The LuGRE project: a scientific opportunity to study GNSS signals at the Moon

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Abstract

The Lunar GNSS Receiver Experiment (LuGRE) is a joint NASA-Italian Space Agency (ASI) payload on the Firefly Blue Ghost Mission 1 with the goal to demonstrate GNSS-based positioning, navigation, and timing at the Moon. When launched, LuGRE will collect GPS and Galileo measurements in transit between Earth and the Moon, in lunar orbit, and on the lunar surface, and will conduct onboard and ground-based navigation experiments using the collected data. These investigations will be based on the observation of the data collected by a custom development performed by the company Qascom, based on the Qascom QN400-Space GNSS receiver. The receiver is able to provide, PVT solutions, the GNSS raw observables obtained by the real time operation, as well as snapshots of IF digital samples collected by the RF front-end at frequencies L1/E1 and L5/E5. These data will be the input for the different science investigations, that require then the development of proper analysis tools that will be the core of the ground segment during the mission. The current work done by the science team of NASA and ASI, which is supported by a research team at Politecnico di Torino, is planning the data acquisitions during the time windows dedicated to the LuGRE payload in the checkout, transit and surface mission phases.

Keywords: GNSS, Moon, GPS, Galilleo

1. Introduction

The use of in-orbit Global Navigation Satellite Systems (GNSS) receivers has been experimentally validated within the Space Service Volume (SSV), at LEO and MEO altitudes as well as up to GEO altitudes. Latest missions, then, have unveiled GNSS performance for distances of about 150,000 km away from the Earth's surface. National Aeronautics and Space Administration (NASA)'s Magnetospheric Multiscale (MMS) mission has demonstrated the feasibility of tracking GPS signals up to such a distance. MMS has demonstrated that future space missions can rely on GNSS even at very high altitudes, even if current GNSSs were not designed for non-terrestrial use.

The study of Earth GNSS signal beyond such an altitude is still matter of research mostly based on modeling and extrapolation from the experience of using GNSS on the Earth and on lower orbits.

Cis-lunar and lunar environments are becoming increasingly attractive because their exploitation represents the step towards the exploration of Mars. In this scenario, it is necessary to have a precise knowledge about spacecraft position and of all the system elements on the Moon surface or orbiting around it. In the last years, many studies discussed the feasibility of using GNSS receivers at Moon Transfer Orbit (MTO) and lunar orbits. As an example, referring to the European Student Moon Orbiter mission, [2] analysed the possibility of using GNSS navigation for Earth-to-Moon missions. In particular, this study investigated the GPS and Galileo signal availability and the achievable C/N0 levels, during different phases of the mission, considering an acquisition threshold of 35 dB-Hz. In [3], the design of a GPS L1 C/A receiver, as proof of concept of navigation system to reach the Moon, is described. The receiver, called WeakHEO, is composed by modules which are specific for the lunar scenario, characterized by high dynamics and low power signal. By processing RF signals generated by a GNSS simulator, it has been verified that this receiver is able to perform acquisition, tracking, data synchronization and demodulation of GPS L1 C/A signals down to 15 dB-Hz. An Orbital Filter (OF) is used to aid the acquisition and tracking stages and to increase the navigation accuracy up to few hundred meters at the Moon altitude. A technology enhancement of WeakHEO has been done developing the SANAG receiver, which shown the possibility of acquiring and tracking (down to 12 dB-Hz) Galileo and BeiDou navigation signals as well. Other studies addressed the use at cis-lunar and lunar environments [7][8]. These studies demonstrated that, thanks to the evolution of the technologies and employing proper algorithmic solutions, it is possible to overcome the obstacles faced by spacecraft at high altitudes, thus extending the SSV of GNSS use. In [5], simulation results show that at the Moon altitude the carrier frequency is affected by a Doppler frequency shift up to 20 kHz and Doppler rate up to 4 Hz/s. Instead, at the beginning of the MTO, the Doppler shift reaches values up to 60 kHz, while the Doppler rate up to 65 Hz/s. Therefore, in order to make the receiver robust against these high dynamics, Doppler shifts and Doppler rates must be compensated. Once the Doppler is compensated, it is possible to apply the techniques allowing to increase the sensitivity of the acquisition stage.

