Architectures and Technology Investment Priorities for Positioning, Navigation, and Timing at the Moon and Mars

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1 EXECUTIVE SUMMARY

Positioning, navigation, and timing (PNT) services at the Moon are needed to support the Artemis program, which will begin launching the first of dozens of landed and orbiting assets to the Moon in the 2020s. These PNT services and standards are currently defined in the LunaNet Interoperability Specification (LNIS), but several details remain to be determined [1]. NASA's Moon-to-Mars program aims to create PNT capabilities to support an initial human Mars exploration campaign and may be able to use some aspects of the lunar PNT architecture.

This white paper describes architectures and technologies needed for providing PNT services at the Moon and Mars and recommends technology investments that will both help enable the envisioned lunar PNT capability as well as successfully extend it to Mars.

Architecturally, an initial lunar deployment of relay satellites in elliptical frozen orbits would maximize coverage over the South Pole, a focus of the Artemis program. We recommend these assets, and future surface assets, establish a free-running autonomous timescale (which we call "LTC") with differences to UTC continually monitored. This is preferable to deploying UTC itself at the Moon, which would involve overcoming unnecessary challenges in handling leap seconds and in closed-loop tracking of significant time-varying relativistic effects. The lunar service providers should establish their orbits and time through a variety of technologies, including existing CCSDS ranging standards, DSN tracking, weak-signal GPS reception, and high-quality atomic clocks. The assets in turn would provide LNIS-standard PNT services to lunar users.

Investments needed to enable a fully capable Lunar PNT system include the development of high-performance space atomic clocks; high-performance software-defined radios such as UST-lite and Iris capable of advanced communications and navigations techniques with multiple frequencies; navigation autonomy; ground stations; and a terrestrial beacon service. In critical aspects, technologies that work at the Moon will not work at Mars. System engineering studies and architecture trades to identify the differences between the lunar and Mars operational scenarios should begin immediately. The outcome of these studies will inform appropriate technology investments to make and test (to the extent possible at the Moon and with precursor missions to Mars) so that they are ready for Mars exploration beginning in the 2030s.

2 INTRODUCTION

This white paper addresses architectures and technologies to provide positioning, navigation, and timing (PNT) services at the Moon, Mars, and beyond.

2.1 PNT AT THE MOON

There is an immediate need to fully define PNT services at the Moon to support the Artemis program, which will begin launching the first of dozens of landed and orbiting assets to the Moon in the 2020s. Interoperability standards are critical to the success of the program because Artemis is a cooperative initiative of the United States's National Aeronautics and Space Administration (NASA), along with three international partner agencies – the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and the Canadian Space Agency (CSA). In many cases, the communications and PNT services will be provided by commercial entities which left to their own devices would most likely not interoperate.

These PNT services and standards are currently defined in the LunaNet Interoperability Specification (LNIS) [1]. As of this writing, LNIS has defined the user services for communications and PNT, and the interfaces between users and LunaNet Service Providers. Details regarding the signal structures needed to support location services for users, the lunar reference frame standard, and the lunar time system standard remain to be determined.

This white paper addresses some technology and architectural considerations for providing PNT services at the Moon applicable to areas not yet fully defined by LNIS.

2.2 PNT AT MARS

The lunar exploration of the 2020s will pave the way to human missions to Mars as early as the 2030s [2][1][3]. In the Moon to Mars initiative, NASA is prioritizing investments in lunar exploration that will support human exploration of Mars in the future.

This white paper addresses technologies and architectures for providing PNT services at Mars. Developing the Mars PNT specifications now is important because the distance to Mars requires fundamentally different approaches to PNT, compared to the Moon.

2.3 PUTTING MARS AND THE MOON DISTANCES IN PERSPECTIVE

The most distant satellites routinely used in terrestrial communications are those in geostationary orbit, at an altitude of 35,786 km. Communications signals from the ground to a geostationary satellite and back experience a delay of about 0.24 s, arising from the speed of light over that distance.

As seen in Table 1, the Moon is about 11 times farther than geostationary orbit (GEO), and the average distance to Mars is about 6,280 times farther than GEO. The longer distance means signals to the Moon experience a round trip delay of about 2.5 s. Among other things, this makes real-time voice conversations to the Moon fundamentally different than those on Earth. The average round trip delay to Mars is about 25 minutes. This makes remote control of a rover or other asset from Earth an impossibility and motivates the development of autonomy.

Table 1. Relative distances

Place	Avg. distance (km)	Distance relative to GEO	Two-way delay	Data rate
GEO	3.58×10^4	1x	0.24 s	10 Gbps
Moon	3.84×10^5	11x	2.5 s	82 Mbps
Mars	2.25×10^8	6,280x	25 min	253 bps

Beyond the simple issue of latency, signals experience a drop off in signal-to-noise ratio inversely proportional to the square of the distance. For example, if a space asset at GEO achieves 10 Gbps, say, the same asset would be capable of 82 Mbps at the Moon, and only 253 bps at Mars, all other things equal.

2.4 USING GPS AT THE MOON – WHAT WOULD IT MEAN AT MARS?

These differences in distance imply that some aspects of architectures that work at the Moon would not work well at Mars.

For example, suppose we wish to provide PNT services at the Moon with a constellation of lunar orbiters broadcasting position and timing signals to users on and around the Moon. Such an orbiter would need to determine its own orbit and the time – whether measured in Coordinated Universal Time (UTC) or another timescale – to a certain precision.

One approach for accomplishing this is for the lunar orbiter to look back at global navigation satellite system (GNSS) satellites orbiting Earth, such as the GPS satellites. GPS satellites are in medium Earth Orbit (MEO) at an altitude of 20,200 km. From the Moon, two GPS satellites at maximum separation would span about 6° and the signal would be about 361 times weaker than Earth reception of GPS. This approach is called weak-signal GPS. Many studies have shown that despite the weaker signal and narrow angles involved, the navigation signals of GNSS satellites can support a variety of lunar navigation and timing scenarios [24][26][27][88].

However, a weak-signal GNSS signal architecture is not viable at Mars: the signal would be 120 *million* times weaker than GPS reception on the Earth, and the angular separation between two GPS satellites would be 0.005°.

Instead, space assets providing PNT services at Mars, or at other deep space bodies, require a dedicated system to help them accomplish the perquisite tasks of orbit determination and timing. As such, this implies the importance of flying highly stable clocks on these assets. However, even at the Moon, weak-signal GPS has poor line-of-sight geometry and the accurate orbit solutions needed for lunar PNT satellites will still require highly stable clocks.

3 INVESTMENT PRIORITIES

The intent of this white paper is to help define architectures and technologies worth investing in now for the long-term goal of providing PNT services for human missions to Mars. The example above shows that PNT technologies that work on Earth may extend in some important ways to the Moon, but that new dedicated back-end architectures may be needed to support PNT services at Mars and beyond.

For NASA to be successful in its Moon to Mars program within the 2030s, we recommend that NASA invest in technologies needed for Mars and be ready to incorporate and test them within the context of the Moon campaign, as a milestone. This will be a more efficient and cheaper approach than designing separate and unrelated PNT infrastructures for the Moon and Mars.

Sections 4 through 7 of this white paper provide the technical reasoning and basis for investments in the following key areas.

3.1 ATOMIC CLOCKS

Initially GNSS clocks such as the rubidium cell clock and the passive hydrogen maser now in use by GPS and Galileo respectively, will suffice to provide the basis for a timescale at the Moon. These clocks have significant drift of greater than 10^{-14}/day and updates are required several times a day to avoid undesirable positioning errors. These clocks can use weak GPS signals from Earth to stay updated even when in orbit around the Moon, though with some SNR degradation the best possible positioning error will likely have some degradation. However, greater autonomy from the link to Earth will make a lunar system more robust and will also enable the eventual establishment of the lunar timescale on the lunar surface. More importantly, a timescale at Mars will not have the benefit of weak GPS signals and so greater autonomy will be a requirement. Clocks with the size, weight, and power (SWaP) of GNSS clocks but with active hydrogen maser performance, including drift < 10^{-15}/day, will enable timescales that can run autonomously for weeks or more.

Currently, the only space clock that has demonstrated this level of drift is the Deep Space Atomic Clock (DSAC) demonstration of a trapped ion clock. The DSAC SWaP was similar to that of the passive hydrogen maser, and it has been estimated that with investment, a follow-on version could reduce SWaP by a factor of two.

3.2 HIGH-PERFORMANCE SOFTWARE-DEFINED RADIOS

The continued development of high-performance software defined radios (such as UST-lite) for use at the Moon and beyond is warranted and an enabling technology for lunar navigation satellite systems. Required features will include multiple frequency capability, frequency agility, advanced one-way tracking and two-way ranging, orbit determination, and some aspects of autonomous operation. Two-way ranging should utilize the CCSDS telemetry ranging standard for maximum link efficiency and performance.

For more detail see Section 5.1.4.2. Continued investment is also recommended for the Iris radio, as a valuable approach to autonomous navigation with either two-way or one-way radiometric tracking. For more detail see Sections 5.1.4.3 and 6.1.1.

3.3 WEAK-SIGNAL GPS RECEIVERS

The continued development of weak signal GPS receivers for use at the Moon and beyond is warranted as they are enabling technologies for meeting the 21-day self-nav requirement for Gateway. For more detail see Section 5.1.4.1.

3.4 GROUND STATIONS AND OPERATIONS

The Deep Space Network (DSN) continues to support many missions in deep space. It will continue to be heavily subscribed in the near, medium, and long term, especially with the advent of deep space cubesats which can accompany deep space missions and carry a separate communications system. Plans for a return to the Moon will stretch the DSN further to provide services for communications, navigation, timing, and atomic clock updates.

Therefore, the DSN will not be able to provide all necessary ground support services. NASA’s plans for the Moon require a robust set of additional ground stations and a plan for their operations. Plans are needed for deploying these ground stations, operating the link between the LunaNet Lunar Segment and LunaNet Earth Segment, and providing standards for interfacing between the LunaNet Earth Segment and the User Earth Segment [1].

4 LUNAR PNT ACTIVITIES

4.1 NASA’S ARTEMIS PROGRAM

The Artemis Program is a space exploration initiative for robotic and human missions to the Moon. It is led by the United States’s National Aeronautics and Space Administration (NASA), along with three international partner agencies – the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and the Canadian Space Agency (CSA). The program is named after the Greek goddess of the Moon, Artemis, and it seeks to establish a sustainable human presence on the Moon for the first time since the Apollo 17 mission in 1972. Artemis also serves as a preparation platform to demonstrate and to develop new technologies that facilitates human missions to Mars [2].

Artemis includes a few key components: the Space Launch System (SLS), the Orion spacecraft, the Lunar Gateway space station, and the commercial Human Landing System (HLS). The program also includes the development of new lunar landers and rovers.

