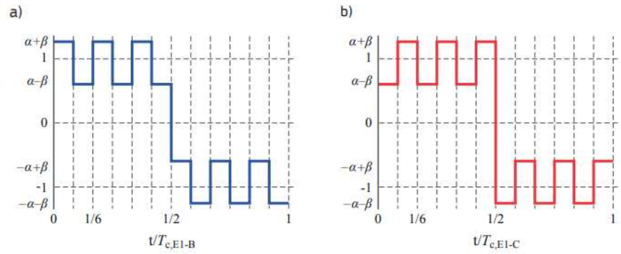

Fig. 4. One period of the CBOC sub-carrier for a) the E1-B signal component, and b) the E1-C signal component [6]

For Earth applications, the Galileo satellites provide Galileo E5, E6 and E1 signal strengths that meet the minimum levels of received power on ground for user elevation angles above 5 degrees. The minimum received power on ground is measured at the output of an ideally matched RHCP 0 dBi user receiving antenna. Assuming the same receiving antenna, the Galileo terrestrial user's received signal power is not expected to exceed the maximum levels.

Signal	Signal Component	Total Received Minimum Power (dBW)	Total Received Maximum Power (dBW)
E5	E5a (total I+Q) (50/50% I/Q power sharing)	-155.25	-150
	E5b (total I+Q) (50/50% I/Q power sharing)	-155.25	-150
E6	E6-B/C (total B+C) (50/50% E6-B/E6-C power sharing)	-155.25	-150
E1	E1-B/C (total B+C) (50/50% E1-B/E1-C power sharing)	-157.25	-152

Fig. 5. Minimum and Maximum Received Power Levels on Ground [6]

EUSPA recommends a dynamic range of up to 7 dB above the corresponding minimum power levels for the receiver, so the minimum received signal's power should be [6]:

$$p_{rx,EGNSS-Galileo} > -150.25\, dB \quad (4)$$

Finally, EUSPA estimates additional losses due to receiver filtering E1 Band and correlation [6]:

$$L_{rx-filtering,E1} = 0.1\ dB \quad (5)$$

$$L_{rx-correlatio} = 0.6\ dB$$

C. LMS Channel

Finally, for channel estimation two models have been studied in previous studies, AWGN and LMS (Land Mobile Satellite). Focusing on LMS, in [8] some measurements were performed to analyze its behavior for wideband conditions.

The campaigns were performed in the L-band at 1820 MHz. A measurement system has been set up with a transmitter part simulated by aircraft and a mobile receiver (handheld or car terminal). The aircraft transmitted a spread spectrum[signal using a pseudonoise bit sequence with a bandwidth of 30 MHz. The channel behaviour can be described by the time delay system function h(t, T) with the echo delay and the time t denoting the time-variant channel [8].