The Lunar GNSS Receiver Experiment (LuGRE) is a joint NASA-Italian Space Agency (ASI) payload on the Firefly Blue Ghost Mission 1 (BGM1) which has the challenging goal of setting a new milestone in the use of Earth GNSS in space demonstrating GNSS-based positioning, navigation, and timing (PNT) at the Moon [6]. When launched in 2024, LuGRE will collect GPS and Galileo measurements in transit between Earth and the Moon, in lunar orbit, and on the lunar surface, and will conduct onboard and ground-based navigation experiments using the collected data. An overview of the mission and of the payload is provided in [9] and the main characteristics are recalled in the following sections of this paper.

In particular in this paper we focus on the ongoing work for the design and implementation of the analysis tool that will be in the ASI part of the ground segment for the implementation of the scientific investigations.

2. LuGRE mission overview

LuGRE is part of the NASA Commercial Lunar Payload Services (CLPS) program as one of ten NASA-funded payloads on its Task Order 19D, which was awarded to Firefly Aerospace, Inc. in 2021. The Firefly BGM1 will deliver these payloads to the Mare Crisium region of the Moon by 2024 and will operate on the surface for a minimum of 12 Earth days [16].

LuGRE is one of three technology development payloads on the flight, and is the only payload provided by NASA's Exploration Systems Development Mission Directorate (ESDMD). The LuGRE project is a partnership between NASA and ASI, with NASA providing the flight, the principal investigator (PI), and overall systems engineering and project management responsibilities, and ASI providing the co-PI, the payload hardware and software, and any payload-level testing and integration. Both partners will jointly operate the payload, receive and analyze the data, and disseminate products and results.

LuGRE has three top-level objectives which together meet its overall goal of demonstrating GNSS-based PNT at the Moon:

- Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
- Demonstrate navigation and time estimation using GNSS data collected at the Moon.
- Utilize collected data to support development of GNSS receivers specific to lunar use.

Programmatically, LuGRE is classified as a "do no harm" mission, and so mission success is defined solely by the requirement that the payload do no harm to the host spacecraft. Payload-level success, however, requires meeting all level 1 science requirements.

2.1 GNSS payload

The LuGRE Payload is a robust, low-mass and power efficient design that enables it to withstand the cislunar and lunar surface environments and be accommodated on the BGM1 lander. The Payload is comprised of four main components:

- A high gain antenna (HGA) optimized for GNSS L1/E1 and L5/E5a bands with filtering stage
- A front-end assembly incorporating a low noise amplifier (LNA)
- Two GNSS receivers in dual cold redundant configuration, managed by a supervisory board

The core of the flight payload is of course the GNSS receiver, which has then to be able to acquire and track both GPS L1 C/A and L5, and Galileo E1 and E5a open signals. It has to employ high performance tracking, processing and navigation algorithms that produce both instantaneous, real-time and filter navigation solutions with position, velocity and time at lunar distances

The GNSS receiver is a custom development performed by the company Qascom, based on the Qascom QN400-Space GNSS receiver. The QN400 is modular in both hardware construction and software implementation. The receiver is made of two core modules: i) a baseband processor and a ii) Radio Frequency (RF) front-end. These modules work in tandem to capture RF signals and process them digitally. The receiver utilizes software defined radio (SDR) technologies which provide a high degree of flexibility in allocation of correlation resources and configurable architectures that are customizable to the signals being processed.

The payload will receive and track GPS L1 C/A and L5, and Galileo E1 and E5a signals and produce pseudorange, carrier phase, and Doppler measurements. The receiver will perform real-time navigation and produce least-squares point solutions and onboard filter solutions. Other telemetry will include number of signals visible and tracked, dilution of precision, and carrier-to-noise-density ratio (C/N0) measurements.

One of the valuable features of the payload is also the fact that it can act as a signal sample grabber, i.e. the receiver has the capability to record short spans of raw I/Q samples, which can then be downlinked and later either replayed as input to a ground- based receiver or used for further signal processing analyses. In summary, the receiver is then able to provide:

i) positioning, velocity and Timing (PVT) solutions
ii) the GNSS raw observables obtained during real time operation,
iii) snapshots of Intermediate Frequency (IF) digital samples (I/Q samples) collected by the RF front-end at frequencies L1/E1 and L5/E5.

These data will be the input for the different science investigations, since the receiver will operate both in-flight during the spacecraft Earth-Moon transfer and on the lunar surface.

2.2 GNSS Measurements during the mission

Given the lander's helium budget, which must account for spacecraft slews for other purposes including the powered descent phase, LuGRE has been allocated 15 hours of total pointed time during the full transit phase, to include both commissioning and operational activities, and with a maximum continuous pointing duration of 1 hour. The LuGRE team has allocated these available operations time windows for the operations along the mission trajectory.