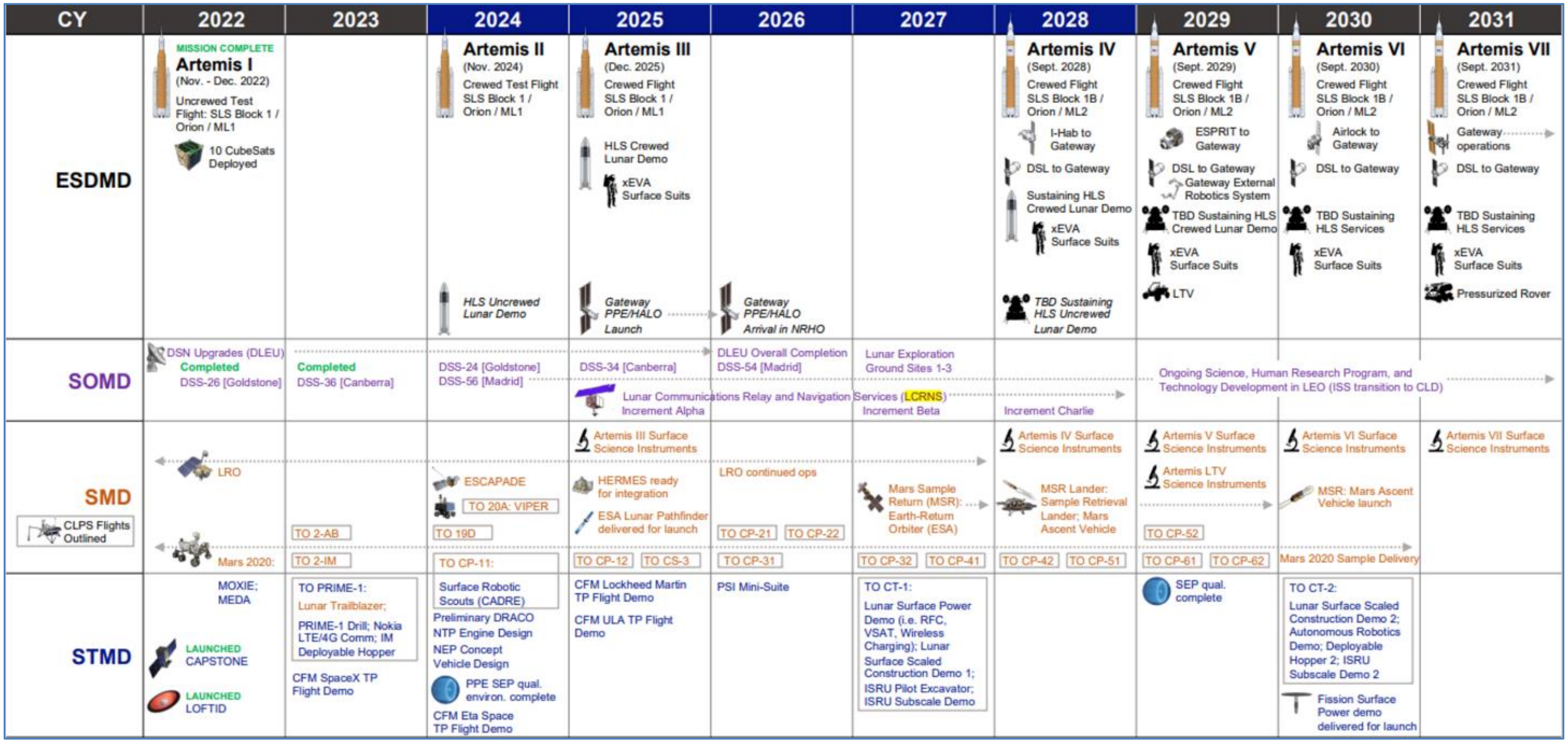
Artemis-I [6] was the first mission of the Artemis Program. It launched November 2022 and was an uncrewed test flight of SLS rocket and the Orion spacecraft to a retrograde orbit around the Moon and return to Earth. The mission lasted for 25 days, with a successful splash-down in the Pacific Ocean off the coast of San Diego on December 11, 2022.

Artemis-II [7] is scheduled to launch in November 2024, and will be the first flight with four crew members onboard Orion. It will orbit the Moon and then return to Earth. Artemis-II will test and demonstrate optical communication to and from Earth using the Orion Artemis II Optical Communication System (O2O) [8]. The O2O hardware includes a 4-inch telescope with gimbals, modem, and control electronics. The O2O flight system will demonstrate optical downlink communications with a data rate of up to 260 Mbps.

Artemis-III [9] is the first landing crew mission at the lunar South Pole. NASA awarded the first Human Landing System (HLS) contract to the commercial company SpaceX in April 2021 to develop the Starship as the landing vehicle for the Artemis-III missions. The mission concept includes sending four astronauts with an SLS rocket and Orion spacecraft to a Near Rectilinear

Halo Orbit (NRHO) orbit around the Moon. SpaceX will launch the uncrewed Starship to the NRHO orbit, and then dock with the Orion spacecraft. Two astronauts will stay onboard the Orion spacecraft, and two astronauts will transfer to the Starship. The Starship, with the two astronauts, will then descend and land on the lunar surface. While on the lunar surface, the two astronauts will conduct up to four Extravehicular Activities (EVA's) and perform a number on in-situ experiments and science observations for about a week. Starship will return them to the NRHO and dock with the orbiting Orion spacecraft. Orion will carry all 4 astronauts back to Earth.

The rest of the Artemis Program manifest is summarized in Figure 1 [10].



CY	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
ESDMD	MISSION COMPLETE **Artemis I** (Nov. - Dec. 2022) Uncrewed Test Flight: SLS Block 1 / Orion / ML1 10 CubeSats Deployed		**Artemis II** (Nov. 2024) Crewed Test Flight SLS Block 1 / Orion / ML1 *HLS Uncrewed Lunar Demo*	**Artemis III** (Dec. 2025) Crewed Flight SLS Block 1 / Orion / ML1 HLS Crewed Lunar Demo xEVA Surface Suits *Gateway PPE/HALO Launch*	*Gateway PPE/HALO Arrival in NRHO*		**Artemis IV** (Sept. 2028) Crewed Flight SLS Block 1B / Orion / ML2 I-Hab to Gateway DSL to Gateway Sustaining HLS Crewed Lunar Demo xEVA Surface Suits *TBD Sustaining HLS Uncrewed Lunar Demo*	**Artemis V** (Sept. 2029) Crewed Flight SLS Block 1B / Orion / ML2 ESPRIT to Gateway DSL to Gateway Gateway External Robotics System TBD Sustaining HLS Crewed Lunar Demo xEVA Surface Suits LTV	**Artemis VI** (Sept. 2030) Crewed Flight SLS Block 1B / Orion / ML2 Airlock to Gateway DSL to Gateway TBD Sustaining HLS Services xEVA Surface Suits	**Artemis VII** (Sept. 2031) Crewed Flight SLS Block 1B / Orion / ML2 Gateway operations DSL to Gateway TBD Sustaining HLS Services xEVA Surface Suits Pressurized Rover
SOMD	DSN Upgrades (DLEU) Completed DSS-26 [Goldstone]	Completed DSS-36 [Canberra]	DSS-24 [Goldstone] DSS-56 [Madrid]	DSS-34 [Canberra] Lunar Communications Relay and Navigation Services (LCRNS) Increment Alpha	DLEU Overall Completion DSS-54 [Madrid]	Lunar Exploration Ground Sites 1-3 Increment Beta	Increment Charlie	Ongoing Science, Human Research Program, and Technology Development in LEO (ISS transition to CLD)		
SMD CLPS Flights Outlined	LRO Mars 2020:	TO 2-AB TO 2-IM	ESCAPADE TO 20A: VIPER TO 19D TO CP-11:	Artemis III Surface Science Instruments HERMES ready for integration ESA Lunar Pathfinder delivered for launch TO CP-12 TO CS-3	LRO continued ops TO CP-21 TO CP-22 TO CP-31	Mars Sample Return (MSR): Earth-Return Orbiter (ESA) TO CP-32 TO CP-41	Artemis IV Surface Science Instruments MSR Lander: Sample Retrieval Lander; Mars Ascent Vehicle TO CP-42 TO CP-51	Artemis V Surface Science Instruments Artemis LTV Science Instruments TO CP-52 TO CP-61 TO CP-62	Artemis VI Surface Science Instruments MSR: Mars Ascent Vehicle launch Mars 2020 Sample Delivery	Artemis VII Surface Science Instruments
STMD	MOXIE; MEDA LAUNCHED CAPSTONE LAUNCHED LOFTID	TO PRIME-1: Lunar Trailblazer; PRIME-1 Drill; Nokia LTE/4G Comm; IM Deployable Hopper CFM SpaceX TP Flight Demo	Surface Robotic Scouts (CADRE) Preliminary DRACO NTP Engine Design NEP Concept Vehicle Design PPE SEP qual. environ. complete CFM Eta Space TP Flight Demo	CFM Lockheed Martin TP Flight Demo CFM ULA TP Flight Demo	PSI Mini-Suite	TO CT-1: Lunar Surface Power Demo (i.e. RFC, VSAT, Wireless Charging); Lunar Surface Scaled Construction Demo 1; ISRU Pilot Excavator; ISRU Subscale Demo		SEP qual. complete	TO CT-2: Lunar Surface Scaled Construction Demo 2; Autonomous Robotics Demo; Deployable Hopper 2; ISRU Subscale Demo 2 Fission Surface Power demo delivered for launch	

Figure 1. The Artemis program manifest (April 4, 2023)

4.2 LUNANET

LunaNet is a proposed network infrastructure that provide communications, navigation, and science services to the robotic and human exploration activities at the Moon as part of the Artemis Program [11]. The architecture will comprise relay satellites in lunar orbit and surface assets that serve as network access points (or nodes) for lunar surface and orbital users. The nodes can be provided by the government, private industry, or international partners that can form a network of nodes, which all adhere to a set of common standards, protocols, and interfaces to ensure interoperability [1]. The network architecture is flexible and extensible, allows gradual built-up of nodes, and provides communications, navigation, and other services to lunar users. Some of the key objectives of LunaNet are:

1. Extend terrestrial network service paradigm to the Moon and beyond – the current space communication and navigation approaches are link-centric and require manual routing of data and configurations of individual links. In the data-driven network service paradigm, the network complexity is hidden from the users, and the network automatically and reliably routes the data from the source to the target via one or more network nodes.
2. Promote Public Private Partnership (PPP) for lunar exploration – the LunaNet relay architecture encourages private companies and international partners to develop and to deploy network nodes that are compliant with the LunaNet Interoperability Specifications [1]. The service providers can then charge a fee for the communications, navigation, and other services provided to lunar users.
3. Support the Moon-to-Mars Initiative [2] – the Moon-to-Mars Initiative is a NASA program that aims to establish a sustainable human presence on the Moon, and then use that experience to enable crewed missions to Mars. It is expected a large part of the LunaNet architecture and the associated technology developments can be applied for other planetary bodies, including Mars.

The LunaNet nodes are capable of providing four standard services:

1. Networking Services: this set of service provides end-to-end routing of data via one or more network nodes. When a network node orbits around the Moon, its visibilities with Earth, users, and other nodes are continually changing and this makes data routing challenging. LunaNet relies on the Consultative Committee for Space Data Systems (CCSDS) Delay/Disruption Tolerant Network (DTN) as the principal internetworking protocol. DTN employs dynamic routing algorithms like contact graph routing [12][13] to forward data packets from the source through the time-varying network to the target. DTN also employs Licklider transmission Protocol (LTP) [14] which is an automatic repeat protocol that ensures reliable data transfer between two nodes.
2. Position, Navigation, and Timing (PNT) Services: PNT services that enable determination of users' position and velocity, as well as time distribution and synchronization. The PNT services enable a user to determine its position and velocity in a timely fashion to meet mission requirements in orbit determination, trajectory and/or path planning, and executing maneuvers. The LunaNet nodes broadcast the PNT signals and messages. Using LunaNet compatible receivers, the

user measures Doppler, range, and time from LunaNet, and receives a navigation message from the LunaNet nodes. With this data, the users can determine their position, velocity, and time. The signal formats and messaging schemes are similar to Earth's Global Positioning System (GPS) and other Global Navigation Satellite Systems (GNSS's) [15]. The Earth's GPS/GNSS signals operate in L-band. The Lunar PNT services are offered in near-Earth S-band.