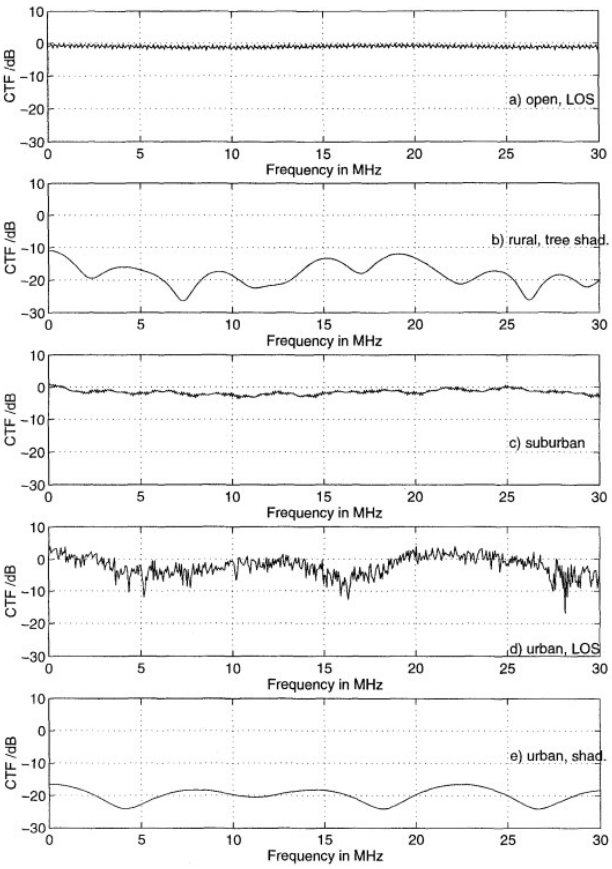

Fig. 6. Channel Transfer Function for different environments

The wideband channel model for LMS services starts from a physical background: a signal is transmitted in many directions. Different reflectors R, cause echoes with a round-trip detour Δs, and a delay $\Delta T_k = \Delta s_k/co$ with respect to the ropagate,ion delay of an undisturbed signal. The parameters of the channel vary depending on the characteristics of the echos (they can be in direct path, near or far with the receiver) [8].

Doppler shift was considered too, resulting on a classical Rayleigh Doppler model [8]:

$$S_D(f_D) = \frac{2\sigma_m^2}{\pi f_{D,max}\sqrt{1-(\frac{f_D - f_{D,Sat}}{f_{D,max}})^2}} \quad (6)$$

where $f_{D,max}$ is related to the speed v_m, of the mobile terminal: $f_{D,max} = \frac{v_m}{\lambda}$ and $f_{D,Sat}$ is the shift of the Doppler spectrum due to the satellite movement v_{sat} relative to the earth surface $f_{D,Sat} = \frac{v_{Sat}}{\lambda}$

For LOS conditions, the Doppler spectrum of the direct paths is Ricean [8]:

$$S_D(f_D) = \frac{1/c}{\pi f_{D,max}\sqrt{1-(\frac{f_D - f_{D,Sat}}{f_{D,max}})^2}} + \delta(f_D - f_{D,Sat}) \quad (7)$$

In our study, multipath and echoes are considered as negligible, so this channel model is considered just because of its characterization of the Doppler shift caused by the satellite velocity.

Finally, we will apply simulations performed in [9] to our study, concluding that we need the following values:

$$\frac{C}{N_{0_{L1}}} > 60.2\ dBHz \qquad \frac{C}{N_{0_{E1}}} > 42.8\ dBHz \quad (8)$$

	Demodulation threshold @ CED error rate = 10^{-2}					
	GPS				Galileo	
	L1 C/A	L2C	L5	L1C	E1 OS/E5b	E5a
Message	NAV	CNAV	CNAV	CNAV-2	I/NAV	F/NAV
Total required C/N_0 [dBHz]	60.2	38.5	42.9	33.8	42.8	32.7

Fig. 7. Data demodulation performance of GPS and Galileo signals in LMS channel [9]

III. LCNS Signals

Lunar constellation will have some differences compared to Earth GNSS constellations. One of them is their Emitted Isotropic Radiated Power (EIRP), which will be lower than GNSS's one, as will suffer less path losses (some elements do not affect to Lunar navigation, such as troposphere and ionosphere delays or multipath). This will allow to reduce satellite's size, weight and power. There has been an emerging interest in the use of a SmallSat platform for the lunar satellite constellation to allow for cost-e ectiveness and rapid deployment.

Designing a SmallSat-based LNSS involves unique challenges as compared to legacy Earth-GPS, leading to additional design limitations, including [10]:

- Limited size of LNSS satellites. A SmallSat platform limits its payload capacity, including the size, weight and power (SWaP) of the onboard clock. Given that lower SWaP clocks tend to have worse timing stabilities, the SWaP limitation of the clock directly a ects the ranging accuracy of transmitted navigation signals.

- Limited ability to monitor LNSS satellites. Given that a limited number of ground monitoring stations can be established on the Moon and that resources on Earth for monitoring the lunar constellation are limited, it is desirable for LNSS satellites to require less maintenance, including fewer stationkeeping maneuvers and clock correction maintenance

- Increased orbital perturbations in lunar environment. Because the Moon has a highly non-uniform distribution of mass, its gravitation field is more anisotropic than Earth's. In addition, Earth's gravity can signi- cantly impact satellites in high-altitude orbits around the Moon, thereby limiting the set of feasible and stable lunar orbits.