Once on the surface, LuGRE will be powered on within 3 hr of landing and will operate continuously for the full duration of the 12-day lunar surface operational period. During surface operations, and when powered during the lunar noon period, the payload will continuously track and downlink GNSS observables and navigation products.

As discussed in the following during these operational windows, the LuGRE payload is able to collect both the measured observables and also IQ samples, namely at both L1/E1 and L5/E5 carriers. Due to the limited data volume manageable in terms of storage and transfer to Earth, the duration of the snapshot of IQS is limited and it depends on the sample rate and band. These samples will then be transmitted slowly to the ground alongside ongoing observation data over the following 24 hr.

Following the baseline 12-day surface operational mission, the BGM1 lander will support an extended mission during lunar night to the extent power is available from the spacecraft batteries. It is anticipated that LuGRE will continue nominal surface operations during this period until power is lost and the payload is decommissioned in-place.

3. LuGRE scientific investigations

LuGRE is fundamentally a technology demonstration payload. Therefore, the typical Mission Science role is used to perform the core technology demonstration activities for the mission, such as characterizing the GNSS signal properties at lunar distance and performing onboard navigation demonstrations. However, the Mission Science activities may also include more conventional fundamental science activities as well, as defined by the Science Team.

The LuGRE Science Team is comprised of the two primary science teams at NASA and ASI, plus any external research partners. The NASA and ASI teams are led by the LuGRE PI and co-PI, respectively, and have primary responsibility for meeting the LuGRE science requirements listed in the Mission Overview section. Each team will lead a Science Processing Center that will receive near-real-time data from the Firefly MCC and perform validation, processing, and analysis to meet the mission science requirements and any specific investigations of interest. It is planned that research partners will be solicited as well. Partners would receive privileged data access and would process the data independently in accordance with their own investigations of interest. Such investigations could include measuring ionospheric properties at the Earth and the Moon, performing lunar regolith reflectometry, or measuring plasma total electron count in cis-lunar space. Ultimately, after an initial data processing and validation period, all LuGRE science data will be made available to the public to the greatest extent possible via an open repository. The exact mechanism for public dissemination is pending.

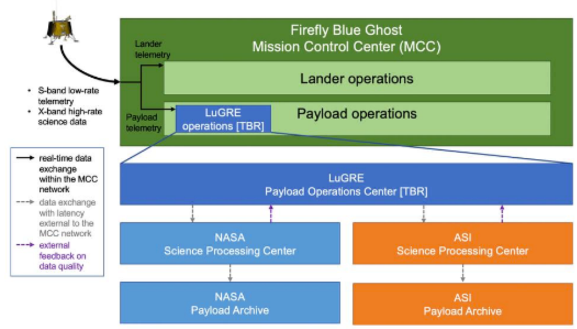

Fig. 1.   LuGRE Ground Concept of Operations

The LuGRE Science Team which is currently encompassing two different teams at NASA and ASI, has identified a set of discrete investigations that together respond to the mission objectives. Each investigation has been associated to a different priority level as driving, baseline, or best-effort, based on its criticality to meet the overall LuGRE science requirements and its relative importance and implementation complexity. A summary of the driving Science investigations is reported in Table I.

These investigations will be based on the observation of the data collected by a Driving LuGRE science investigations

Objective 1
a) Measure the signal strength throughout the mission and empirically evaluate link budget model.
b) Determine signal availability throughout the mission.
c) Measure Doppler-shift and Doppler-rate profiles throughout the mission.
d) Measure pseudorange from visible satellites during all planned operations periods.
Objective 2
a) Calculate and characterize least-squares multi-GNSS point solutions throughout the mission where sufficient signals are available.
b) Calculate and characterize Kalman filter based navigation solutions onboard throughout the mission.
c) Compare onboard navigation solutions to external sources (e.g., ground-based measurement processing, planned trajectory, Blue Ghost navigation solution).
d) Characterize position, velocity, and time uncertainty and convergence properties throughout mission.
Objective 3
a) Process GNSS observables (e.g., Doppler, pseudorange) with ground-based tools to predict achievable onboard navigation performance.
b) Calibrate ground models with LuGRE data and utilize to predict achievable navigation performance for future missions.