3. Detection and Information Services: this set of services provide alerts and critical information for lunar user operations. One example is the space weather alerting services that monitor space weather conditions. Solar energetic particles (SEP) and the radiation effects resulting from solar eruptions can be harmful to humans and sensitive instruments in the lunar environments. The space weather alerting services can provide advance warnings so that the sensitive instruments can be shut off and the astronauts can take safety precautions before the SEP events. Another example is the Lunar Search and Rescue (LunaSAR) services that enable users to report location and to request for assistance during off-nominal situations.
4. Science Utilization Services: the Moon-orbiting LunaNet nodes form a dynamic and diversify (in time and space) platform that can perform science and exploration observations and measurements. LunaNet nodes may be able to support science objectives by using available radio and optical links. It is expected that some specific modes of the RF and optical communications and PNT equipment can be operated to support science investigation like radio science, radar science, and radio astronomy/Very Long Baseline Interferometry.

4.3 LUNANET INTEROPERABILITY SPECIFICATIONS (LNIS)

The LNIS is a draft document that covers a wide range of technical areas including signal formats, frequency assignments, data protocols, communication interfaces, navigation, science, security, and encryption requirements. The LNIS development is a collaboration effort with contributors from NASA and ESA. At the time of this writing, the publicly available document is draft Version 5 [1].

The LNIS include a set of technical requirements, standards, and internal/external interfaces that would govern the operation and communications of the LunaNet network to provide networking services, PNT services, detection and information services, and science utilization services to the users at the Moon. The main objective of the specifications is to ensure that all components of the network can communicate and interoperate with each other, and that the network can support a wide range of user requirements. The LNIS specifications are designed to be flexible and adaptable, allowing them to evolve over time as new technologies and requirements emerge.

The LNIS development has been closely coordinated with other standardization efforts like the International Communication System Interoperability Standards (ICSIS) [16] and the Interagency Operations Advisory Group's (IOAG) Lunar Communication Architecture Document [17]. The LNIS intends to provide the minimum set of standard services and interfaces that will be available to lunar users, such that users may design their systems with the expectation of available providers. Any individual provider is not required to offer all services and interfaces in the LNIS. It is also possible for providers to offer services and interfaces beyond those described in the LNIS document.

The LNIS includes internal standards and interfaces between service providers and Earth, and external standards and interfaces between LunaNet nodes and users. This paper will not discuss the internal interfaces and will describe the three standard user services and their interfaces.

1. Communications Services – LNIS offers communication services to users in near-Earth S-band (low-rate) and in K-band (high-rate). There are three communication service types:
    a. Real-time data services provide end-to-end data delivery between source and target with minimal delay. The latency will be limited to light-time-delay and the processing delay related to channel coding and data buffering and synchronization.
    b. Store-and-forward data services provide end-to-end data delivery with additional delay due to onboard storage of data that are required to mitigate expected and unexpected link outages, and re-transmissions of corrupted data to ensure reliable data transfer.
    c. Messaging services provide a way to send standardized messages between LunaNet nodes and LunaNet users over specific message channels within the communication services. The messages can be transport over a link layer service or a network layer service to be utilized by LunaNet applications or protocols. LunaNet applications are applications for service acquisitions, PNT, alerts, and other LunaNet services.
2. Position, Navigation, and Timing (PNT) Services - the PNT services can be classified in two groups:
    a. Dedicated links: this group includes PNT services that are provided by direct single-access links between the user and the provider. A dedicated link can provide a reference signal for PNT observables (e.g., Doppler and range) and associated message, or it can transmit messages only that support PNT.
    b. Lunar Augment Navigation System (LANS): this is a broadcast service from multiple LunaNet nodes to multiple users at the same time, and the service operates in S-band (2.5 GHz). The signal and messaging formats are similar to the Earth's GPS/GNSS constellations. Users can perform trilateration via range measurements via LANS broadcasts that can provide real-time kinematic position and time estimates when a minimum of four LunaNet nodes are simultaneously in view with a user.
3. Detection and Information Services – there are at least two kinds of services:
    a. Lunar Search and Rescue (LunaSAR) Services enable users to report location and distress information via internationally recognized messaging standards modelled after current state-of-the-art messaging content used in terrestrial search and rescue (SAR) activities. LunaSAR services require a combination of reception, prioritization, and re-broadcast/pass-through of distress messages on LunaNet direct-to-Earth and proximity links.
    b. Space Weather Alerting Services monitor space weather conditions and broadcast advance warning and related messages using the LunaNet communication messaging services.

4. Science Utilization Services – the Moon-orbiting LunaNet nodes provide a stable platform for multiple science observation instruments distributed in space and in time. Some examples of science observations are space weather monitoring, sampling of solar wind, and solar imaging.

4.4 LUNAR COMMUNICATION RELAY AND NAVIGATION SYSTEM (LCRNS)

NASA initiated the Lunar Communication Relay and Navigation System (LCRNS) project in 2022 to develop the long-term communications and navigation infrastructure at the Moon to meet the needs of the Artemis missions and other lunar missions [18]. The LCRNS project has defined a set of requirements and specifications for reliable and secure relay communications and navigation services by LunaNet service providers, which can be from government, industry, and international partners, to support Artemis missions and other lunar missions and assets like HLS, Orion, Lunar Terrain Vehicle (LTV), EVA, Commercial Lunar Payload Services (CLPS), and other robotic and science missions. The LCRNS relay network is expected to build up incrementally starting with a few relay orbiters that focus on the lunar South Pole region, and to evolve to provide global coverage of the Moon. The Initial Operating Capability (IOC) covers the 2025 through 2028 timeframe. By the end of the IOC, the LCRNS will cover lunar surface areas below -75 degrees south latitude and up to an altitude of 200 km. The Extended Operating Capability (EOC) is expected to start in 2030 and upon completion, will provide global communications and navigation services for the Moon. Currently NASA is soliciting proposals from commercial companies to develop and to deploy the LunaNet as part of its broader efforts to enable lunar exploration and resource utilization [19].

4.5 LUNAR DEVELOPMENTS BY OTHER SPACE AGENCIES

There are several lunar relay network constellations proposed by different space agencies. They are collaborating to ensure that the relay orbiters developed by different space agencies would fit into the overall LunaNet architecture, would conform to the LNIS, and the relay nodes would be interoperable with each other.

4.5.1 ESA: MOONLIGHT

Similar to LCRNS, Moonlight is an ESA initiative that encourages private space companies in Europe and Canada to offer lunar communications and navigation services by launching relay satellites around the Moon [20]. The Moonlight relay orbiters will be LNIS-compliant and interoperable with the LCRNS relay orbiters. The United Kingdom’s Lunar Pathfinder developed by Surrey Satellite Technology Ltd. is due to launch in mid-2025 and is a first step towards ESA’s Moonlight vision, though it is not LNIS-compliant. Lunar Pathfinder offers communication services to lunar users in S and UHF bands.

4.5.2 JAXA: LNSS, DIFFERENTIAL POSITIONING

JAXA proposed a Lunar Navigation Satellite System (LNSS) concept that provides GPS-like navigation services for users at the lunar South Pole with eight relay orbiters in two Elliptical Lunar Frozen Orbits (ELFO’s) [21]. JAXA has initiated discussion with NASA and ESA to ensure that the LNSS relay orbiters are complaint with LNIS and can be interoperable with the

LCRNS and Moonlight relay orbiters. In addition to position, navigation, and timing services LNSS will also provide radio frequency and optical communications services. As part of the LNSS development, JAXA also proposed a PNT interoperability demonstration mission in 2028 to deploy one LNSS orbiter in a ELFO orbit and a lander at the lunar South Pole. The lander's receiver will demonstrate the acquisition of the PNT signals available from LNSS, LCRNS, and Moonlight orbiters to estimate the lander's position.

LCRNS, Moonlight, and LNSS orbiters all rely on the weak signals from the side-lobes of the Earth GPS/GNSS constellations for orbit determinations (OD) of relay orbiters at lunar distance of approximately 400 thousand kilometers. This is very challenging for the following reasons:

1. The GPS/GNSS side-loop signals are weak at lunar distance, and the lunar spacecraft will need a high-gain antenna with low-noise amplifier to detect the signals.
2. The Geometric Dilution of Precision (GDOP) is of the order of a thousand at lunar distance [22][23]. Therefore, any residual systematic and random noises not removed by the onboard navigation filters can be greatly amplified.

Winternitz et al. [24] analyzed and simulated the OD performance of an autonomous navigation system based on weak GPS signal measurements for the lunar Gateway in the NRHO orbit. The paper shows that with an Earth-pointing HGA, the onboard GPS receiver will see three GPS signals on average, with a standard deviation of about 1.5 signals. With a high accuracy atomic clock such as the Spectratime Rubidium Atomic Frequency Standard (RAFS) [25], the OD accuracy (3-sigma) is 32 meters for uncrewed scenario, and 80 meters for crewed scenario respectively. A similar analysis was performed at JPL and appears in § 5.1.4.1 and yields commensurate positioning performance and illustrates that velocity (an important requirement for NASA's Lunar Gateway) would require an atomic clock to meet requirements using weak-signal GPS. Small et al. [26] discussed the lunar relay onboard navigation performance and effects on lander descent to surface. The lunar relay orbiter is assumed to be in a 12-hour frozen orbit. In addition to Earth's weak GPS signals, this paper also considers various combinations of using Earth's ground stations, different clocks, onboard optical navigation, and terrain relative navigation to perform OD. The OD accuracy performance (1-sigma) ranges from 2.1 meters to 113 meters. On the experimental side, NASA's CLPS mission Firefly Aerospace Blue Ghost Lander is scheduled to launch in 2024 [27]. The spacecraft carries the Lunar GNSS Receiver Experiment (LuGRE) payload.

4.5.3 LUNAR GNSS EXPERIMENT (LUGRE) – NASA, ASI

LuGRE is a collaboration between NASA, ASI, and Qascom SRL (an Italian aerospace company). There are three main objectives:

1. Demonstrate the reception of Earth's GPS/GNSS signals at lunar distance and to characterize the signal environment, e.g., multipath effects.
2. Perform real-time onboard positioning, navigation, and timing (PNT) using the GPS/GNSS signals from Earth.
3. Leverage on the experiment results to support development of lunar GPS/GNSS receivers.

5 ARCHITECTURAL CONSIDERATIONS

5.1 LUNAR

5.1.1 CURRENT LUNAR RELAY PROGRAMMATICS AND LNIS CONCEPTS RELEVANT TO PNT AT THE MOON

As outlined in the LNIS the PNT Services can be classified in two groups:

1. Dedicated links: this group includes PNT services that are provided by direct single-access links between the user and the provider. A dedicated link can provide a reference signal for PNT observables (e.g., Doppler and range) and associated message, or it can transmit messages only that support PNT.
2. Lunar Augment Navigation System (LANS): this is a broadcast service from multiple LunaNet nodes to multiple users at the same time. The service operates at S-band (2.5 GHz) and uses CDMA to facilitate connections multiple users, simultaneously. The signal and messaging formats are similar to the Earth's GPS/GNSS constellations.

5.1.1.1 Dedicated links

The dedicated services link is the traditional approach utilized by the DSN to support users, including cis-lunar and lunar users, in which the user coherently transponds the signal and the DSN collects two-way range and Doppler. However, it might also be utilized by a LunaNet service provider (LNSP), especially, in the IOC phase where capability is being built up. In these early phases, the LNSP collects two-way coherent range and Doppler tracking on its in-situ proximity links to orbiting and/or surface users. This data would then be telemetered to a user (with sufficient onboard navigation processing capabilities) to conduct its own navigation or back to Earth for traditional ground-based navigation. Existing radio technologies, such as Iris or UST, are well adapted to support this type of service with minimal to no modification. Since two-way tracking services do not require advanced or particularly stable clocks by the user, use of this type of service requires little modification to the typical deep space user navigation concept of operations. This two-way data would likely be transmitted to a ground-based navigation team for processing.

