16th International Conference on Space Operations, Virtual Edition - 3 - 5 May 2021.
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Applications and Benefits of GNSS for Lunar Exploration

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Abstract

This paper explores the role of Global Navigation Satellite Systems (GNSS) in NASA's lunar exploration plans. Robust position, navigation and timing (PNT) at the Moon will rely on a variety of measurement sources, each with its own advantages and disadvantages. The best navigation solution will depend on mission type, the phase within each mission, the state of lunar infrastructure development at the time, and a host of other considerations. No single method will provide all PNT for all scenarios, but GNSS offers a continuously available, flight-proven source of navigation and timing with unique features that make it a valuable option. As NASA launches a new era of lunar exploration missions in 2021, development of the supporting navigation architecture is underway. This paper describes the role GNSS can or will play in the components of NASA's lunar exploration plans: the Artemis missions designed to return humans to the lunar surface, the Gateway platform orbiting near the Moon that will host astronauts as well as science and technology payloads, and the robotic lander missions administered by the Commercial Lunar Payload Services (CLPS) program. GNSS-based autonomous navigation has the potential to dramatically expand lunar exploration capabilities. Through the use of GNSS and GNSS-like augmentations, navigation performance could be improved while simultaneously reducing operational complexity relative to conventional, ground-based navigation methods. As NASA begins to implement its lunar exploration plans this year and assemble the enabling communications and navigation infrastructure, GNSS will provide an important part of the diverse measurements required for robust lunar PNT.

Keywords: GNSS, GPS, lunar navigation, PNT

Acronyms/Abbreviations

ASI	Italian Space Agency
C&DH	Command and Data Handling
CFP	Conceptual Flight Profile
CLPS	Commercial Lander and Payload Services
CNSA	China National Space Administration
DCO	Data Cutoff
DRO	Distant Retrograde Orbit
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
EFT-1	Exploration Flight Test 1
EKF	Extended Kalman Filter

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ESA	European Space Agency
ESM	European Service Module
ESPRIT	European System Providing Refuelling, Infrastructure and Telecommunications
GEO	Geosynchronous Earth Orbit
GER	Global Exploration Roadmap
GGMS	GEONS Ground MATLAB Simulation
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPS ACE	GPS Antenna Characterization Experiment
GSFC	Goddard Space Flight Center
HALO	Habitation and Logistics Outpost
HEO	High Earth Orbit
HLS	Human Lander System
ICPS	Interim Cryogenic Propulsion Stage
IF	Intermediate Frequency
IGS	International GNSS Service
I-HAB	International—Habitat
ISECG	International Space Exploration Coordination Group
ISRO	Indian Space Research Organisation
JAXA	Japanese Aerospace Exploration Agency
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCROSS	Lunar Crater Observation and Sensing Satellite
LEO	Low Earth Orbit
LRA	Laser Retroreflector Array
LSITP	Lunar Surface Instruments and Technology Payloads
LuGRE	Lunar GNSS Receiver Experiment
MCC	Mission Control Center
MMS	Magnetospheric Multiscale
NASA	National Aeronautics and Space Administration
NDL	Navigation Doppler Lidar for Precise Velocity and Range Sensing
NGLR	Next Generation Lunar Retroreflector
NPLP	NASA Provided Lunar Payloads
NRA	NASA Research Announcement
NRHO	Near Rectilinear Halo Orbit
OD	orbit determination
ODTBX	Orbit Determination Toolbox
PNT	position, navigation and timing
PPE	Power and Propulsion Element
PRIME-1	Polar Resources Ice Mining Experiment 1
PRISM	Payloads and Research Investigations on the Surface of the Moon
RAFS	Rubidium Atomic Frequency Standard
RFTOP	Request for Task Order Proposals
ROSES	Research Opportunities in Space and Earth Sciences
RSS	root-sum-square
SFU	Solar Flux Units
SLS	Space Launch System
SMD	Science Mission Directorate
SSV	Space Service Volume
TLI	Trans-lunar Injection
TSV	Terrestrial Service Volume
USO	Ultra-stable Oscillator
VIPER	Volatiles Investigating Polar Exploration Rover

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1. Introduction

Global Navigation Satellite Systems (GNSS) routinely provide real-time position, navigation and timing (PNT) to spacecraft operating in the Space Service Volume (SSV). This region extends from Low Earth Orbit (LEO) to Geosynchronous Orbit (GEO) [1]. Our paper at the 2018 SpaceOps conference enumerated the advantages of using GNSS in space applications, and described how usability extends beyond the SSV, even to the Moon [2]. Much that was then speculative about how and when NASA might return to the Moon is now better defined, and global interest in lunar exploration has only increased. This paper explores the benefits of GNSS for lunar missions and details the role for GNSS in NASA's exploration plans.

Spacecraft were sent to the Moon almost as soon as the space age began. Impactor, flyby, and orbiter missions in the late 1950s and early 1960s led to a series of robotic landings by the Soviet Union and the United States, culminating in the U.S. Apollo program's six crewed landings between 1969 and 1972. The Moon is an attractive destination for several reasons. From a science perspective, it is a relatively accessible target for studying a variety of planetary science topics, and it provides insight into the 3.9-4.5-billion-year-old chapter of Earth's geologic past [2]. Its proximity makes the Moon a natural proving ground for space exploration technology and, perhaps most significantly, the feat of lunar exploration has served as a demonstration of national pre-eminence [4]. Yet after the final mission of the Soviet Union's Luna program in 1976, the Moon ceased to be a priority for more than thirty years. This has changed dramatically over the past decade.

Table 1. Recent lunar missions

Year	Mission	Type	Agency or Company
2007	SELENE	orbiter/impactor	Japanese Aerospace Exploration Agency (JAXA)
2007	Chang'e 1	orbiter	China National Space Administration (CNSA)
2008	Chandrayaan-1	orbiter + impactor	Indian Space Research Organisation (ISRO)
2009	Lunar Crater Observation and Sensing Satellite (LCROSS)	impactor	NASA
2009	Lunar Reconnaissance Orbiter (LRO)	orbiter	NASA
2010	Chang'e 2	orbiter	CNSA
2011*	THEMIS-ARTEMIS	orbiters	NASA
2011	Gravity Recovery and Interior Laboratory (GRAIL)	orbiters	NASA
2013	Chang'e 3	near-side lander	CNSA
2014	Lunar Atmosphere and Dust Environment Explorer (LADEE)	impactor	NASA
2014	Chang'e 5-T1	orbiting relay	CNSA
2014	4M	cubesat flyby (deployed by Chang'e 5-T1)	LuxSpace
2019	Chang'e 4	far-side lander	CNSA
2019	Chandrayaan-1	near-side landing attempt	ISRO
2019	Beresheet	near-side landing attempt	SpaceIL and Israel Aerospace Industries
2020	Chang'e 5	lander/sample return	CNSA

* date of lunar orbit insertion, extension of the THEMIS mission launched in 2007

A resurgence in lunar activity is taking place, and the pace of Moon-bound launches is only expected to increase. Although driven by the same motives of science, technology, and prestige as their predecessors, the entities planning

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missions to the Moon are more collaborative and more diverse, spanning national space agencies to private companies, large and small. There are parallels between this new era of lunar exploration and the past—the scientific questions and research goals, the gradations of mission complexity from orbiters to crewed landers—but the execution is markedly different. A dozen missions have already launched to the Moon in this new era, shown in Table 1. There are now more than 80 government space agencies and an increasing number of private space companies; many of these are planning missions to the Moon. The space agencies that constitute the International Space Exploration Coordination Group (ISECG) identified 14 planned lunar missions in their 2018 Global Exploration Roadmap (GER) [5] and in a 2020 Lunar Supplement acknowledged that many space agencies had since "set new national priorities and intensified and accelerated lunar exploration plans" [6].

All of the past missions cited above relied on ground-based tracking for navigation, with the exception of some onboard navigation performed by astronauts in the Apollo program. The ability of Apollo 12 to land within 200 meters of the Surveyor 3 probe, for example, relied on active piloting by Pete Conrad relative to landmarks he identified out the Lunar Module window [7]. From a navigation perspective, the goals of future missions are no less ambitious (e.g., the 2018 GER identified 100-meter position accuracy as a performance target for precision landing) but will not all be able to rely on this human-in-the-loop approach—and the sheer volume of planned missions makes ground-based tracking impractical. Although robust lunar PNT will rely on a variety of sources, GNSS offers several unique features that make it valuable to lunar exploration, especially in the near-term while planned Moon-based communications and navigation infrastructure is still in development [8][9]. In the next section, Section 2, we provide an overview of the applications and benefits of GNSS for lunar missions. In Section 3 we consider NASA's lunar exploration plans, specifically, and the role GNSS can or will have. We provide concluding remarks in Section 4.