As modelling channel LMS will be considered, due to LCNSS signal has the same conditions as Earth GNSS signals propagating to the Moon. Moreover, minimum power level will be considered the same as for Galileo signals:

$$p_{rx,LCNS} > -150.25\ dB \tag{9}$$

A. LCNS Orbits Scenario

Several types of lunar orbits that have previously been investigated include low lunar orbit (LLO), prograde circular orbit (PCO), near-rectilinear halo orbit (NRHO), and elliptical lunar frozen orbit (ELFO) [10]:

- ELFOs refer to a specific category of frozen orbits providing a greater coverage of the lunar poles, wherein the term frozen indicates that these orbits maintain nearly constant orbital parameters for extensive periods of time, without requiring station keeping.
- Although PCOs are not frozen, they maintain multi-year stability with orbital parameters exhibiting predictable, repeatable behavior.
- Due to their low orbiting altitude, LLOs have shorter orbital periods around the Moon, and there exist a few inclinations in which LLOs are also considered to be frozen or quasi-frozen.
- While NRHOs are less stable than the above orbits, thereby requiring more frequent station keeping maneuvers, these orbits are highly elliptical with nearly constant visibility of Earth and the lunar poles.

Orbit Type	Altitude (km)	Eccentricity	Inclination (°)	Argument of Perigee (°)	RAAN (°)	Mean Anomaly (°)
ELFO	9750.5	0.7	63.5	90	0	0
LLO	100	0	28.5	0	0	0
PCO	3000	0	75	0	90	0

Fig. 8. Keplarian parameters of the three (ELFO, LLO and PCO) among the four lunar orbit types considered in our case study analysis.

In our study we have considered ELFOs satellites, as future LCNS constellation is expected to be in those orbits. As shown in Figure 1, LCNS satellites are spread to maximize the Geometric Dilution Of Precision (GDOP) on the Moon surface.

N	Orbital Parameters					
	SMA [km]	*e [-]*	*i [deg]*	*RAAN [deg]*	*Arg. Per. [deg]*	*Initial θ [deg]*
1	9750.5	0.7	63.2	0	90	0
2	9750.5	0.7	63.2	120	90	164
3	9750.5	0.7	63.2	240	90	196
4	9750.5	0.7	63.2	120	90	245
5	9750.5	0.7	63.2	240	90	184

Fig. 9. LCNS Orbital Parameter [1]

B. LCNS Proposed Modulation

In this section some assumptions will be done. Firstly, as in [1] we will fix a carrier frequency at the S-band as it would allow to re-use many of the Earth GNSS technology, while avoiding interference with them when weak GNSS signals are used in cis-lunar space [1]:

$$f_{c-\ LCNS} = 2.495\ GHz \tag{10}$$

Modulation scheme will not affect our study, but as LCNS is an ESA's project, it is reasonable to think they will choose a similar modulation than in Galileo. Specifically, maybe a CBOC or an AltBOC scheme will be used. The reasons are that they do not need spread spectrum techniques (interference cancellation is assured as the radio magnetic spectrum is almost free).

With CBOC (6,1,1/11) modulation, excellent multipath mitigation and low tracking noise is achieved. It is appropriated for pilot-only tracking. However, the traditional processing of a CBOC signal implies that a replica of the CBOC signal has to be locally generated by the receiver. As the CBOC is a linear combination of two sub-carriers, it has more than two levels. This means that the local replica has to be encoded on at least 2 bits, which implies the need for a more challenging receiver architecture. This could be detrimental to the use of this signal and it is then interesting to look at techniques that would only use local replicas encoded on 1-bit, while maintaining interesting tracking performances [11].