5.1.1.2 Lunar Augmented Navigation System

The LNIS provides the option for the LNSP to transpond a two-way signal from the user which then receives the signal and collects the radiometric data. This is "flipped" relative to the preceding discussion for the dedicated link. In this mode, the user would either process the data in situ or telemeter it back to Earth for processing. An important distinction with this mode, versus the dedicated mode, is the stability of the user's onboard time keeping becomes more critical as the user radio will need to timetag collected measurements (rather than the LNSP). Because this mode requires dedicated links to users it would likely only be useful in early stages when there is a limited user set and the need to support simultaneous links would be minimal.

A more scalable LNSP navigation service is the broadcast mode on a dedicated PNT channel that supports all in-view users simultaneously. This is an analog to the Earth GNSS services but, at the Moon, uses a specified S-band channel (rather than L-band) with CDMA modulation. Each LNSP asset broadcasts a unique PN code and associated navigation and time message to the user, which provides one-way tracking signals to end users with the intended receiver. This represents an opportunity to combine JPL's expertise in GPS receiver and deep space transponder technologies to come up with a high performance comm and nav radio that is compatible with the LunaNet service providers broadcast signals. Indeed, the recent Iris radio update to use a CSAC and collect one-way radiometric tracking is an example that could be adapted to interoperate with LunaNet [46]. Currently, this capability is being tested by the CAPSTONE mission. The performance level of these LNSP PNT services will depend on the user's location (orbiting or surface), the number of LNSP relays that are simultaneously in view of the user, the quality of the LNSP oscillator/clocks on the relays, and the quality of the user receiving system and clocks.

Stable clocks will be needed on all LNSP assets that broadcast and, in the early stages when few LNSP assets are available, the user will need a stable clock as well. There are many available options but, as with Earth GNSS, the LNSPs would likely need atomic clocks such as a Rubidium (initially) and eventually a Deep Space Atomic Clock (DSAC-2) (when available). The use of DSAC-2 would significantly reduce the overhead/ground support needed to maintain a stable lunar time base for the LNSPs to broadcast. Note that GPS clocks are predominately Rbs and, because of their significant drifts, require an extensive ground system to track and upload multiple clock updates per day. DSAC-2's extremely low drift would enable clock ephemerides that could be accurate for weeks (vs. hours) and significantly reduce the ground-based effort to maintain a stable time. User clocks could range from chip scale atomic clocks (CSACs), miniature (rubidium) atomic clocks (MACs), ultra-stable oscillators (USOs), or even Deep Space Atomic Clocks (DSACs), with the choice depending on the user's needs.

5.1.2 LUNAR TIMESCALES

PNT and other applications at the Moon will be more robust and autonomous with a local timescale. Ideally, this would be a representation of UTC at the Moon synchronized with UTC [104]. This could be referred to as UTC(Moon) and would be modelled after the UTC(k) maintained at each of the major timing metrology laboratories on Earth. However, this may not be practical for PNT at the Moon: due to relativistic shifts, UTC(Moon) would vary rapidly with respect to un-steered local clocks. For example, Figure 2 shows calculated variations between a clock at the Moon and one located at the solar system barycenter (center of mass) [140]. Similar variations between clocks at the Moon and UTC would require constant adjustment (unlike UTC(k) on Earth whose relativistic offsets are static) and would complicate navigational implementations and applications. In addition, synchronization would require a frequency control loop that continuously monitors the difference between UTC(Moon) and UTC and applies a steering correction to UTC(Moon) equal to this difference. Closed loop operation of this type between clocks on the ground and those in Earth orbit is challenging because of significant noise in the time and frequency transfer methods used to perform the comparison. For instance, GPS time transfer only becomes less noisy than the underlying

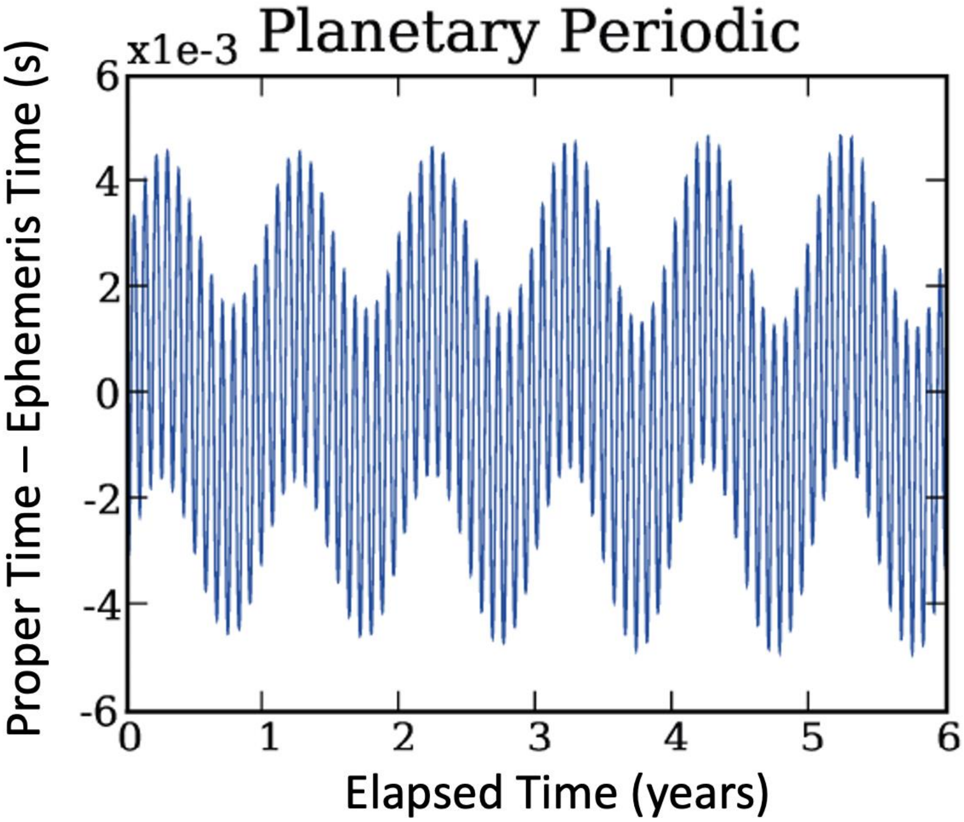


Figure 2. Proper time minus the time ephemeris at the Moon. Time ephemeris is a solar system barycenter coordinate time. The graph shows the monthly and annual variations due to relativistic effects that a local time scale at the Moon would experience relative to time in a coordinate system fixed to the solar system center of mass. The large amplitude variations give an order of magnitude for how a clock at the Moon will vary relative to UTC. Steering such a clock to UTC would complicate PNT applications.

clocks at about 10,000 seconds of averaging time [105] so that updates on timescales < 10,000s would degrade clock performance and are not currently feasible (it is possible to make continuous updates but only if they are based on a running average of 10,000 s, so they will still have a significant lag). Due to increased light travel time delays and increased noise, closing the loop becomes even more difficult with increasing distance.

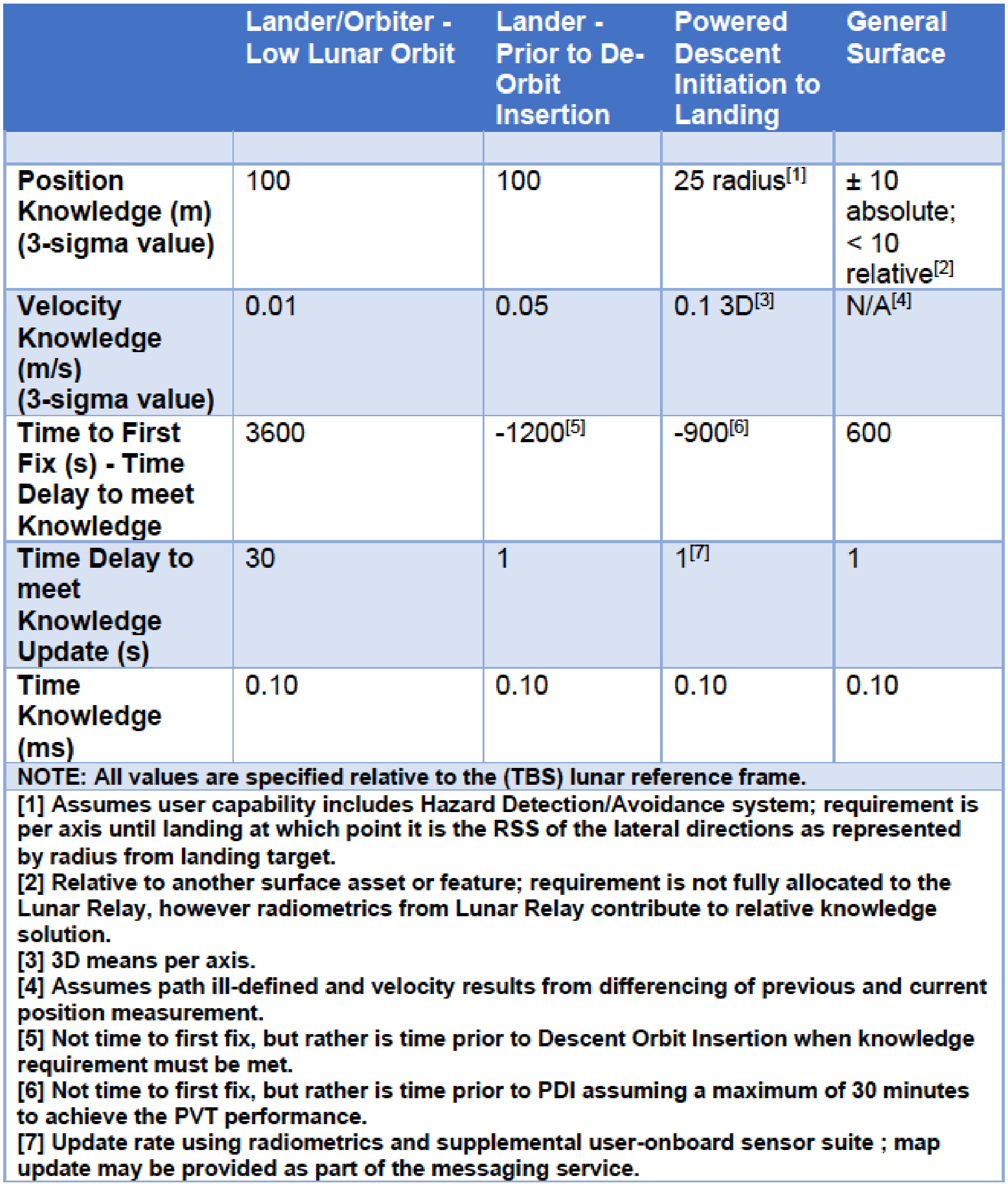
Another important aspect of UTC is that it currently uses leap seconds to keep it synchronized with Earth's rotation, which is continuously slowing down (see the leap second section above). The leap second is implemented by occasionally adding a second at the end of June 30 or December 31. This jump would be highly disruptive to GNSS systems, so they synchronize to TAI [106] instead, which can be considered UTC without the leap second.

With these considerations, a free-running autonomous timescale at the Moon with differences to UTC continually monitored would be more practical. Such a system might be referred to as Coordinated Lunar Time or LTC and would be derived from stable clocks located at the Moon (initially in orbit, but ultimately on the surface). Earth-based GNSS systems employ satellite clocks that have frequency drifts $> 10^{-14}$/day. As a result, they must be updated several times a day to avoid undesirable positioning errors. As a starting point, a similar approach could be used at the Moon using weak GPS signals [24][26][27][88]. Due to a lower signal-to-noise ratio for these signals relative to GNSS systems around Earth, there would be some loss of positioning precision. This operation requires a very precise quasi-continuous comparison to more stable clocks on the ground. As more stable clocks become available for this lunar timescale, it will gain more autonomy, robustness, and precision. A timescale located on the surface of the Moon would provide further precision but would then need to account for the Earth being out of view for two-weeks at a time. This would require a more complex infrastructure for relaying monitor signals to and from Earth or would require more stable clocks able to run with minimal impact from drift over this period, or both.