2. Lunar Applications for GNSS

2.1 High Altitude GNSS

GNSS use is rapidly expanding to regions of space unimagined just a decade ago. Spaceflight experiments in the 1980s and 1990s demonstrated practical use of real-time GNSS within the Terrestrial Service Volume (TSV), defined to encompass the Earth's surface to 3,000 km above the Earth. Many missions orbiting Earth, including several mega-constellations, are reaping great benefits from the real-time navigation and time sensing afforded by GNSS in this TSV region. A second generation of GNSS spaceflight experiments performed in the late 1990s and early 2000s confirmed that GNSS signals could be robustly employed in high Earth orbit, or what is now defined as the Space Service Volume, or SSV [1]. The SSV spans the region of space from 3,000 km to 36,000 km above the Earth's surface [2]. Operational missions in and above the SSV are providing transformative science data return and making our lives on Earth and in space safer, healthier, and more productive. These emerging operational missions in the SSV employ special weak signal receivers and higher gain antennas to robustly obtain a PNT solution. Surprisingly, some of these SSV missions have demonstrated the practicality of expanding GNSS operations far beyond the SSV. GNSS data from operational missions at very high apogees, combined with calibrated GNSS simulations, shows that the operational reach of GNSS can be extended to cislunar space, the lunar surface, and beyond.

The Magnetospheric Multiscale (MMS) mission is a notable example of high-altitude operational use of GNSS. Navigation performance of the mission in its Phase 2b, with an apogee radius of 25 Earth radii (R_E), has served as the basis for some projections of lunar GNSS potential [10]. In early February 2019, the mission performed a series of maneuvers to raise the apogee radius to 29.34 R_E. MMS consists of a formation of four spacecraft in highly elliptical orbits designed to study magnetic reconnection energy in the Earth's ionosphere. The mission is flying NASA Goddard Space Flight Center's (GSFC's) Navigator Global Positioning System (GPS) receiver for onboard, real-time navigation [11]. The new apogee set a record for the highest altitude use of GPS to date, extending proven operational use halfway to the Moon. Navigation performance continues to be exceptional, with an average of one signal in view at apogee; Figure **1** shows the number of GPS signals tracked by MMS 1 over the first two weeks of March 2021. These signals are processed by the Goddard Enhanced Onboard Navigation System (GEONS), an Extended Kalman Filter (EKF) discussed in more detail in Section 3.2.1, to form real-time position, velocity, and time estimates. As shown in Figure **2**, the root-sum-square (RSS) position variance increased at this higher apogee relative to previous mission phases, but it has remained small after perigee where maneuver planning is performed.

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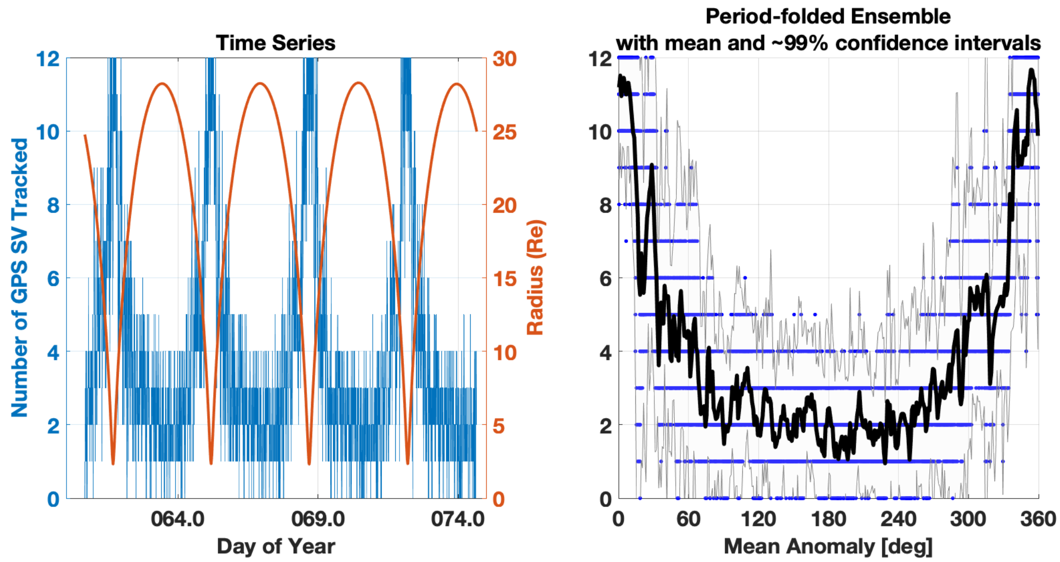

Figure 1. MMS 1 signals tracked March 1-14, 2021 (courtesy of the MMS navigation team)

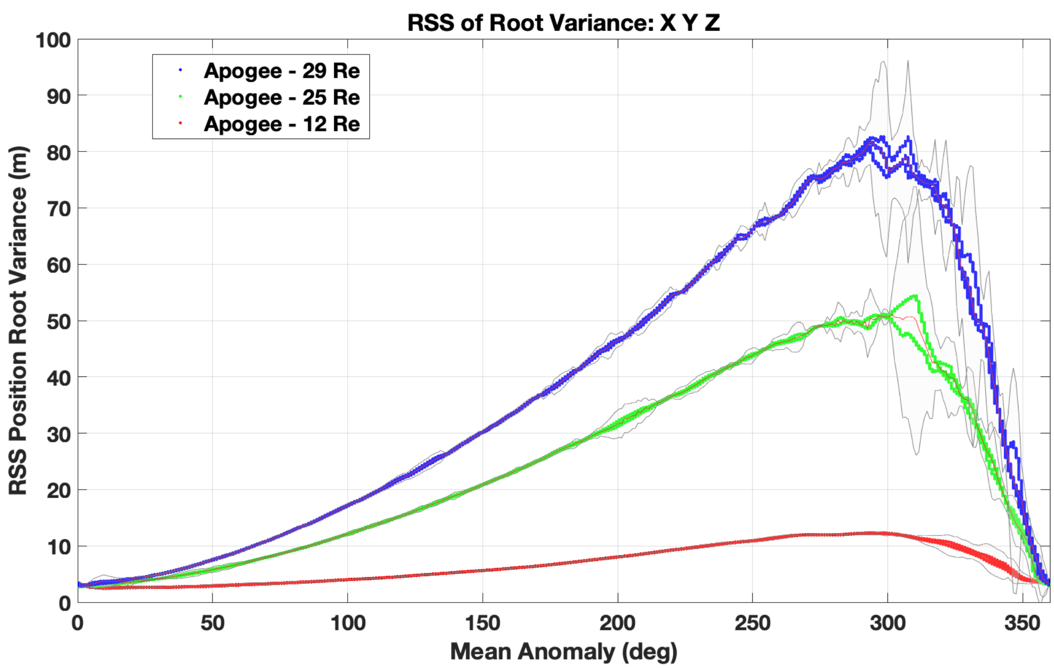

Figure 2. GEONS Root Sum Squared position variance (courtesy of the MMS navigation team)

Operations at the current MMS apogee are nearing the tracking threshold of the Navigator receiver and antenna system (7 dB antenna gain, ~23 dB-Hz acquisition and tracking threshold). However, higher antenna gain or increased receiver sensitivity can extend signal availability to the Moon [10]. The significance of this potential new domain for GNSS is underscored by Space Policy Directive 7 (SPD-7), signed by the President of the United States on January 15, 2021 [13]. This directive states that "PNT services will also play an important role in space traffic management and future applications in the Cislunar Service Volume, which extends from GEO out to and including the Moon's orbit." SPD-7 requests that relevant U.S. government agencies, including NASA, "develop requirements for GPS support of space operations and science in higher orbits within the SSV and beyond to cislunar space." In the following section, we identify cislunar GNSS use cases and mission applications.

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2.2 Lunar Applications

Lunar exploration encompasses human and robotic exploration missions which either orbit the Moon, operate on the lunar surface, or transition between lunar orbit and the surface. Lunar exploration plans include the development of an international lunar Gateway to support sustained robotic and human operations on and around the Moon, establishing a long-term human presence on the lunar surface, and promoting growing private sector investments in lunar and deep space exploration [14][15][16]. NASA-specific plans are discussed further in Section 3. The 2018 GER identified 31 critical technologies that are needed to conduct future exploration missions [5]. Of these, lunar GNSS can either completely or partially fulfil eight of these technologies. The contribution of GNSS to each of the GNSS-relevant technologies presented in the Roadmap:

- **In-space timing and navigation:** GNSS completely fulfils PNT need if GNSS capabilities meet mission requirements; sensor augmentation improves vehicle resiliency
- **Autonomous rendezvous and docking:** GNSS supports rendezvous and close approach phases; augments other sensors during docking
- **Proximity operations, relative navigation:** GNSS supports all mission phases except closest approach when signal reflections and blockages by vehicles impact navigation accuracy
- **Lunar lander:** GNSS supports 100-meter accuracy and provides navigation augmentation to other prime sensors for 10s of meters hazard detection
- **Beyond LEO crew autonomy:** GNSS is a prime sensor input to autonomous navigation algorithms
- **Deep space human factors** (e.g., reducing mission risk by optimally defining human-autonomy interface): GNSS is a prime sensor input to human-autonomy interfaces
- **Autonomous vehicle system management:** GNSS is a prime sensor input to autonomous vehicle management systems
- **Autonomous 90% of nominal operations:** GNSS is a prime sensor input to autonomous algorithms