3. The LuGRE Analysis tool

The software analysis tool is part of the ground segment embeds different processing units able to receive as inputs both the raw observables collected by the receiver on-board during normal operation and the raw IQ samples of the GNSS signals. As depicted in Fig.1 it is basically made of three main parts:

1. A software receiver able to process the IQ samples collected in space throughout a full operational chain (acquisition, tracking, pseudorange construction and navigation solution) for GPS and Galileo in the L1/E1 and L5/E5 frequency bands. This receiver, thanks to the flexibility of the fully software implementation has a high grade of flexibility, thus allowing to configure the parameters of the baseband processing
2. A set of advanced signal processing algorithms that working on the raw IQ samples are able to analyze the signal quality
3. A set of signal processing algorithms that, based on the collected raw observables, can perform analysis tasks (e.g. multipath detection) and replicate the on-board navigation solution, or implement more complex post-processing w.r.t. what is implemented in the on-board receiver

The analysis tool will take advantage also of external sources of information (e.g. corrections, or precise ephemeris messages, and assistance data when needed).

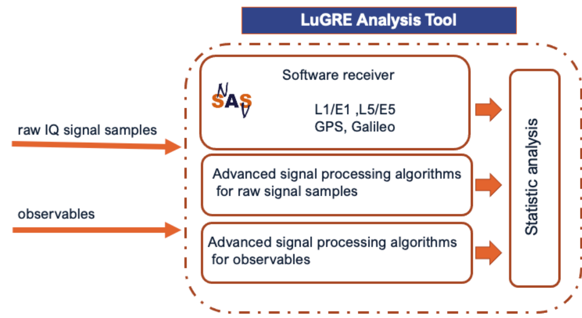

Fig. 2. Block diagram of the software analysis tool for LuGRE

A large part of the work performed by the ASI science team focuses on the post-processing of the IF raw samples that can be handled by hardware or software receivers at the mission ground segment. While limited in duration, these samples can be used to “replay” the lunar signal environment, thus enabling further investigations and characterization of the environment. This approach has been already used for critical environments with specific features that would be poorly modeled by signal simulators such as data collected by monitoring stations in Arctic and Antarctica region [15].

Furthermore, the tool includes a user interface for the analysis of results from the LuGRE mission. From the interface it is possible to load files containing data about observables, PVT solutions and true trajectory as well if it is available. The tool is also equipped with parser files to transform input data from other file types such as RINEX into standard data structures that the tool can use to analyze and plot the results. Plots of the observables data can be automatically generated from the input data and dynamically adjusted by sliding the desired time interval and using the checkbox of satellite PRNs. Similarly, also PVT solution data can be automatically plotted and dynamically adjusted using the same dedicated tab of the analysis tool. All generated plots can also be exported altogether, with multiple file formats supported.

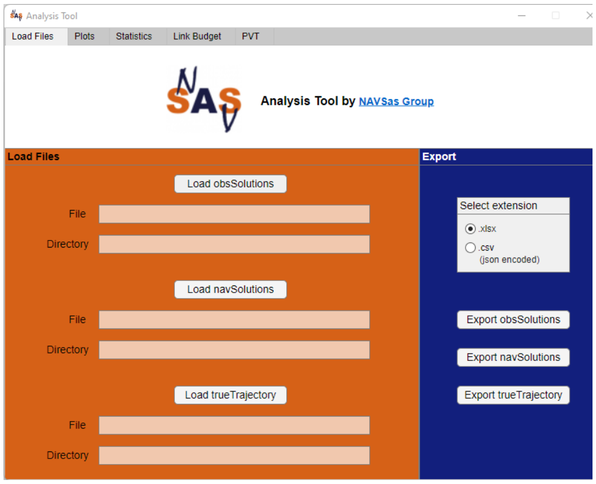

Fig. 3. User interface of the analysis tool. From the main tab it is possible to load input data.

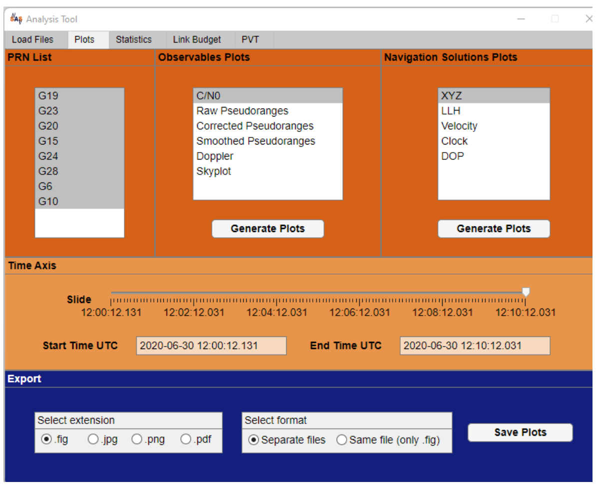

Fig. 4. Plot tab of the analysis tool interface.