5.1.3 SPACE RELAY COMMUNICATION AND NAVIGATION SERVICES

NASA is evaluating proposals from the recent NENS RFP and is anticipating making an award for its Category 2 services that covers Space Relay communication and navigation services for customer missions, spacecraft, or payloads up to two million kilometers from Earth. In particular, Section 4.3.2 (Category 2.2: GEO-to-Cislunar Relay Services) specifies the lunar relay services to lunar users and includes compliance with both the LNIS and requirements from Lunar Communications Relay and Navigation Systems (LCRNS) project’s Lunar Relay Services Requirements scenarios including a low lunar orbiter at 100 km altitude, deorbit for landing, lander trajectory knowledge at the start of powered descent, and a surface user (fixed and moving at ~10 km/h). The selected LNSP would be able to provide signals that support PNT services using their deployed lunar relay system. For convenience, the required performance specifications are repeated in Table 2.

Table 2. Representative user scenario PNT performance requirements



	Lander/Orbiter - Low Lunar Orbit	Lander - Prior to De-Orbit Insertion	Powered Descent Initiation to Landing	General Surface
Position Knowledge (m) (3-sigma value)	100	100	25 radius[1]	± 10 absolute; < 10 relative[2]
Velocity Knowledge (m/s) (3-sigma value)	0.01	0.05	0.1 3D[3]	N/A[4]
Time to First Fix (s) - Time Delay to meet Knowledge	3600	-1200[5]	-900[6]	600
Time Delay to meet Knowledge Update (s)	30	1	1[7]	1
Time Knowledge (ms)	0.10	0.10	0.10	0.10

NOTE: All values are specified relative to the (TBS) lunar reference frame.

[1] Assumes user capability includes Hazard Detection/Avoidance system; requirement is per axis until landing at which point it is the RSS of the lateral directions as represented by radius from landing target.
[2] Relative to another surface asset or feature; requirement is not fully allocated to the Lunar Relay, however radiometrics from Lunar Relay contribute to relative knowledge solution.
[3] 3D means per axis.
[4] Assumes path ill-defined and velocity results from differencing of previous and current position measurement.
[5] Not time to first fix, but rather is time prior to Descent Orbit Insertion when knowledge requirement must be met.
[6] Not time to first fix, but rather is time prior to PDI assuming a maximum of 30 minutes to achieve the PVT performance.
[7] Update rate using radiometrics and supplemental user-onboard sensor suite ; map update may be provided as part of the messaging service.

We are aware of several commercial concepts for these relay systems, notably, LMCO's Cresent Space [107] Parsec constellation and ArgoTec's [108] Andromeda constellation. Others may have also responded to the NASA's RFP.

5.1.4 SUMMARY OF RELEVANT LUNAR NAVIGATION ANALYSIS RESULTS

For the past year, Todd Ely has conducted PNT analyses of lunar relay systems (in their early operations) that included analyzing the navigation performance of the relay system itself (and how that contributes to the accuracy of a broadcast ephemeris and time message to users), and the performance of the initial operational navigation services provided to surface users (specifically, a South Pole user). The analysis trades examined performance with different clock assumptions and network topologies (i.e., dedicated link vs CDMA). JPL has engaged in early conversations with both LMCO and ArgoTec on their constellation concepts. This has been facilitated and supported by John Baker's JPL institutional small satellite program.

A particular relay concept that has become popular is deploying the relay satellites in twelve-hour elliptical frozen orbits that are designed to maximize coverage over the poles [45]. Indeed, this is the orbit type selected for ArgoTec's Andromeda and LMCO's Parsec constellations. These constellations would focus their coverage and services to the Moon's South pole, the focus of the Artemis program, but lunar they both have expansion plans to provide full lunar coverage when complete.

When examining possible navigation performance for the user scenarios outlined in the table above and for Gateway there are four leading tracking cases to consider

- Direct to Earth tracking initially by the DSN but eventually expanding to other Earth-based ground systems
- Lunar relay tracking by constellations such as Andromeda and Parsec
- Weak signal GPS – mostly for orbiting assets since surface users at the Poles do not have good visibility (an interesting visualization of the Earth and Sun from Shackelton is contained in [44])
- Optical based methods for terrain relative navigation while in orbit and horizon matching while on the surface

5.1.4.1 Weak-signal GPS and atomic clock technology

Results from Ely's analysis for Gateway highlight DSN DTE performance as well as weak-signal GPS. Some key requirements for Gateway while uncrewed are the following:

- Maintain 10 km (3-sigma) or better position knowledge,
- Maintain 10 cm/s (3-sigma) or better velocity knowledge, and
- Demonstrate the ability to self-navigate for 21 days while uncrewed.

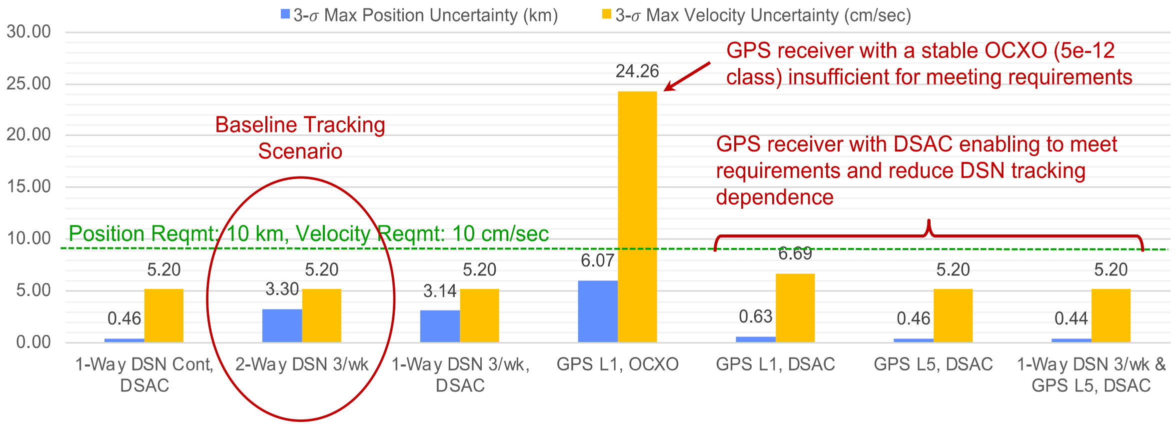


Figure 3. Maximum 3-σ RSS position and velocity uncertainties

For nominal operations, the velocity requirement is the most stressing to maintain and is present to ensure Gateway maintains a stable NRHO with the station keeping delta-V it has available. Gateway nominal uncrewed operations will rely on DSN tracking for navigation with a three-passes-per-week schedule (this is increased during crewed operations). The analysis results summarized in Figure 3 demonstrate that this level of tracking is sufficient to meet the 10 km and 10 cm/s requirements. The self-navigation requirement is intended to both reduce operations costs as well as incentivize development of methods for autonomous navigation that could feed forward to Mars. For reducing operations costs, the weak-signal GPS approach has potential as it is readily available for Gateway and, as the analysis results below show, can meet the velocity requirement when a high-quality clock with minimal drift (such as DSAC) is used as a reference for the GPS receiver. Indeed, the results show that an OCXO is NOT sufficient to meet the velocity requirement (the 3-sigma max velocity error is ~ 24 cm/s, exceeding the 10 cm/s requirement) even with the near continuous level of tracking that is provided by GPS.

What about adding tracking from other GNSS constellations, such as Galileo, to improve the performance with an OCXO? The results in Figure 4 for the RSS velocity error with GPS & Galileo tracking using an OCXO still yield a 3-sigma velocity uncertainty of 16.4 cm/sec – an improvement but still not sufficient.

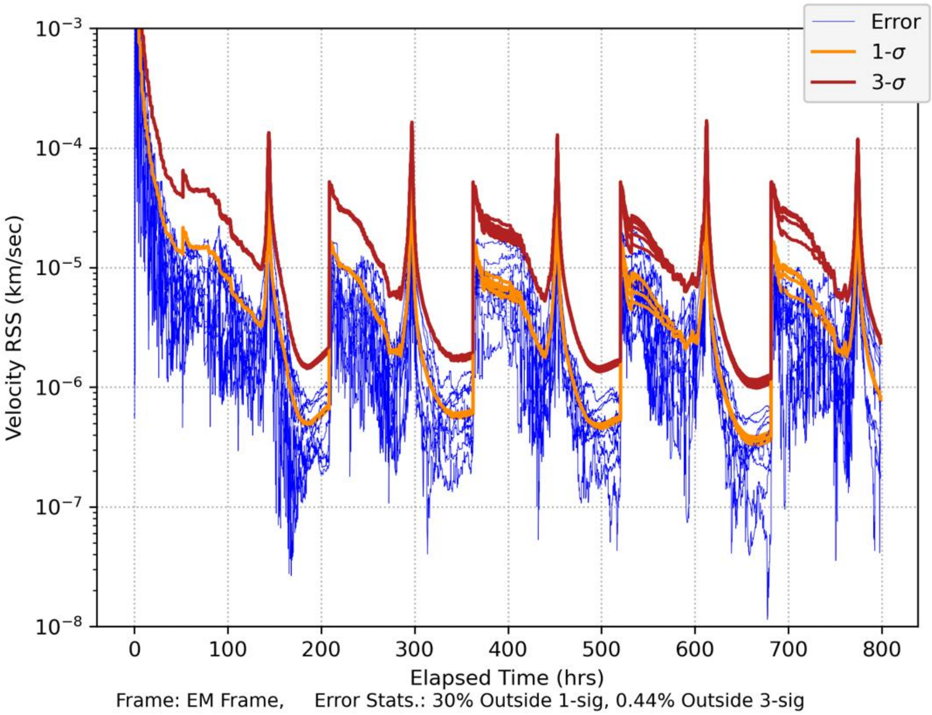


Figure 4. RSS velocity error with GPS & Galileo tracking using an OCXO showing simulated velocity errors and 1-sigma and 3-sigma uncertainties. Note that the maximum 3-sigma uncertainties exceed the 10 cm/sec requirement.

In summary, the continued development of weak-signal GPS receivers and space atomic clocks (such as DSAC) for use at the Moon and beyond is warranted as they are enabling technologies for meeting the 21-day self-nav requirement for Gateway.

5.1.4.2 Navigation performance and radio technology

Turning to navigation performance simulations for potential lunar relay constellations, a representative example is the Andromeda constellation that will eventually employ 24 twelve-hour elliptical, inclined frozen orbits to provide continuous multi-fold lunar coverage (like GPS or Galileo) to provide communication relay and navigation services to lunar surface and orbiting users [45]. Initially, Andromeda will utilize the DSN to provide tracking and relay services to the satellites in the Andromeda constellation and, after a couple of years, transition to their own Earth-based ground network. These initial plans call for DSN tracking of about four hours per orbit (thus eight hours per day) and to facilitate time transfer to Andromeda this will consist of the two-way Doppler and one-way uplink Doppler and range. Currently, the Andromeda constellation is baselining use of JPL’s UST-lite radio for both its DTE links and in-situ links. A key consideration for a constellation’s potential navigation services is the presence, location, and knowledge of maneuvers used to maintain the constellation’s formation and/or desaturating momentum wheels used to maintain satellite attitude. For Andromeda there are desaturation events that occur every three days and could impart up to 2 cm/s delta-V in the orbit radial direction. Characterizing the impact of these maneuvers is a key consideration. The simulation results in Figure 5 illustrate Andromeda position and velocity uncertainties using DSN tracking over 15 orbits and then propagating for 10 orbits. There are four desaturation maneuvers in this period – two covered by DSN tracking DSN and two that are not.