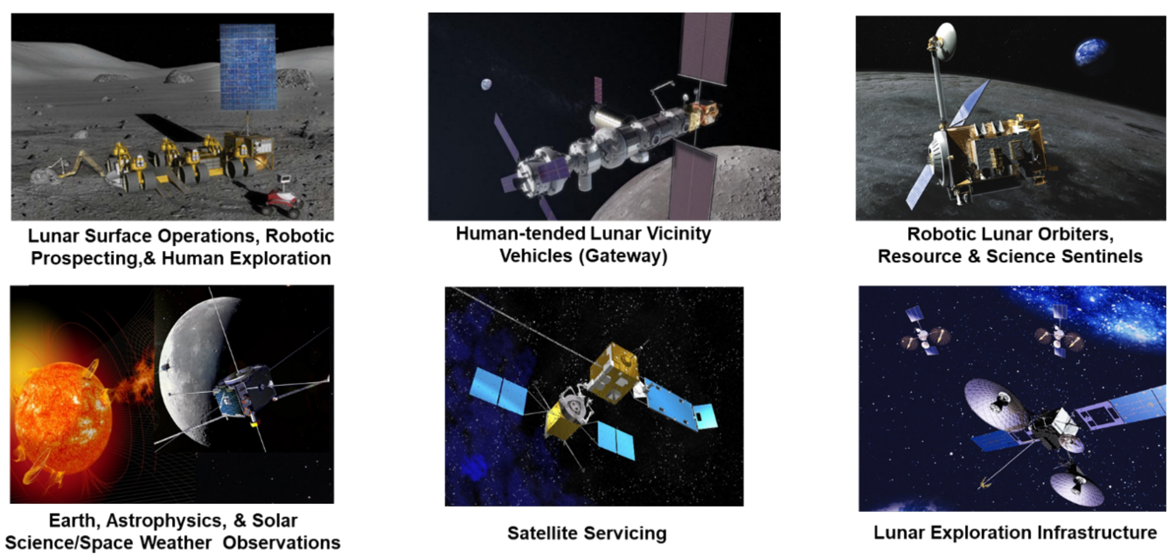

Figure 3. Lunar mission types and science investigations enabled by GNSS navigation and timing

Figure **3** depicts sample mission or technology classes that will benefit from exploiting GNSS navigation and timing. When augmented with a precise clock, lunar GNSS users can expect 100-meter-class absolute navigation, centimeter-class relative navigation, and time-synchronization on the order of 1 microsecond or better. Whether employed alone or in lock step with other navigation sources, lunar GNSS users will benefit from:

a) **real-time navigation and timing updates**–improving position, velocity and time accuracy, transforming updates from hours to seconds and, as a result, reducing ground system and tracking network dependence
b) **fast recovery from trajectory maneuvers**–improving operations cadence and enabling quicker response to system anomalies
c) **more accurate trajectory correction maneuvers**–resulting in less propellant used and higher payload mass margins

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d) **increased vehicle autonomy**–enabling lunar formation flying, robotic servicing and satellite construction, reducing or eliminating ground station tracking and ground-based orbit determination
e) **precise positioning and timing, particularly when augmented with surveyed beacons**–supporting geologic mapping, instrument placement, sample collections, surveying, mining, and prospecting resources in-situ
f) **improved vehicle safety and mission success**–early, accurate, and frequent navigation updates have proven to be crucial for deep space mission success, as they lead directly into safe planetary transitions (e.g., entry and orbit insertion).

An additional technology not explicitly cited in the GER is the use of Search and Rescue (SAR) on lunar vehicles and space suits. SAR would protect crew members in lunar orbit or on the lunar surface by identifying their locations when lost or when in a perilous situation. GNSS, augmented at times with other beacons, could readily support this capability.

As a source of position, velocity, time, and potentially attitude, lunar GNSS would enable increased vehicle autonomy and provide the option of reducing reliance on Earth-based tracking networks for navigation functions. Of equal importance, GNSS would provide a stable and accurate timing source–an important resource for science investigations, mission synchronization, and technology payloads. Lunar GNSS can enable enhanced rendezvous and docking techniques that, in turn, enable in-space construction, assembly of assets, and satellite repair. It provides safer landing systems and transforms lunar surface operations. These will have a profound effect on lunar exploration and will allow the space community to affordably live and work around the Moon and on its surface.

3. GNSS and NASA's Lunar Exploration Plans

NASA's lunar exploration strategy can be divided into three areas. The first of these is the Artemis program, a series of missions that will bring humans into orbit around the Moon and then eventually down onto the lunar surface. The second area is Gateway, a small space station in a lunar-vicinity orbit, likely a Near Rectilinear Halo Orbit (NRHO), that will serve as a crew staging point for surface operations or other deep space destinations. An international collaborative effort, Gateway will also serve as a host for science and technology experiments. The third area is a series of robotic precursor landers, designed for both technology demonstration and science data collection that will pave the way for the return of humans to the Moon. These robotic missions are executed through partnerships with commercial entities by the CLPS program in which NASA pays for rides on commercially owned, designed, and operated landers. In the following sections we provide an overview of Artemis, Gateway, and CLPS, based on recent public information. We then discuss the role GNSS can or will have for each. The specifics of these plans are fast evolving and likely to change from what we present here, but the navigation needs will broadly remain.

3.1 Artemis

The Artemis program seeks to return humans to the surface of the Moon with a series of increasingly complex missions. Like Apollo (the twin brother of Artemis in Greek mythology), landing on the Moon will be preceded by uncrewed and crewed missions to the lunar vicinity. The mission architecture bears similarities to the Apollo program as well: A super heavy-lift expendable launch vehicle, the Space Launch System (SLS), will carry the Orion crew capsule and European Service Module (ESM) into a high Earth orbit (HEO). SLS's Interim Cryogenic Propulsion Stage (ICPS) will perform the Trans Lunar Injection (TLI) burn and, once in lunar orbit, the crew will transfer to the Human Lander System (HLS) to journey down to the Moon's surface. HLS will return the crew to Orion after surface operations for an eventual parachuted splashdown in the Pacific Ocean. In contrast to Apollo, the Artemis program intends to establish a sustainable human presence at the Moon, in part to develop the technology and expertise required for a future crewed landing on Mars [17]. In addition to ground-based tracking, Artemis will use optical navigation techniques to make coarse position updates based on images of the Earth and Moon [18].

The uncrewed Artemis I mission will be the first integrated test of the Orion spacecraft and SLS. An overview of the mission plan is shown in Figure **4**. Currently scheduled to launch later this year, the three-week flight will take the Orion spacecraft through a distant retrograde orbit (DRO), passing 100 km above the lunar surface, and deploying CubeSat-based science and technology experiments along the way [19]. The ten-day Artemis II will be the first crewed mission, inserting into a lunar free-return trajectory after checkout procedures and proximity operations demonstrations in HEO. Although the Deep Space Network (DSN) is baselined for navigation and communications beyond Earth orbit for these early missions, GNSS has an operational role as well. In addition to GPS receivers on the launch vehicle, two GPS receivers are flown on the Orion capsule to provide onboard guidance, navigation, and control during re-entry and splashdown [20][21]. These receivers are equipped with fast acquisition technology developed at NASA GSFC [22]. As stated in the 2020 Artemis Plan, however, NASA is actively developing GNSS capabilities "to support robust

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navigation at and or near the Moon" [17]. The Orion GPS receivers will remain on throughout Artemis I and will provide a first look at signal availability in the lunar regime, albeit on a system designed for near-Earth applications. Flight experiences on MMS and subsequent analyses make it clear high-altitude systems would provide real-time, onboard navigation far beyond the expected range of the GPS navigation system on Artemis I.