If the true trajectory is available, the statistics tab of the tool can provide quantitative results as well as plots of the errors and ECDF. All these results can also be exported according to different formats.

Moreover, a dedicated PVT tab can be used to launch the software receiver with custom parameters and settings in order to perform more advanced post-processing techniques and compare the performance of different configurations.

Finally, additional tabs allow to test the different objectives of the LuGRE mission (e.g. link budget as foreseen by Objective 1a) once again with the possibility to plot and export the results.

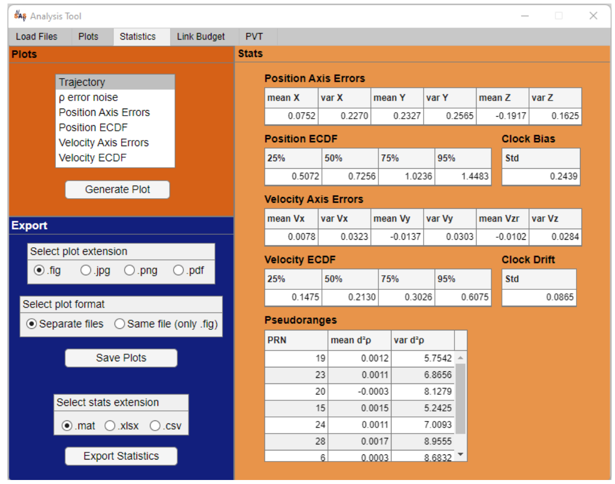

Fig. 5. Example of some results obtained through the statistics tab of the analysis tool interface.

3.1 The processing of IQS data

Storage capabilities on board are of course limited, putting severe constraints to the collection of IQ samples. Another compelling constraint is the limited downlink rate available for the telemetry and the time allocated to the LuGRE payload for the data download over the telemetry channel.

All this considered, a preliminary trade-off analysis, led to the result that the IQ collection that can be allocated matching the system constraints, will include a time window between 300 and 400 ms. Despite of the very short duration of the snapshot the collection of real samples of GNSS signals received in space environment, is still considered valuable as a mean to enable scientific investigations.

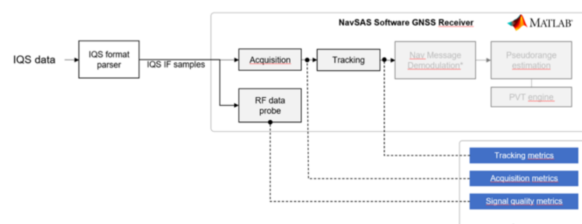

Fig. 6. Concept block diagram of the analysis tool interface for the IQS.

Figure 6 depicts the conceptual scheme of the analysis tool as far as the IQS data are concerned. It embeds a custom implementation of a muti-constellation multi-frequency GNSS software receiver developed by the team at Politecnico di Torino.

The flexibility of the tool and of the implementation of the receiver, is being used to design the collection phases for the experiments along the mission.

Exploiting simulated data of the received GNSS signals during the checkout, transit and lunar surface, the acquisition and tracking capabilities of the GPS and Galileo are being tested.
Thanks to the reconfigurability of the software implementation it can act both as a digitial-twin of the on board receiver, but it can also be seen as a post processing tool to test different settings of the receiver parameters.

The current analysis has the goal to maximise the scientific return from the hundreds of milliseconds of IQS data, exploiting them as a source of information for the presence, for example, of signal distortions due to multipath generated by the lunar surface.

4. Conclusions

In this paper the Lunar GNSS Receiver Experiment (LuGRE) mission was introduced as a joint NASA-Italian Space Agency activity that will allow, when launched, demonstrate GNSS-based positioning, navigation, and timing at the Moon. LuGRE will collect GPS and Galileo measurements in transit between Earth and the Moon, in lunar orbit, and on the lunar surface, and will provide results of onboard experiments but also transfer to ground measurements that will enable navigation experiments using the collected data. These investigations will allow a better characterisation of the lunar environment as far as the GNSS signals are concerned. Current work performed by ASI with the support of Politecnico di Torino is focused on the implementation of the analysis tools for the ground segment, and it is already being used for the simulation and testing of the experiments during the different mission phases.

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