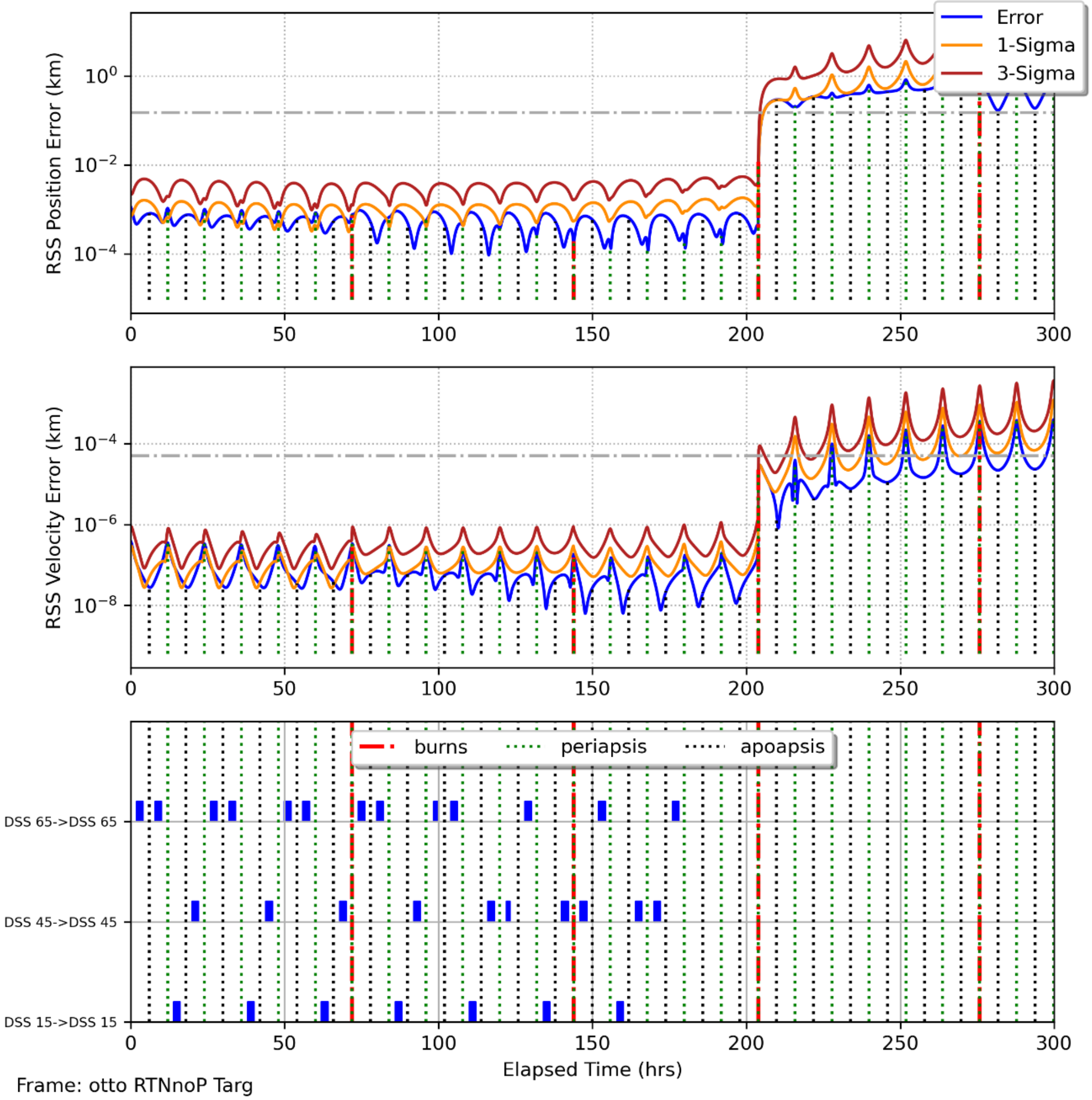


Figure 5. Position and velocity errors/uncertainties for one satellite of the proposed Andromeda Lunar PNT constellation using DSN tracking (4 hrs/orbit ~8 hrs a day). The first three days represent the performance of the trajectory reconstruction, and the final day reflects the propagation errors/uncertainties for the case when a momentum desaturation maneuver occurs on day 3. This case represents the worst-case error scenario for a broadcast navigation message to users.

The reconstructed orbit is accurate to ~5 m (3-sigma) but the propagated orbit error grows quickly when a maneuver occurs – growing to several kilometers in 10 orbits. This has obvious implications for navigation messages that would be broadcast to users (which always use orbit predicts). Indeed, preliminary analysis of the navigation services provided by initial operational versions of the Andromeda constellation (i.e., two to eight satellites with primary South Pole coverage) indicate that meeting 10 m (3-sigma) would be difficult unless Andromeda broadcasts augmented ephemeris information that includes knowledge of the desaturations to within 0.1 mm/sec (1-sigma). A summary of the surface navigation results for lunar South Pole users using the following Andromeda tracking information include:

- 2-way ranging provided with TDMA yields accurate solutions. For fixed South Pole users under 10 m (3-sigma) position knowledge is obtained (on various timescales) when no desaturations are present and under 50 m (3-sigma) when the desaturation (with 0.1 mm/sec knowledge) occurs at the start of the broadcast ephemeris. However, these results are
    - Limited to a small, finite number of users because of the need coherently transpond, and
    - Cannot readily support moving users.
- 1-way tracking with CDMA and lunar navigation satellites manifested with CSACs can produce 100 m-class solutions and is readily scalable to support unlimited numbers of users
- Augmenting the lunar navigation satellites with DSAC-stable clocks yields the best most agile solutions (note that the users can use CSAC). Indeed, the one-way position solutions are similar to two-way at under 10 m (3-sigma) when no desaturation event is in the broadcast ephemeris over time and better than 2-way at under 20 m (3-sigma) when there is a desaturation event (known to 0.1 mm/sec) in the broadcast ephemeris. Additionally, the results with DSAC and 1-way when multiple Andromeda satellites are in view enable sub-50 m-class solutions for moving users.

An illustration of this performance is shown in Figure 6 when there are eight lunar navigation satellites, each with a DSAC, and a South Pole user with a CSAC. The tracking periods are shown in the bottom plot and the user position solutions errors and uncertainties in the top plot. In this case there is no desaturation maneuver in the ephemeris. The user position error quickly becomes sub-100 m and approaches 2 m after a day of tracking.

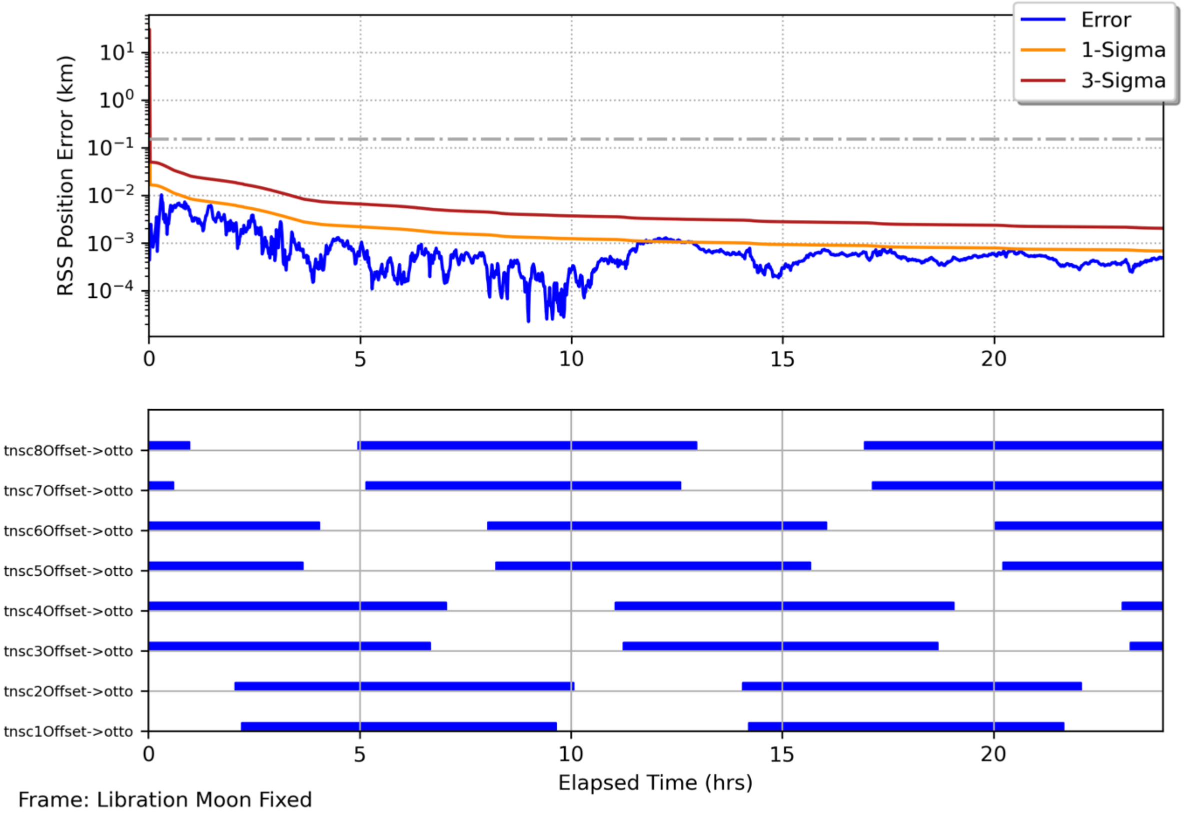


Figure 6. Surface positioning results for a South Pole user receiving one-way range tracking from an early operational Andromeda constellation consisting of 8 satellites (of the proposed 24). Note that the position uncertainty is below 17 m (1-sigma), 50 meters (3-sigma), instantaneously with the first observations (i.e., at Elapsed Time = 0) and is sustainable because there is a minimum of 5 satellites always in view.

In summary, the continued development of high-performance software defined radios (such as UST-lite) and space atomic clocks (such as DSAC) for use at the Moon and beyond is warranted and enabling technologies for lunar navigation satellite systems.

5.1.4.3 User radio technology

Finally turning to user radios, a recent advance for the Iris radio combined with a CSAC that can measure and form one-way Doppler and range is being demonstrated in a lunar NRHO as part of the CAPSTONE mission. This Iris/CSAC advance is a combined JPL, SDL, and Advanced Space technology achievement. Based on pre-flight experimentation and analysis conducted at JPL in support of the CAPSTONE mission, using this one-way technique, the expected measurement noise (1-sigma) for range and range-rate due to the onboard CSAC oscillator stability are approximately 2.5 meters and 11 mm/s (for a 60 second count) respectively. These results are thoroughly documented in [109].

In summary, the Iris radio represents a valuable option as a user radio to use for self-navigation with either two-way or one-way radiometric tracking. Continued investment is recommended.

5.1.5 OPERATIONAL CONSIDERATIONS

Any terrestrial navigation infrastructure dedicated to support lunar navigation is, necessarily, a complex and costly endeavor. Existing analogs can be found with the DSN and with operational GPS. Such a system will have to be global, redundant, and time synchronized.

The simplest possible navigation services are broadcast-only, akin to GNSS. A terrestrial beacon service will have worse geometry (PDOP) at the Moon than GNSS but could compensate for that with stronger signals. Of course, terrestrial beacons cannot transmit on GNSS frequencies, forcing lunar users to either ditch GNSS or deploy a dual navigation capability.

A ground-processing navigation system, akin to some DSN navigation modes, will have to contend with multiple transmitters/users in cis-Lunar space, with the attendant cost and complexity. It will need to upload the navigation solutions to the Lunar assets, adding latency and complexity.