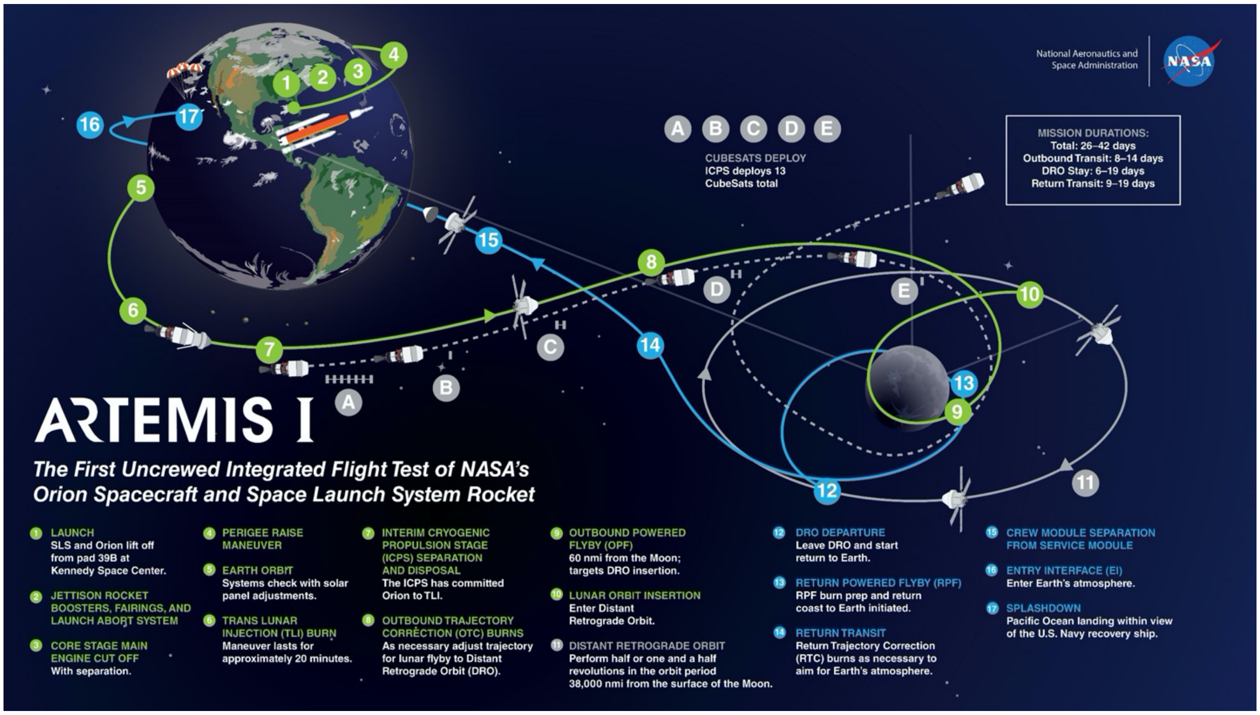

Figure 4. Plan for the Artemis I mission [23]

3.1.1 Artemis Navigation Using GNSS

We assessed the potential availability of GPS signals during Artemis I by modelling the GPS constellation and computing the received carrier-to-noise spectral density (C/N_0) of each transmitted signal according to the link budget,

$$C/N_0 = P_T + A_d + G_T + G_R - N_0 \quad (1)$$

where P_T is the transmitted power, A_d the propagation path loss, G_T the transmit antenna gain, and G_R the receive antenna gain. The noise power N_0 was modeled as the sum,

$$N_0 = 10log_{10}(kT_s) + Nf + MA \quad (2)$$

where T_s is the system noise temperature, k is Boltzmann's constant, Nf the receiver noise figure, and MA the multiple access noise [24]. System noise temperature includes the effects of the antenna noise temperature, ambient temperature, and losses between the antenna and preamplifier, while the receiver noise figure includes polarization and implementation losses. This link was computed over an early Conceptual Flight Profile (CFP) of the mission DRO [25] using Orbit Determination Toolbox (ODTBX), an open-source, MATLAB-based mission simulation and analysis tool developed at GSFC [26]. Signals are considered "visible" if the line-of-sight is not obstructed (e.g., by the Earth) and the computed received C/N_0 exceeds the receiver's acquisition and tracking C/N_0 threshold.

The GPS constellation was modeled using per-satellite transmit gain as a function of off-boresight azimuth and elevation from the GPS Antenna Characterization Experiment (GPS ACE) [12] combined with publicly released per-block main lobe gain [27]. As with previous analysis [2], flight data from MMS and GOES-16 were used to determine the per-block transmit powers; further tuning has improved agreement with the flight data to within a few dB.

On 5 December 2014, Exploration Flight Test 1 (EFT-1) performed the first flight test of the Orion crew capsule, including one GPS receiver and two antennas of its absolute navigation system [21]. The capsule orbited the Earth twice, reaching a maximum altitude of approximately 5900 km before separating from the launch vehicle upper stage, re-entering the atmosphere, and parachuting safely into the Pacific Ocean. We used flight data from this experiment to verify the spacecraft and antenna coordinate systems, as well as to refine link budget parameters and empirically determine the effective acquisition and tracking threshold of the receiver. For the Artemis I case we included high-

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fidelity patterns for all four antennas that will be flown [28] and adjusted link budget parameters according to the MMS and GOES-16 high-altitude calibrations; the parameters used are shown in Table **2**.

Table 2. Artemis I nominal link budget parameters

Receiver Acq/Trk Threshold	30 dB-Hz
System Noise Temperature (T_s)	132 K
Receiver Noise Figure (Nf)	-2.7 dB
Nominal peak G_R	7.2 dB

Figure **5** shows visibility statistics for Artemis I under four different configurations. The average number of signals visible for each distance bin is indicated by triangles for each configuration, with dots showing all numbers of signals seen by altitude throughout the 25.5-day mission. Note that the receivers flown on Orion will only have 12 channels, so the maximum number of visible signals shown here at lower altitudes doesn't reflect the number of signals actually acquired. The "Nom. Att. + Nom. Gain" case (i.e., nominal attitude and nominal receive properties, such as antenna gain) represents the planned configuration for the mission: The four GPS antennas will be arranged around the nose of the Orion capsule, but the capsule will typically face away from the Earth during outbound cruise. Under this arrangement and the nominal link budget parameters in Table **2**, few GPS signals are received above 10 R_E (approximately twice GEO distance). Changing the Orion capsule attitude to point the antennas at Earth throughout the mission ("Nadir Att. + Nom. Gain") increases the number of visible signals above the GPS constellation. This case is analogous to MMS in terms of peak antenna gain and the antennas' view of Earth, but more signals are visible in the MMS case because the Navigator receiver on MMS is specially designed for high altitude operations (e.g., weak signal tracking). We modeled a high-altitude receiver system designed for lunar applications by increasing the peak antenna gain to 10 dB and lowering the acquisition and tracking threshold to 20 dB-Hz, as in [11]. Under these conditions, one or more signals are available at lunar distance (approximately 60 R_E) under both the nadir and nominal pointing cases ("Nom. Att. + High Gain" and "Nadir Att. + High Gain," respectively). Note that the nominal pointing during the lunar flybys of the DRO is more variable than during the cruise phases, as evidenced by the increase in available signals around 55 R_E.

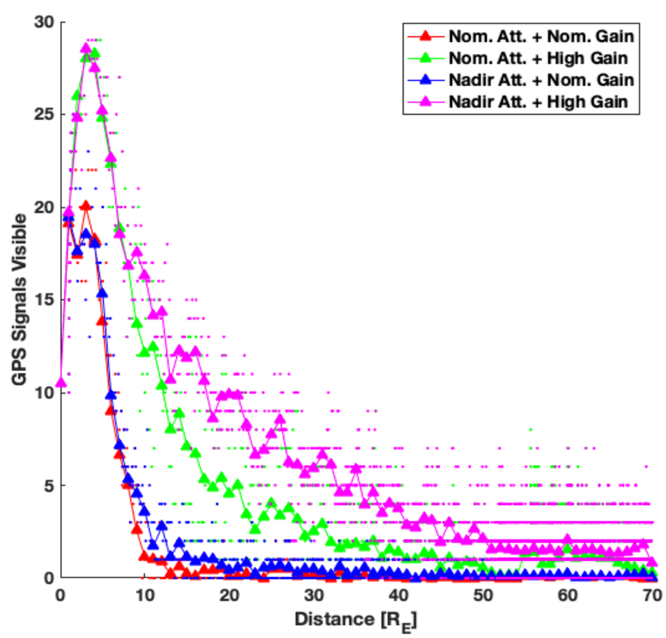

Figure 5. Simulated GPS signal availability for Artemis I under different pointing and receiver conditions

Signal availability provides only a partial picture of potential navigation performance. A wide array of factors influences the usability of signals and the quality of the resulting navigation solution, such as spacecraft dynamics and measurement geometric diversity. This analysis shows that vehicle design, receiver sensitivity, antenna gain, and pointing can make the difference between whether or not GNSS-based navigation is feasible for a particular lunar

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mission. In the following section we consider the lunar Gateway and provide a more thorough investigation of the PNT capabilities afforded by a high-altitude receiver system and navigation filter.

3.2 Gateway

The Gateway will be an outpost orbiting in the lunar vicinity, intended as a platform for science and technology research as well as a staging point for astronauts en route to the lunar surface or destinations farther afield [29]. As NASA's human exploration plans have evolved, so has the role of Gateway. At the time of writing, Canada, Japan, and the European Space Agency (ESA) have signed agreements with NASA to contribute components to the Gateway. The first two modules, NASA's Power and Propulsion Element (PPE) and Habitation and Logistics Outpost (HALO), are scheduled to launch as a co-manifested vehicle on a SpaceX Falcon Heavy no earlier than May 2024 [30]. ESA's International - Habitat (I-HAB), including contributions from Japan and Canada, is scheduled to launch in 2026, and their European System Providing Refuelling, Infrastructure and Telecommunications (ESPRIT) module in 2027 [31].