AltBOC is a complex signal composed of four codes multiplexed to have a constant envelope. The main lobes of the signal span over 50 MHz range that means the signal bandwidth is about thirty times larger than the current GPS signal's bandwidth and the signal uses complex modulation. However, in Galileo constellation, the intricacy of the E5 AltBOC signal is extremely challenging for the baseband signal processing. The AltBOC consist of four Pseudo-Random Noise (PRN) codes that are used for the transmission of four channels: the in-phase components carry the data and the quadrature components do not carry any data (pilot channels). The prize is the loss of power but processing the upper or lower main lobe (phase and quadrature respectively) would make no difference since both are modulated with the same PRN code [12].

IV. LinkBudget Computation

In this section the link budget between Earth GNSS and receiver and LCNS and receiver will be computed in order to analyze the feasibility of this solution.

The link budget will have the following expression:

$$p_{rx} = EIRP - L_{path} + G_{rx} - L_{tx} - L_{rx} \quad [dB] \tag{11}$$

The chosen path losses model is the Free Space Model (as an obstacle-free, line-of-sight path through free space is considered):

$$L_{path} = 20\log_{10} d + 20\log_{10} f + 92.45 \quad [dB] \tag{12}$$

where d is the distance between transmitter and receiver in km and f is the central frequency in GHz.

Regarding the distance we have different scenarios (considering the worst scenario where Moon is at its apogee, the point at which the moon is farthest from Earth, the distance is approximately 405,000 km):

$$d_{GPS} = 405{,}000 - 20{,}200 = 384{,}800\ [km]$$
$$d_{Galileo} = 405{,}000 - 23{,}222 = 381{,}778\ [km] \quad (13)$$
$$d_{LCNS} = 9{,}750\ [km]$$

The different central frequencies are:

$$f_{L1} = f_{E1} = 1.57542\ [\text{GHz}] \quad (14)$$
$$f_{LCNS} = 2.495\ [\text{GHz}]$$

As transmitter and receiver losses are unknown, as well as the receiver gain, so we will assume:

$$L_{tx} = 1\ dB$$
$$L_{rx,GPS} = 1\ dB$$
$$L_{rx,Gal} = 1 + L_{rx-filtering,E1} + L_{rx-correlation} = 1.7\ dB$$
$$G_{rx} = 15\ dB \quad (15)$$

With these assumptions we can compute the path losses:

$$L_{path,GPS} = 208.1026\ dB$$
$$L_{path,Gal} = 208.0341\ dB$$
$$L_{path,GPS} = 180.1715\ dB \quad (16)$$

Finally, we will compute the link budget equation with the minimum received power to find the minimum EIRP for each scenario:

$$EIRP_{min,GPS} = 41.6026\ dBW$$
$$EIRP_{min,Gal} = 50.3841\ dBW$$
$$EIRP_{min,LCNS} = 21.9215\ dBW \quad (17)$$

Considering GPS and Galileo characteristics:

$$EIRP_{GPS} = 35.51\ dBW$$
$$EIRP_{Gal} = 32.79\ dBW \quad (18)$$

so, although our values are higher, it is probably due to our estimations (Ltx, Lrx or Grx).

The last step is to compute the carrier to noise ratio:

$$\frac{C}{N_0} = p_{rx} + {}^{g}/_{T} - k \quad (19)$$

Assuming power values from (1) and (4) and ${}^{g}/_{T} = -11.849\ dB/K$ we obtain:

$$\frac{C}{N_{0\,GPS}} = 28.25\ dB - Hz$$
$$\frac{C}{N_{0\,Gal}} = 36.5\ dB - Hz \quad (20)$$

We can see these values are lower than required in LMS channel (8) but they are valid if we consider an AWGN channel [9], where values must be higher than 26.5 and 27.7 for L1 and E1 respectively. For LCNS, values would be similar to Earth GNSS ones if the received power is the minimum that the receiver can detect.

Considering that LMS channel was picked because the Doppler shift but it also considers multipath effect, probably increasing the received power some dB above the minimum value for receiving it we will be able to demodulate the signal.

V. Conclusion

This paper has studied the feasibility of demodulating Earth GNSS and a potential LCNS signals for Moon navigation. Also, LCNS potential orbits and modulations have been studied.

In simulations we have obtained values which are slightly above from the GPS and Galileo datasheets, but considering that we have made some pesimistic assumptions, we think that receiving and demodulating weak GNSS signals and LCNS signals in the Moon can be possible.