However, since a terrestrial two-way communication infrastructure is an imperative, some of the capabilities required to navigate cis-Lunar assets will already be built-in.

On balance, a beacon system leveraging a telecom infrastructure may offer the lowest operational cost and complexity (for a terrestrial system), competing with GNSS in performance, if not simplicity. If the navigation signals can be GNSS-like, receivers in lunar space could possibly be adopted from common GNSS receiver architecture, with the attendant cost savings. In addition, unlike GNSS, a terrestrial navigation infrastructure could also provide a pathway for supporting navigation at Mars.

5.2 MOON TO MARS

NASA’s “Moon to Mars Architecture” [2] is a long-term overarching exploration strategy which involves human missions to the Moon as a steppingstone for crewed missions to Mars. The plan is to use the Moon as a testbed for technologies, systems, and operations necessary for human missions to Mars. By establishing a sustainable presence on the Moon, NASA aims to gain valuable experience and knowledge that will help in preparing for crewed missions to the red planet.

While the Moon to Mars approach is a logical and sound strategy, we must also recognize the differences between the Moon and Mars, and to interpret the strategy accordingly. The Moon is less than 400,000 km from Earth, whereas Mars distance is between 75 million km and 400 million km. The difference in range results in the following:

- Unlike lunar spacecraft, Mars spacecraft cannot receive the Earth's GPS and GNSS signals. Mars relay orbiters would have to rely on either the Earth's deep space ground antennas, or a local Mars frequency and timing reference to perform orbit determination. The latter would relieve the burden of the Earth's ground antenna infrastructures and provides additional in situ PNT capabilities for Mars orbiters and surface assets.
- The one-way-light-time delay with Mars is between 4 minutes to 20 minutes and thus real-time communications with Earth is not possible. Mars spacecraft cannot rely on Earth for real-time commanding and must be more autonomous in responding to unexpected and off-nominal situations. Therefore, autonomy and real-time kinematic PNT during spacecraft dynamic events are more relevant for Mars than for Moon.
- It is more costly to send orbiting and surface spacecraft to Mars than to the Moon.

There is also a big difference in the rotation rates. A Mars day is 24 hours and 37 minutes, while a lunar day is about 27.3 Earth days.

Some aspects of the signal structures being planned for communications and time distribution time at the Moon may be carried over to Mars, while others may not. For example, an LNSS might be at S-band, while a Mars-GPS-like signal would be more likely to be at X-band. An 18m Earth antenna beam may not cover all of Moon, unlike Mars. DTE from Moon with small power/antenna is possible and would be significantly more challenging at Mars.

Early human exploration of the Moon focuses on the lunar South Pole, and this presents a unique and challenging operation environment in terms of Earth and relay communications, sun illumination, and thermal variation. To provide maximum coverage, the proposed lunar relay constellation favors frozen elliptical orbits that loiter above the lunar South Pole. Due to the Earth-Moon geometry and long lunar night because of tidal-locking, many regions at the lunar South Pole do not see Earth for an extended period in each lunar cycle. Also, Earth and Sun appear at low-elevation angles as viewed from the lunar South Pole. Even in view, direct communication with Earth suffers from high multipath loss. The combination of low glazing angle of sunlight, absence of an atmosphere, and low rotation rate results in large thermal variations and extremely low temperature in some parts of the lunar South Pole. As an example, the temperatures at the rim of Shackleton Crater ranges from 75 K to 300 K, with an average of 150 K [129]. The extreme thermal environment requires communications and PNT equipment on the lunar surface to be housed within a temperature-controlled vault, which impacts SWaP.

Human exploration of Mars, on the other hand, focuses on the equatorial and mid-latitude regions. Most proposed relay network designs favor circular equatorial orbits. The sun illumination and thermal environments are more benign. However, Mars has a thin atmosphere, and the occasional sandstorms can pose different kinds of challenges to communications and navigation on the Mars surface.

Consequently, we should not assume that the human lunar communications and PNT flight and ground architectures and operation concepts can be directly applicable to the human Mars exploration. We propose to perform holistic system engineering studies and architecture trade to identify the differences between the lunar and Mars operation scenarios, to understand the inter-dependency between engineering systems and the environments, and to adapt and adjust the “Moon to Mars” strategy accordingly.

5.3 MARS TIMESCALE

As with the Moon, a local timescale at Mars will be required for effective PNT. While it may be possible to rely on weak GPS signals to maintain such a timescale at the Moon this option will not be possible at Mars and other planets. The need for greater autonomy and robustness drives the need for even more stable clocks than those employed at the Moon. Stable metrology clocks that are used as the ground clock reference for GPS on Earth [130] are not currently space qualified, may not be available to form a remote timescale at Mars for some time, and even when available, may be prohibitively expensive. Until they are available, the most feasible option is likely to be highly stable autonomous in situ space-qualified clocks with maser-level performance having significantly lower drift than current GNSS clocks [36], together with occasional adjustments to take out any small residual drift. To satisfy the autonomy requirement, a reference clock frequency stability of $1 \times 10^{-13}\tau^{-1/2}$ and a drift rate of $< 3 \times 10^{-16}$/day are needed. This level of clock stability would only require updates on a weekly basis or longer. As with LTC, occasional monitoring of the Mars timescale relative to UTC would also be required to facilitate interoperability.

On Earth, forming a local timescale representation of UTC (UTC(k)) may involve comparison of several local clocks with UTC over a long period of time to determine which clock has the lowest drift and best stability in the long term. This clock then becomes the “master clock” instantiation of the local UTC(k). Continued monitoring may reveal that a different clock in the ensemble has become more stable and if this remains true for a given amount of time, the new clock may be swapped in as the master clock. In some cases, the master clock may be steered to a weighted local ensemble average to gain improved performance [103]. For a local timescale at Mars, initially a single stable clock would suffice, but eventually multiple clocks would be needed to provide redundancy and to form an ensemble average clock with possibly better stability than any of the constituent clocks. Indeed, it is likely that a timescale located on the Martian surface would experience extended periods of time in which the Earth is not visible, during which low clock drift will be paramount for maintaining a sufficiently precise timescale. Indeed, using the GPS experience as a guide where clock calibration uploads occur twice a day to ensure that clock drifts of 1×10^{-14}/day don’t accumulate more than 1 nano-second of timing error per day, a timescale at Mars would need clocks with commensurately lower drift to accommodate an update cadence of weeks or more. For a two-week cadence, a simple calculation reveals that the needed drift should be on the order of 3×10^{-16}/day.

A remote autonomous timescale at Mars and other planets drives the need for highly stable and reliable clocks. While a remote stable clock need not necessarily operate in space (for instance, it might operate in a human habitat located at the surface at standard temperature and pressure), it must survive launch and transport to the remote location and so be space qualified. Thus, not only are high performance, high reliability and long life needed, but also lower SWaP. In addition, these clocks may need to operate in less benign environments than their counterparts in controlled laboratories on Earth. So, low environmental sensitivity must be considered as well. RAFS, which is the current primary GNSS space clock, has a magnetic sensitivity of 1×10^{-12}/G. The Excelitas has a temperature sensitivity of 2×10^{-13}/°C and an uncorrected drift of 1×10^{-14}/day [83]. In addition to the fact that lower drift is needed for the Mars timescale, the RAFS environmental sensitivities would require significant environmental isolation. Mercury ion clocks have the lowest environmental sensitivity of any microwave clock due to the high clock transition frequency (40.5 GHz as compared to 6.8 GHz for rubidium). A possible candidate clock would be a follow-on to the DSAC mercury ion clock, which demonstrated magnetic and temperature sensitivities of 2 and 1 order of magnitude lower than RAFS, respectively. DSAC also had an improvement in drift over RAFS by 2 orders of magnitude at 3×10^{-16}/day [36]. A DSAC-FO clock is currently in development and would meet or exceed this level of performance. The DSAC-FO technology is being designed with a goal of extending DSAC's approximate 5-year life to 10 years while also reducing SWaP.

6 RELEVANT EMERGING TECHNOLOGIES

6.1 CLOCKS

6.1.1 UNDERSTANDING THE VALUE OF CLOCKS

Radio-based space navigation fundamentally relies on measurements of time and frequency, more specifically the time for a signal to transit (i.e., signal light time) between two entities (such as an Earth-based tracking station and a target spacecraft) and the frequency change (i.e., Doppler shift) resulting from the relative motion of those two entities. Via the constancy of the speed of light, the light time can be converted to a slant range and the Doppler shift can be related to the relative speed of the two entities. Combining these measurements with detailed models of the entities position and velocity (using both Newton and relativistic formulations) enables one to determine the trajectory of a target spacecraft. Light time delays and Doppler shifts are the physics behind these observations but the basis of for these measurements relies on stable clocks/oscillators in forming the time differences to determine light-time delays and signal-phase changes to determine average Doppler shifts over a prescribed integration time. Indeed, to achieve the phenomenal accuracies needed to navigate spacecraft to solar system destinations requires stabilities typical of atomic clocks to achieve the DSN's typical X-band precision of 0.1 mm/s at 60 second count time for range rate and 1 m noise +/-2 m bias for range, both 1-sigma levels.

At the DSN this is enabled by masers that form the time/frequency basis for the two-way and three-way radiometric measurements that are collected by each station to the spacecraft they support. The chief advantage of two-way/three-way measurements are that they are designed to eliminate (or significantly reduce) the inaccuracies introduced by a clock/oscillator onboard the receiving spacecraft. That is, the two-way light time delay is the transit time of a signal that is sent to a spacecraft from a station, transponded, and returned to the station and is determined by differencing the send and receive times from the *same clock*. A similar situation applies for the carrier phase measurements used to form Doppler. When considering one-way measurements, those that begin from a tracking station and terminate at the receiving spacecraft (or turned around sent by the spacecraft and received by the station), there are *two independent clocks* forming the time and phase differences. Therefore, to achieve the same precision with one-way data as its two-way counterpart requires clocks on board the spacecraft with stabilities (or to a lesser extent accuracies) that are commensurate with their ground-based counterparts (i.e., masers).

Section 6.1.2 outlines the many/varied space clocks and their associated performance that could be considered for deep space one-way radio navigation and Section 6.1.3.4.1 reviews the progress in making a DSAC-follow-on that has promise for being a maser replacement in space. To first order, as the stability of the spacecraft clock decreases the trajectory solution uncertainty based on this data increases [73]; hence, if a spacecraft's navigation requirements are on par with current NASA flagship or most competed missions, then DSAC-like stability would be needed to routinely use one-way radio navigation [74]. If the navigation requirements are relaxed, a lesser clock might suffice but a careful analysis is required to ensure the right clock is selected that meets the mission's requirements (reference [75] demonstrates that a CSAC at Mars has 100 m class orbit determination solution uncertainty vs. meter class using DSAC or two-way data).

The preceding comments relate to the traditional use of DSN radiometrics for navigation; however, a key benefit for using one-way radiometric data is the possibility for onboard, autonomous navigation. Autonomous navigation has the potential for enabling mission scenarios where light-time delays and ground processing make it difficult to "close the loop" when navigating with tight error bounds (i.e., high precision Mars atmosphere entry). A study by Ely [76] reveals that one-way radiometric-based uplink tracking when combined with onboard optical imaging could enable autonomous Mars atmosphere entry with sub-150 m (3-sigma) entry knowledge while reducing DSN utilization by 93% as compared to typical Mars lander approach navigation.