Gateway is expected to primarily reside in an Earth-Moon L2 NRHO, allowing a nearly continuous view of Earth while providing coverage of the lunar South Pole with minimal orbit maintenance [32]. Numerous studies have been performed to assess GNSS-based navigation for Gateway, with some results published previously [11][33]. The always-available nature of GNSS would particularly benefit Gateway, reducing reliance on dedicated ground tracking passes for navigation and timing, increasing the accuracy and stability of position and velocity knowledge throughout the NRHO, and improving the outpost's autonomy, responsiveness, and operational robustness. Onboard navigation would reduce the ground operations burden (e.g., scheduling, cost) and provide assurance of PNT in the case of communications loss, which is especially important when crew is aboard. Including real-time, precise PNT distribution as part of the Gateway infrastructure would benefit hosted science and technology payloads as well, eliminating the need for payloads to provide separate PNT systems, antennas, etc. Here we discuss analysis performed since [11] that has further refined our understanding of the navigation performance that would be provided by GNSS on Gateway.

3.2.1 Gateway Navigation Using GNSS

As with the previously published analysis, GEONS was used to produce a navigation solution from simulated GNSS and/or DSN measurements. GEONS is a flight proven navigation software package developed at GSFC with more than two decades of flight heritage, including the Terra mission, the MMS mission, the GPM mission, and the SEXTANT technology demonstration. MATLAB scripts from the GEONS Ground MATLAB Simulation (GGMS) tool were used to call functions in the GEONS flight software library to generate and process measurements and produce estimated states and covariance updates. We used a Gateway NRHO truth trajectory with crewed and uncrewed disturbance models, periodically adjusted to maintain consistency with the NAIF SPICE 15-year Reference Trajectory for the Gateway orbit [34].

Table 3. Ground tracking simulation parameters

Noise/Bias Type	Value
Measurement Rate	10 s
Range Noise	1.0 m (1-sigma)
Range Bias	2.5 m (1-sigma)
Doppler Noise	0.33 mm/s (1-sigma)

DSN range and X-band Doppler measurements were simulated according to the values in Table **3** with a three-contacts-per-orbit tracking schedule based on [32] for the uncrewed case and near-continuous tracking when crewed. The GPS signal simulation model was based on link calibration using MMS Phase 2b flight data [11], including a high-fidelity GPS side lobe link model using in-orbit measured per-vehicle transmit patterns from GPS ACE [12], and the International GNSS Service (IGS) GPS yaw model [35]. Per-block GPS transmit power and receiver parameters were adjusted to obtain close agreement with the MMS flight data and independent simulation using ODTBX. Similar link budget and parameter values were used as in [11] except that the receiver system noise temperature also included the effect of the Sun at nominal solar maximum consistent with a typical average solar maximum value of 150 Solar Flux Units (SFU) near GPS frequencies [36]. Under typical conditions (as in this simulation) the impact to C/N_0 is less than 1 dB, but the impact could be much greater during transient space weather events. We also added a conservative Galileo measurement model based on the GPS model described above but with the transmission signal strength as a function of off-boresight angle used in [37]. Note that this transmitter antenna model is very conservative and does not include side lobes that are known to extend beyond an off-boresight angle of 60 degrees.

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The same receiver clock modelling approach was used as previously (i.e., fitting a q-parameter model to Hadamard variance data) with the Deep Space Atomic Clock (DSAC) [38] included in addition to the Ultra-stable Oscillator (USO) and Rubidium Atomic Frequency Standard (RAFS) in a GPS sensitivity analysis. Process noise was tuned to achieve a realistic covariance aligned with observed errors and increased at perilune to account for lunar gravity errors.

This analysis focused on how orbit determination (OD) errors impacted maneuver planning dispersions by assessing the maximum OD error at the data cut off (DCO) 24 hours before the orbit maintenance maneuvers as well as at the final two perilunes and apolunes. We also evaluated the overall position and velocity accuracy against goals of 10 km and 10 cm/s, respectively. Seventy Monte Carlo samples were run for uncrewed and crewed cases of each Gateway tracking configuration: DSN only, GPS only, and both DSN and GPS. The RAFS clock was used for all GPS configurations. Ground-based OD was assumed for cases involving DSN, but the GPS only case was configured for onboard OD.

Table **4** summarizes statistics for the uncrewed case and Figure **6** shows the uncrewed, GPS only configuration simulation results, where the errors for each Monte Carlo sample are plotted in grey and 3-sigma plotted in green. The errors along the direction of the Earth-to-Gateway position vector (i.e., range) and perpendicular to this direction (i.e., RSS lateral) are plotted separately to illustrate geometric dependencies. Statistics in the "All" column of the table are maximums and are dominated by perilune velocity spikes; velocity is better away from perilune, as shown in the plots. Note that velocities are in units of cm/s in the table and m/s in the plots. For the uncrewed case it is clear that GPS can provide greatly improved performance over ground-based tracking due to the continuous availability of GPS and its greater geometric diversity. Two orbits are required for the GPS only configuration to fully resolve correlation of clock bias and range position errors, but even a single DSN contact per orbit (as opposed to the three included in the DSN+GPS results shown) enabled the solution to quickly converge to the steady-state errors of the GPS only solution.

Table 4. Maximum steady-state (last two orbits) RSS position and velocity errors for the uncrewed configuration

	Case	DCO	Apolune	Perilune	All
Position [m]	DSN	103.5	160.5	38.3	2138.4
	GPS	21.9	33.5	51.3	112.2
	DSN+GPS	22.8	35.8	34.7	102.4
Velocity [cm/s]	DSN	0.078	0.932	1.316	6.660
	GPS	0.020	0.645	1.438	2.445
	DSN+GPS	0.022	0.870	1.480	2.525

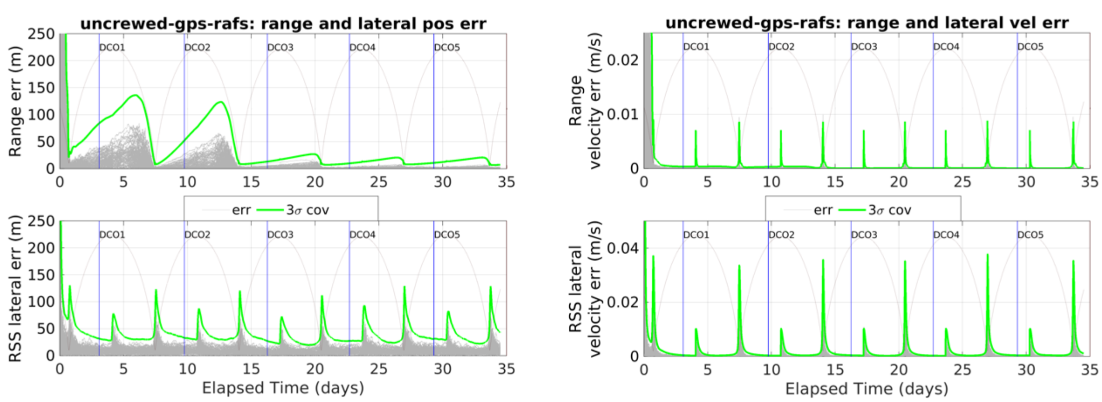

Figure 6. Uncrewed GPS only position (left) and velocity (right) errors

Table **5** summarizes statistics for the crewed case and Figure **7** shows the crewed, GPS only configuration simulation results. In all the crewed cases that were evaluated, the reaction wheel desaturation (1 cm/s 3-sigma every 118 min) and venting disturbances drive velocity performance. The DSN only case required continuous tracking to meet target performance and although both DSN and GPS errors increased relative to the uncrewed case, DSN only errors increased much more dramatically. Steady-state position accuracy for onboard OD using GPS was significantly

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more accurate than ground OD using only DSN measurements. As with the uncrewed case, adding DSN to GPS greatly reduced initial errors but did not reduce steady-state errors over the GPS only configuration.