For future works it would be interesting to analyze the advantages and disadvantages of the potential LCNS modulations, performing simulations in order to choose the best possible option.

Finally, the obtained results from the simulations performed in this paper will probably need to be updated after a real receiver has been proven at the Moon.

References

[1] M. Mangialardo, M. M. Jurado, D. Hagan, P. Giordano, P. Zoccarato and J. Ventura-Traveset, "Autonomous Navigation For Moon Missions: A Realistic Performance Assessment, Considering Earth GNSS Signals And LCNS Constellation," 2022 10th Workshop on Satellite Navigation Technology (NAVITEC), 2022, pp. 1-11, doi: 10.1109/NAVITEC53682.2022.9847542.

[2] P. Giordano, A. Grenier, P. Zoccarato, L. Bucci, A. Cropp, R. Swinden, D. Gomez Ortero, W. El-Dali, W. Carey, L. Duvet, B. Hufenbach, F. Joly and J. Ventura-Traveset, "Moonlight navigation service - how to land on peaks of eternal light," IAC 2021 Congress Proceedings, 72nd International Astronautical Congress. https://dl.iafastro.directory/event/IAC2021/paper/64096/

[3] A. Grenier, P. Giordano, L. Bucci, A. Cropp, P. Zpccarato, R. Swinden, J. Ventura-Traveset, "Positioning and velocity performance levels for a Lunar Lander using a dedicated Lunar Communication and Navigation System," Navig. (Journal Inst. Navig. - Submitt. PEER Rev

[4] NASA, "Global Positioning System standard positioning service performance standard", April 2020, 5th edition. https://www.gps.gov/technical/ps/2020-SPS-performance-standard.pdf

[5] EUSPA, "European GNSS (Galileo). Open Service: Service Definition Document", May 2019.
https://galileognss.eu/wp-content/uploads/2020/08/Galileo-OS-SDD_v1.1.pdf

[6] EUSPA, "European GNSS (GALILEO) Open Service. Signal-In-Space Interface Control Document", January 2021. https://galileognss.eu/wp-content/uploads/2021/01/Galileo_OS_SIS_ICD_v2.0.pdf

[7] L. Zhao, S. Gao, J. Ding, and L. Guo, "Optimized FFT Algorithm and its Application to Fast GPS Signal Acquisition", in Fourier Transforms - Approach to Scientific Principles. London, United Kingdom: IntechOpen, 2011 [Online]. Available: https://www.intechopen.com/chapters/15150 doi: 10.5772/15929

[8] A. Jahn, H. Bischl and G. Heiss, "Channel characterisation for spread spectrum satellite communications," Proceedings of ISSSTA'95 International Symposium on Spread Spectrum Techniques and Applications, 1996, pp. 1221-1226 vol.3, doi: 10.1109/ISSSTA.1996.563500.

[9] M. Anghileri, M. Paonni, D. Fontaneila, and B. Eissfeller, "GNSS data message performance: A new methodology for its understanding and ideas for its improvement," Inst. Navig. Int. Tech. Meet. 2013, ITM 2013, pp. 638–650, 2013.

[10] S. Bhamidipati, T. Mina and G. Gao, "Lunar Navigation: A Case Study Analysis", Inside GNSS, vol. November/December 2022 pp. 40-47, Dec. 5, 2022 Accesed: Dec. 11, 2022. Available: https://insidegnss.com/lunar-navigation-a-case-study-analysis/

[11] O. Julien, C. Macabiau, L. Ries, J.-L. Issler, 1 - Bit processing of Composite BOC (CBOC) Signals, First CNES Workshop on Galileo Signals and Signal Processing, 12-13 October 2006, IAS (Institut Aero Spatial) Toulouse, France.

[12] Khan, S., Zhu, Y., Jawad, M., Safder, M. U., Jaffery, M. H., & Javid, S. (2021), "Analysis of the satellite navigational data in the Baseband signal processing of Galileo E5 AltBOC signal". arXiv preprint arXiv:2101.01381.