Table 5. Maximum steady-state (last two orbits) RSS position and velocity errors for the crewed configuration

	Case	DCO	Apolune	Perilune	All
Position [m]	DSN	1469.7	1326.4	319.8	2353.6
	GPS	60.4	84.5	73.0	118.7
	DSN+GPS	57.7	81.7	107.0	117.4
Velocity [cm/s]	DSN	2.56	3.07	8.47	32.15
	GPS	0.96	1.16	2.44	3.24
	DSN+GPS	1.03	1.14	3.51	3.92

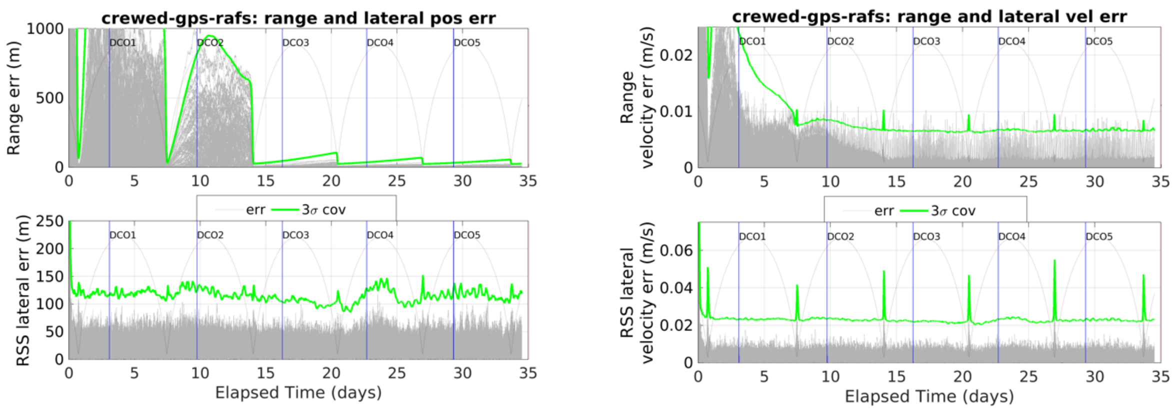

Figure 7. Crewed GPS only position (left) and velocity (right) errors

We also performed sensitivity studies considering signal degradation, reduced signal visibility, and reduced and improved clock performance. Signal degradations of 3 to 9 dB caused a corresponding degradation in performance, which was gradual over the span of link losses and not abrupt at any particular threshold. Furthermore, navigation performance for the cases considered was robust to short (30 min) and long (8.5 hr) GPS outages. Under our assumptions, increased stability of the DSAC did not provide a meaningful improvement over the RAFS, and indeed the lower quality USO might be adequate to meet current Gateway requirements. The DSAC may provide more benefit under different noise and filter tuning assumptions, especially if carrier phase measurements are used or clock states didn't need to be estimated at all. Finally, we considered the effect of adding Galileo measurements to GPS. The addition of Galileo signals increased the total number of signals tracked and would improve the overall resilience of the navigation system. However, it was clear from our analysis that a more accurate transmit pattern (with more complete representation of the side lobes) is required to adequately assess the benefit to navigation of multi-GNSS for Gateway.

Overall, the Gateway simulation presented here represents a practical and realistic implementation of GNSS at the Moon: a high-gain (e.g., 14 dBi), Earth-pointed antenna; a sensitive, high-altitude receiver (e.g., tracking and acquisition threshold in the low 20 dB-Hz); an onboard navigation filter; and, optionally, occasional ground station contacts. This analysis indicates that OD using GPS pseudorange measurements can provide significantly improved performance versus DSN given the assumed tracking schedule, on-board, in real-time, without reliance on ground-based assets for both uncrewed and crewed cases. This benefit derives from the fact that GPS can provide continuous tracking with better geometric diversity than ground-based tracking. Furthermore, a companion analysis by ESA using an updated, more realistic Galileo gain pattern (expected to be released by the European Commission for general use soon) showed that Galileo exhibits a level of signal availability comparable to GPS, effectively doubling the number of signals if a multi-constellation receiver is used.

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3.3 Commercial Lunar Payload Services

The NASA CLPS project within the Science Mission Directorate (SMD) seeks to rapidly deliver high-value NASA science and technology payloads to the lunar surface via commercial landers. CLPS is structured as an indefinite-delivery, indefinite-quantity contract with a set of 14 commercial lander providers. Each individual flight is procured via a competition between contractors for a flight-specific Request for Task Order Proposals (RFTOP) reflecting requirements associated with the set of NASA payloads slated for delivery [39].

The CLPS task orders are focused narrowly on delivery of the selected NASA payloads to the lunar surface, a "delivery truck" model. Other aspects, such as the lander design, delivery mechanism, and potential additional commercial payloads are not dictated.

NASA scientific payloads are selected via open solicitations and augmented with high-priority technology payloads, then are assigned to a specific RFTOP for award and flight. The first sets of science payloads were selected in 2019 via the NASA Provided Lunar Payloads (NPLP) and Lunar Surface Instruments and Technology Payloads (LSITP) solicitations. For flights starting in in late 2023, the principal mechanism for science payload selection is via the Payloads and Research Investigations on the Surface of the Moon (PRISM) opportunities announced via the annual omnibus Research Opportunities in Space and Earth Sciences (ROSES) NASA Research Announcement (NRA) calls.

As of February 2020, six CLPS flights with a total of 37 NASA payloads have been awarded [39]. These flights are captured in Table 6. Several assigned payloads have direct relevance to lunar navigation and are highlighted in the table as key payloads.

Table 6. Awarded CLPS Flights and Key Navigation Payloads

Mission Name	CLPS Provider/Lander	Expected Launch Date	Landing Site	Key Navigation Payloads	Ref.
Peregrine Mission One	Astrobotic Peregrine	2021	Lacus Mortis	• Laser Retroreflector Array (LRA) • Navigation Doppler Lidar for Precise Velocity and Range Sensing (NDL)	[40][41]
IM-1	Intuitive Machines Nova-C	2021	Oceanus Procellarum	• Lunar Node 1 Navigation Demonstrator	[41][42]
Masten Mission One	Masten XL-1	2022	South Pole	• Laser Retroreflector Array (LRA)	[43][44]
PRIME-1	Intuitive Machines Nova-C	2022	South Pole	• Polar Resources Ice Mining Experiment (PRIME-1)	[45]
VIPER	Astrobotic Griffin	2022	South Pole	• Volatiles Investigating Polar Exploration Rover (VIPER)	[40]
Blue Ghost 1	Firefly Blue Ghost	2023	Mare Crisium	• Next Generation Lunar Retroreflector (NGLR) • Lunar GNSS Receiver Experiment (LuGRE)	[46][47]

3.3.1 Lunar GNSS Receiver Experiment

The Lunar GNSS Receiver Experiment (LuGRE) is a joint payload by NASA and the Italian Space Agency (ASI) to demonstrate GNSS-based navigation and timing at the Moon. NASA selected LuGRE to fly on the CLPS Task Order 19D flight awarded to Firefly Aerospace in 2021. The mission will fly a weeks-long transfer to the Moon and land in the near-side equatorial Mare Crisium region in late 2023 for a minimum 12-day period of surface operations.

The LuGRE payload consists of a dual-frequency, multi-GNSS receiver and high-gain antenna. The payload is capable of weak-signal acquisition and tracking of GPS L1 C/A and L5, and Galileo Open Service E1 and E5a signals. The mission's goal is to extend high-altitude GNSS-based PNT to the Moon. This technology demonstration will serve as an enabler for future operational uses. The mission has three overall objectives:

OBJECTIVE 1: Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
OBJECTIVE 2: Demonstrate navigation and time estimation using GNSS data collected at the Moon.
OBJECTIVE 3: Utilize collected data to support development of GNSS receivers specific to lunar use.

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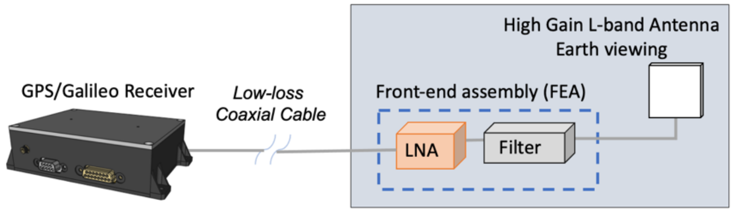

Figure 8. LuGRE payload components

The LuGRE payload is provided by ASI and consists of the receiver, antenna, and front-end assembly including an RF filter and low-noise amplifier, as shown in Figure **8**. The LuGRE receiver is a custom-built, lunar-capable receiver from Qascom based on the QN400 series with flight heritage on the 2019 SL-14 sounding rocket flight by UP Aerospace and on the 2020 Bobcat-1 LEO CubeSat [48]. The receiver is being designed specifically for the LuGRE mission by adding weak-signal tracking, a lunar-capable embedded Kalman filter, and reliability updates for the cislunar radiation environment. The receiver will be paired with a commercially procured high-gain L1/L5 (E1/E5a) antenna with peak gain of at least 14 dBi and full beamwidth of at least 10 deg. The antenna will be mounted on the Blue Ghost lander's Earth-pointed platform, adjacent to the lander's high-gain communications antenna. The platform will point the LuGRE antenna to Earth within 1 degree, ensuring coverage of the GPS and Galileo constellations from lunar distance. The antenna, front-end assembly, and receiver will be integrated as distinct components on the lander and connected via a low-loss coaxial cable. The receiver will connect to the lander's command and data handling (C&DH) system and utilize the mission's Earth communications system for telemetry and commanding.

The LuGRE concept of operations is shown in Figure **9**. LuGRE will launch on the Firefly Blue Ghost 1 mission in late 2023. After a brief checkout period the payload will operate throughout the lander's Earth-Moon transfer period, which is expected to consist of 1 to 4 phasing loops with perigee in LEO and apogee at lunar distance. The phasing loops will be followed by several days in low lunar orbit for phasing with the landing site, followed by a brief powered descent and landing on the lunar surface. LuGRE will operate at least until the initiation of the powered descent sequence, then again shortly after landing for the duration of the surface mission. Payload-collected data will be downlinked by the lander to the Firefly Mission Control Center (MCC), where it will be provided in real-time to the on-site LuGRE payload operations team and to the joint NASA/ASI science teams for processing and archiving.

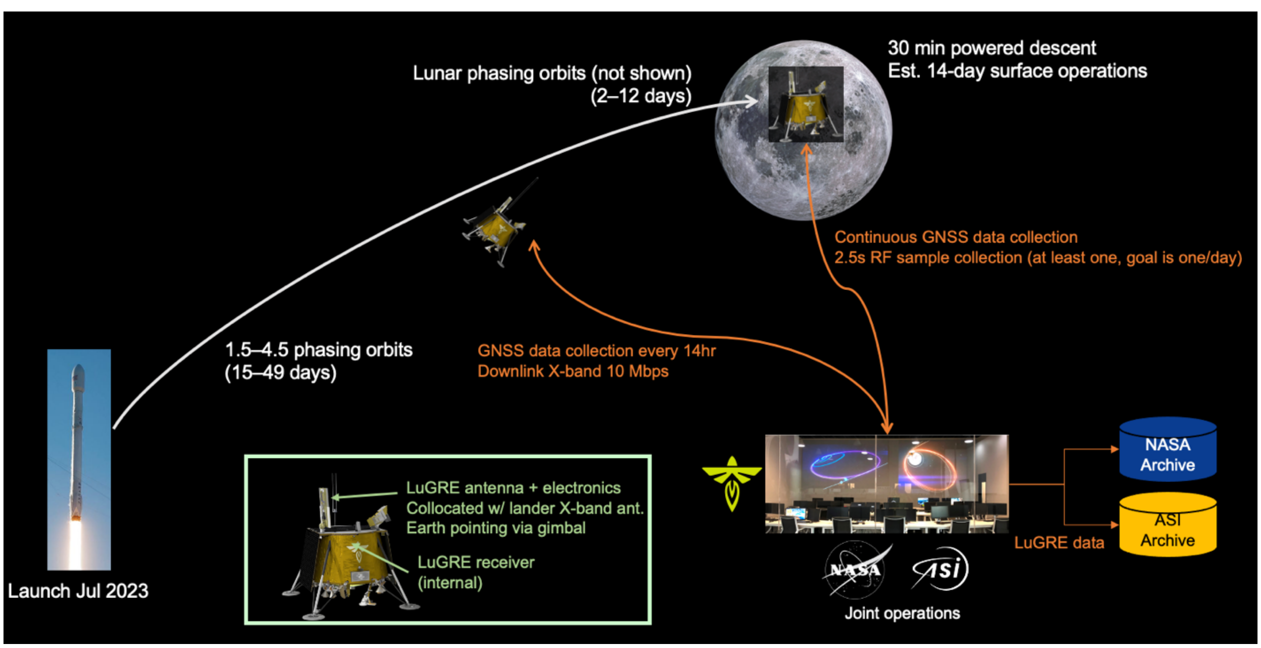

Figure 9. LuGRE mission concept of operations

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The LuGRE dataset will consist of GNSS data at various levels of processing, from raw L-band intermediate frequency (IF) samples to real-time onboard navigation products. The payload will perform real-time navigation during transit and lunar surface operations and will supply multi-GNSS, multi-frequency point solutions and embedded EKF navigation solutions to the ground. These solutions will be paired with direct GNSS observables including pseudorange and carrier phase for ground-based post-processing. In addition, the receiver is capable of direct sampling of the digitized intermediate frequency signal. The payload will perform at least one sampling event during surface operations, collecting up to 2.5 seconds of combined L1 and L5 samples or a longer duration of single-frequency samples.

The LuGRE mission is a fully international activity, with NASA providing the flight and the overall science, programmatic, and systems engineering oversight, and ASI providing the payload and participating in coordinated science activities. This collaborative international aspect is a fitting complement to the international nature of both GNSS-based PNT and the new era of lunar exploration. As such, all LuGRE payload data is intended to be released to the public for utilization by the space-based PNT community to advance the state of lunar navigation and high-altitude GNSS receiver technology.

4. Conclusions

As the frequency, quantity, and complexity of Moon missions increases, navigation needs will soon outstrip the capacity and capabilities of ground-based tracking networks. In the long term, Moon-based communication and navigation networks will likely be established, such as NASA's planned LunaNet [49], but near-term plans will require the autonomy afforded by onboard navigation. Activities like spacecraft rendezvous and docking or precision landing will require in-situ navigation measurements such as optical navigation or inter-vehicle crosslinks. Even the nodes of future Moon-based networks themselves would benefit from independent position, velocity, and time estimation. Use of GNSS in cislunar space faces a number of challenges: The weakness of signals at Moon distances requires a sufficiently strong antenna and sensitive receiver. The Earth-orbiting GNSS constellations span only 8 degrees when viewed from the Moon; this geometry makes range and clock errors highly correlated. Earth-pointing and an unobstructed view of the Earth are essential.

Advancements in receiver technology and mission conops have demonstrated that these challenges can be overcome. Despite any limitations, GNSS offers an always-on, proven source of one-way range, Doppler, and time transfer unique among the available navigation measurements. For many mission classes, including some specifically planned by NASA and discussed in this paper, GNSS is capable of providing 100-meter-class absolute navigation, centimeter-class relative navigation, and time synchronization on the order of 1 microsecond or better. In other applications, GNSS can have a role as a back-up source of PNT or play a part in a combination of measurement sources. As NASA and other space-faring entities begin to assemble the communications and navigation infrastructure needed for lunar exploration, GNSS will provide an important part of the diverse measurements required for robust lunar PNT.

Acknowledgements

This paper was written by the GSFC PNT Policy Team and colleagues under the auspices of the Space Communications and Navigation (SCaN) Program's Policy and Strategic Communications Office, with particular support from deputy director J.J. Miller. We thank Scott Cryan and the JSC Gateway team for their support of the GPS study in Section 3.2. We also thank John McGregor, Greg Holt, Susan Gomez, and the Artemis program for their review, assistance, Orion antenna patterns, and EFT-1 flight data. We appreciate the information and feedback from Mark Dillard and the CLPS program. Abe Aguilar and other members of the MMS navigation team contributed important information about recent MMS performance, including the two plots in Section 2.1. Additional thanks and high fives are extended to those members of GSFC Code 593 for their tireless efforts to make GNSS at the Moon a reality.

References

[1] F.H. Bauer, M.C. Moreau, M.E. Dahle-Melsaether, W.P. Petrofski, B.J. Stanton, S. Thomason, G.A Harris, R.P. Sena, L. Parker Temple III, The GPS Space Service Volume, Proceedings of the 19th international technical meeting of the Satellite Division of the Institute of Navigation (ION GNSS 2006), Fort Worth, TX, USA, 2006, 26 - 29 September.

[2] B. Ashman, J.J.K. Parker, F. Bauer, M.C. Esswein, Exploring the Limits of High Altitude GPS for Future Lunar Missions, 41st Annual AAS Guidance & Control Conference, Breckenridge, CO, USA, 2018 1-7 February.

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[3] J.W. Head III, Increasing Science Capabilities in the Apollo Lunar Exploration Program: Perspectives for Artemis, NASA GSFC Scientific Colloquium, 2021 10 February.
[4] R. Launius, Compelling Rationales for Spaceflight? History and the Search for Relevance, in: S.J. Dick, R. D. Launius (Eds.), Critical Issues in the History of Spaceflight, NASA, Washington, DC, USA, 2006, pp. 49-53.
[5] International Space Exploration Coordination Group, Global Exploration Roadmap, 2018 January NASA https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf, (accessed 4 March 2021).
[6] International Space Exploration Coordination Group, Global Exploration Roadmap Supplement August 2020: Lunar Surface Exploration Scenario Update, 2020 August, https://www.globalspaceexploration.org/wp-content/uploads/2020/08/GER_2020_supplement.pdf, (accessed 7 March 2021).
[7] R.W. Orloff, D.M., Apollo: The Definitive Sourcebook, Praxis Publishing Company, Chichester, UK Publishing Company, ISBN 978-0-387-30043-6, 2006, pp 334-335.
[8] M. Schönfeldt, A. Grenier, A. Delépaut, R. Swinden, P. Giordano, J. Ventura-Traveset, Across the Lunar Landscape Exploration with GNSS Technology, InsideGNSS, September/October, 2020.
[9] M. Schönfeldt, A. Grenier, A. Delépaut, R. Swinden, P. Giordano, J. Ventura-Traveset, Across the Lunar Landscape Towards a Dedicated Lunar PNT System, InsideGNSS, November/December, 2020.
[10] L.B. Winternitz, W.A. Bamford, S.R. Price, New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances, Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017), Portland, OR, USA, 2017, 25-29 September.
[11] L.B. Winternitz, W.A. Bamford, A.C. Long, M. Hassouneh, GPS Based Autonomous Navigation Study for the Lunar Gateway, 42nd Annual American Astronautical Society (AAS) Guidance, Navigation, and Control Conference, Breckenridge, CO, USA, 2019, 1-6 February.
[12] J. Donaldson, J. Parker, M. Moreau, D. Highsmith, and P. Martzen, Characterization of On-Orbit GPS Transmit Antenna Patterns for Space Users, Proceedings of the Institute of Navigation GNSS+, Miami, FL, USA, 2018, 24-28 September.
[13] The White House, Space Policy Directive 7, 2020 15 January, https://trumpwhitehouse.archives.gov/presidential-actions/memorandum-space-policy-directive-7/, (accessed 4 February 2021).
[14] NASA, National Space Exploration Campaign Report, 2018, September, https://www.nasa.gov/sites/default/files/atoms/files/nationalspaceexplorationcampaign.pdf, (accessed 15 January 2021).
[15] J. Crusan, D.G. Chavers, J. Krezel, N. Herrmann, E. Mahoney, R.M. Smith, Lunar Exploration Campaign: Development of the Gateway and Establishing the Cislunar and Surface Architecture, IAC-18-A5.1.1, 69th International Astronautical Congress, Bremen, Germany, 2018, 1-5 October.
[16] R.M. Smith, J. Jenkins, D. Craig, E. Mahony, Lunar Rover Virtual Mobility Forum, 12 February 2020, https://www.nasa.gov/sites/default/files/atoms/files/ltv-lssm-virtual-industry-forum.pdf, (accessed 15 January 2021).
[17] NASA, 2020 Artemis Plan, https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf, (accessed 15 January 2021).
[18] C.N. D'Souza, K. Smith, R. Inman, Orion Optical Navigation Testing and Performance, AIAA Scitech 2020 Forum, Orlando, FL, USA, 2020 6-10 January.
[19] K. Hambleton (Ed.), Around the Moon with NASA's First Launch of SLS with Orion, 8 March 2018, https://www.nasa.gov/feature/around-the-moon-with-nasa-s-first-launch-of-sls-with-orion, (accessed 15 January 2021).
[20] G.N. Holt, R. Zanetti, C.N. D'Souza, Tuning and Robustness Analysis for the Orion Absolute Navigation System, AIAA Guidance, Navigation, and Control (GNC) Conference, Boston, MA, USA, 2013, 19-22 August.
[21] R. Zanetti, G. Holt, R. Gay, C. D'Souza, J. Sud, H. Mamich, M. Begley, E. King, F.D. Clark, Absolute Navigation Performance of the Orion Exploration Flight Test 1. Journal of Guidance, Control, and Dynamics 40.5 (2017) 1106-1116.
[22] L. Barker, H. Mamich, J. McGregor, Post-Flight Analysis of GPSR Performance During Orion Exploration Flight Test 1, 39th Annual AAS Guidance and Control Conference, Breckenridge, CO, USA, 2016, 5-10 February.

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[23] K. Hambleton (Ed.), Artemis I Map, 9 February 2018, https://www.nasa.gov/sites/default/files/thumbnails/image/artemis_i_map_20210315_1.jpg, (accessed 15 January 2021).
[24] J.J. Spilker, GPS Signal Structure and Theoretical Performance, in: B.W. Parkinson, J.J. Spilker Jr. (Eds.), GPS: Theory and Applications, AIAA, Inc., Washington, DC, USA, pp. 88-93.
[25] Orion Program End-to-End Mission Performance Team (EMPT), EM-1 Distant Retrograde Orbit (DRO) Preliminary Mission Analysis (PMA) Cycle Conceptual Flight Profile A (CFP-A), EG-CEV-17-2, 2017 March 2017.
[26] Orbit Determination Toolbox (ODTBX) 6.5, 2017 January, http://opensource.gsfc.nasa.gov/projects/ODTBX/, (accessed 15 January 2021).
[27] United States Coast Guard, GPS Technical References, https://navcen.uscg.gov/?pageName=gpsTechnicalReferences, (accessed 1 April 2021).
[28] J. Hoffman, J. Lovejoy, GPS Antenna Spatial Coverage Analysis EM-1 Configurations, 17 February 2016, (internal report).
[29] K. Mars (Ed.), Gateway, 11 February 2021, https://www.nasa.gov/gateway, (accessed 31 March 2021).
[30] M. Witt, P. Bielling, I. Reyna, R. Kraft, NASA Awards Contract to Launch Initial Elements for Lunar Outpost, 9 February 2021, https://www.nasa.gov/press-release/nasa-awards-contract-to-launch-initial-elements-for-lunar-outpost, (accessed 31 March 2021).
[31] S. Bielecki, C. des Arcis, M. Kovac, Thales Alenia Space on its Way to Reach the Moon, 14 October 2020, https://www.thalesgroup.com/en/worldwide/space/press-release/thales-alenia-space-its-way-reach-moon, (accessed 31 March 2021).
[32] N. Parrish, M.J. Bolliger, E. Kayser, M.R. Thompson, J.S. Parker, B.W. Cheetham, D.C. Davis, D.J. Sweeney, Near Rectilinear Halo Orbit Determination with Simulated DSN Observations, AIAA Scitech 2020 Forum, Orlando, FL, USA, 2020, 10 January.
[33] K. Cheung, C. Lee, D. Heckman, Feasibility of "Weak GPS" Real-Time Positioning and Timing at Lunar Distance, 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, 7-14 March.
[34] NASA Planetary Geometry System for Space Science Missions, receding_horiz_3189_1burnApo_DiffCor_15yr.bsp, 2018 July 18, https://naif.jpl.nasa.gov/pub/naif/misc/MORE_PROJECTS/DSG/, (accessed 6 June 2020).
[35] J. Kouba, A Simplified Yaw-Attitude Model for Eclipsing GPS Satellites, GPS Solut (2009) 13:1-12, 20 March 2008, http://acc.igs.org/orbits/yaw-attitude_kouba_gpssoln09.pdf, (accessed 1 June 2020).
[36] H. Coffey, E.H. Erwin, Online Solar Databases at NGDC – RSTN Solar Radio Databases, 2004, http://lasp.colorado.edu/sdo/meetings/session_1_2_3/posters/session2/2_13P_Coffey.pdf, (accessed September 2020).
[37] W. Enderle, F. Gini, E. Schonemann, V. Mayer, PROBA-3 Precise Orbit Determination based on GNSS observation, 32nd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2019), Miami, FL, USA, 2019, 16-20 September.
[38] R.L. Tjoelker et al., Mercury Ion Clock for a NASA Technology Demonstration Mission, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 63, no. 7, (2016), 1034-1043.
[39] G. Daines (Ed.), Commercial Lunar Payload Services, 1 October 2020, https://www.nasa.gov/content/commercial-lunar-payload-services, (accessed 31 March 2021).
[40] Astrobotic, Payload Manifest, 2021, https://www.astrobotic.com/manifest, (accessed 31 March 2021).
[41] C. Warner, First Commercial Moon Delivery Assignments to Advance Artemis, 2 January 2020, https://www.nasa.gov/feature/first-commercial-moon-delivery-assignments-to-advance-artemis, (accessed 31 March 2021).
[42] Intuitive Machines, Launch Date and Landing Site Selected for 2021 Moon Mission, 13 April 2020, https://www.intuitivemachines.com/post/launch-date-and-landing-site-selected-for-2021-moon-mission, (accessed 31 March 2021).
[43] G. Hautaluoma, R. Kraft, J. Knotts, NASA Awards Contract to Deliver Science, Tech to Moon Ahead of Human Missions, 8 April 2020, https://www.nasa.gov/press-release/nasa-awards-contract-to-deliver-science-tech-to-moon-ahead-of-human-missions, (accessed 31 March 2021).
[44] Masten Aerospace, Lunar Mission 1 Fly Me to the Moon, https://masten.aero/lunar-lander/, (accessed 31 March 2021).

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[45] Intuitive Machines, NASA Selects Intuitive Machines to Deliver Lunar Ice Drill in 2022, 16 October 2020, https://www.intuitivemachines.com/post/nasa-selects-intuitive-machines-to-deliver-lunar-ice-drill-in-2022, (accessed 31 March 2021).
[46] G. Hautaluoma, J. Handal, N. Ramji, R. Kraft, NASA Selects Firefly Aerospace for Artemis Commercial Moon Delivery in 2023, 4 February 2021, https://www.nasa.gov/press-release/nasa-selects-firefly-aerospace-for-artemis-commercial-moon-delivery-in-2023, (accessed 31 March 2021).
[47] Firefly Aerospace, Lunar Lander, 2021, https://firefly.com/lunar-lander/, (accessed 31 March 2021).
[48] S. Ugazio, K. Croissant, B.C. Peters, F. van Graas, Bobcat-1: The Ohio University CubeSat for Inter-Constellation Time Offset Determination, Proceedings of the ION 2019 Pacific PNT Meeting, Honolulu, HI, USA, 2019, 8-11 April.
[49] D. Israel, A LunaNet Implementation Approach, Proceedings of the 16th International Conference on Space Operations, SpaceOps 2021, virtual, 2021, 3-5 May.