Autonomous navigation also offers the possibility of reducing ground-based navigation costs and DSN utilization. This is especially true when the one-way transmit signals come from an Earth-station that is operating in beacon mode, an automated approach to broadcasting signals for schedule times and sky locations that can be picked up by spacecraft that know to listen at the right time and is described by Wyatt [77]. A particularly relevant scenario at the Moon is that over half of the Moon is in the field of view of an Earth antenna when broadcasting at S-band; therefore, any spacecraft in the beam of the signal could opportunistically track and form one-way radiometric data and generate a solution using onboard navigation software. The quality of the orbit solution from this data would be commensurate with the stability of the clock onboard the spacecraft.

Finally, when considering lunar or Mars satellite positioning systems, just like the DSN or the Earth GNSS constellations, atomic clocks should be the cornerstone of these systems and only the most stable clocks should be considered for deployment to enable support all levels user and positioning navigation needs. Indeed, the navigation and surface positioning performance needs identified in Table 2 are demanding and simulations to date indicate that the lunar PNT system will need DSAC-level stability local clocks in the orbiting relays to support user surface positioning to meet the levels indicated in the table. The capabilities of these systems might roll out in phases, so that early installments could use readily available space clocks but as the systems evolve improved clocks, such as DSAC, should be planned for later deployments.

6.1.2 AVAILABLE INDUSTRIAL SPACE CLOCKS

One of the most mature space clocks currently in use is the quartz crystal USO. Its short-term performance has been used on many missions, including Voyager where one is still operating after 40 years. With a fractional frequency stability of 10^{-13} at one second of averaging time, the quartz USO is state of the art among space clocks, but since it is a mechanical oscillator, it has an inherently high drift of about 10^{-10}/day. When the USO is disciplined by an atomic reference, the resulting instrument is an atomic clock that can have the short-term stability of the USO, but unlike the USO, its stability will improve with averaging time and its drift can be more than 4 orders of magnitude less than the USO.

Rubidium vapor cell atomic clocks are the primary frequency reference on board GPS satellites. These have a stability of about 10^{-12} at a second and a drift of about 10^{-14}/day [47]. A proposed enhancement to this standard is the Pulsed Optically Pumped (POP) rubidium clock, which has demonstrated 1.7×10^{-13} at one second in a laboratory version and 6×10^{-13} in a more packaged version [48]. Also demonstrated in GPS are cesium beam tube (CBT) clocks. These are not as stable as rubidium clocks in the short term (about 1.6×10^{-11} at one second) but have lower drift and so are more stable in the long term [47]. An optically pumped version of the space rubidium clocks is in development and can improve short term stability [48]. Active hydrogen masers, which oscillate at and produce a coherent microwave frequency output, in the same way that lasers oscillate at an optical frequency, have been flown but have not achieved the stability and operability in flight of their ground counterparts [49]. Passive hydrogen masers, in which the atoms serve only as a reference for a USO in the conventional way are central to the Galileo GNSS system and have achieved a performance level similar to that of rubidium atomic clocks [50].

The tools of laser cooling [51] and ion/atom trapping [52] have had a profound effect on ground clock metrology for many years but have only recently been demonstrated in space. A laser-cooled atomic beam clock was launched in 2017 with a stability of 3×10^{-13} at one second [53], but did not have long-term data. JPL's Deep Space Atomic Clock (DSAC) mission launched a trapped ion atomic clock in 2019 and demonstrated a stability of 1.5×10^{-13} at one second, 3×10^{-15} at one day and a drift of 3×10^{-16}/day - the last two were performance records for space clocks [36]. These recent space clock technologies are not yet commercially available.

Figure 7 shows a summary of current clock performance plotted against the mean time between physical interactions with the clock required to keep it operating. This graph is an attempt to capture the complex multi-dimensional space of parameters and the viability of various technologies for applications in space that will require a high degree of autonomy. For each point on the graph the volume of the corresponding clock is capture by the size of the circle or square around it. Circles indicate space clocks (light blue) or clocks that are current candidates for space clock development (darker blue). Squares indicate ground clocks, using a different scale as shown in the legend. This graph should be considered a snapshot in time of a dynamic situation. Many entries, particularly the newer ones, will move their positions on the graph as they become more mature. The specific clocks shown in the graph are listed in Table 3.

Table 3: Space and ground clocks shown in Figure 7.

Clock	Abbreviation	Reference
Chinese cold rubidium space clock	cRb	[87]
Cesium beam tube atomic clock	Cs	[84]
Chip Scale Atomic Clock	CSAC	[81]
Cryogenic sapphire oscillator	CS	[131]
Deep Space Atomic Clock	DSAC	[36]
DSAC Follow-On	DSAC-FO	[141]
Hydrogen maser	HM	[132]
Trapped room temperature mercury ion standard with a hydrogen maser LO	LITS/HM	[111]
Trapped room temperature mercury ion standard with a quartz crystal LO	LITS/USO	[133]
Iodine cell optical clock	Iodine	[134]
Miniature Atomic Clock	MAC	[82]
Optical Rubidium Atomic Frequency Standard	ORAFS	[135]
Passive Hydrogen Maser	PHM	[85]
Photonics Local Oscillator (optical to microwave conversion using an ultra-stable laser and frequency comb)	PLO	[136]
Pulsed optically pumped rubidium	POP-Rb	[48]
Rubidium Atomic Frequency Standard	RAFS	[83]
Spectradynamics cold cesium clock	Spectra	[137]
Strontium optical clock	Sr Opt	[138]
Ultra-stable quartz crystal oscillator	USO	[80]
Trapped Ytterbium ion clock	Yb+	[139]
Trapped Ytterbium ion optical clock	Yb+ Opt	[142]

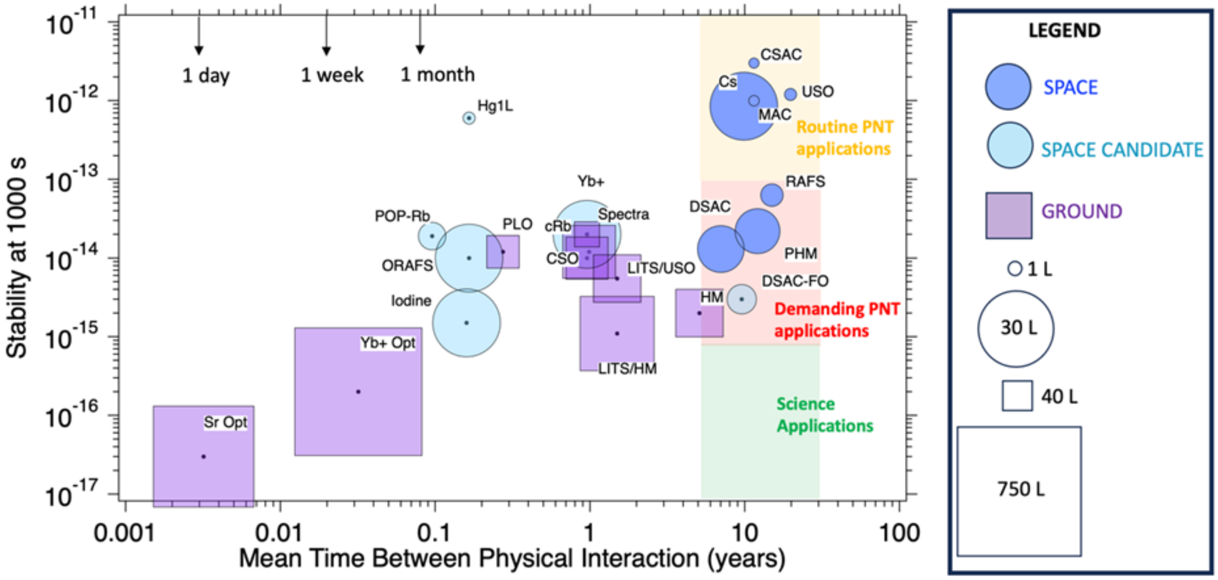


Figure 7. Clock Allan deviation at 1000 s vs. the mean time between physical interactions required to keep the clock operational. For each point the volume of the associated clock is captured by the relative size of the surrounding circle (light blue for space clocks, darker blue for clocks that are current space clock candidates) and squares for ground clocks. The lightly shaded boxes on the right side of the graph show the desired operational characteristics for routine PNT applications (orange), demanding PNT applications (red) and science applications (green).

Table 4. Available Space Clocks and Properties

Clock	Stability at 1 s	Stability at 1000 s	Drift (per day)	TRL	Power (W)	Mass (kg)	Lifetime (years)	Ref.
OCXO	5×10^{-13}	8×10^{-12}	7×10^{-10}	9	3	0.075	> 20	[78]
VCXO	-	-	-	9	0.07	0.001	> 20	[79]
USO[8]	1×10^{-13}	1.5×10^{-13}	1×10^{-11}	9	6.5	2	> 20	[80]
CSAC	3×10^{-10}	1×10^{-11}	3×10^{-11}	9	0.12	0.035	> 11	[81]
MAC	3×10^{-11}	1×10^{-12}	2.5×10^{-11}	9	6.3[1]	0.1	17	[82]
GNSS Rb	2×10^{-12}	7×10^{-14}	5×10^{-14} Note[2]	9	39	6.4	> 20	[83]
GNSS Cs	1.2×10^{-11}	8.5×10^{-13}	$< 1 \times 10^{-14}$	9	40	16.6	> 10	[84][3]
GNSS PHM	7×10^{-13}	2.2×10^{-14}	$< 1 \times 10^{-15}$	9	60	18.2	> 12	[85]
Active HM	2.5×10^{-13}	3×10^{-15}	3.6×10^{-14}	8	-	-	-	[86][4]
DSAC[5]	1.5×10^{-13}	1.5×10^{-14}	3×10^{-16}	7	56	19	5	[36]
DSAC-FO[6]	1×10^{-13}	3×10^{-15}	$< 1 \times 10^{-15}$	5	34	10	>10	

Clock	Stability at 1 s	Stability at 1000 s	Drift (per day)	TRL	Power (W)	Mass (kg)	Lifetime (years)	Ref.
Cold Rb[7]	3×10^{-13}	1×10^{-14}	$< 1 \times 10^{-15}$	7	-	-	-	[87]

1. At 25 C
2. No drift removal
3. Lifetime not stated in data sheet
4. Note that SWaP and expected lifetime were not mentioned in this reference. This instrument is not commercially available.
5. This instrument is not commercially available.
6. This instrument is under development. It simplifies the design of DSAC by eliminating one of the ion traps. It improves optical collection efficiency to obtain better short-term stability and integrates electronics to reduce SWaP. All specifications are estimates.
7. This instrument is not commercially available. SWaP was not given in the reference.
8. Note that the power and mass for this unit are only estimates because this data is not included in the reference.

6.1.3 JPL CLOCK ACTIVITIES

JPL clock activities break down into three broad categories: 1) providing state-of-the-art time and frequency references for JPL and NASA, 2) performing research and development on new clock technology, and 3) characterizing performance and sensitivities of clocks.

6.1.3.1 The Frequency Standards Test Laboratory

JPL maintains ultra-stable frequency references in its Frequency Standards Test Laboratory (FSTL). This serves an essential function, both as a reference for external customers and as an internal reference used to characterize other clocks and oscillators. The reference standard must be significantly more stable than the device under test (DUT). The DUT may be a flight oscillator with exceptional short-term stability, or it may be a hydrogen maser that will be installed in the DSN and has excellent long-term stability. For instance, the best flight oscillators may have a stability of 10^{-13} or lower at 1 second but can drift at 10^{-10}/day, while hydrogen masers can reach a stability less than 10^{-15} and can drift less than 10^{-15}/day. To be able to characterize instruments across this wide range of performance levels, the FSTL maintains a suite of clocks that can be combined to give excellent stability on all timescales. Figure 8 shows how combining a Photonic Local Oscillator (PLO) [110], a hydrogen maser, and a trapped ion standard with stability at the 10^{-15} level or below on all timescales up to several weeks. This type of ensemble enables unambiguous characterization of the best oscillators in the short term as well as the drift of masers in the long term.

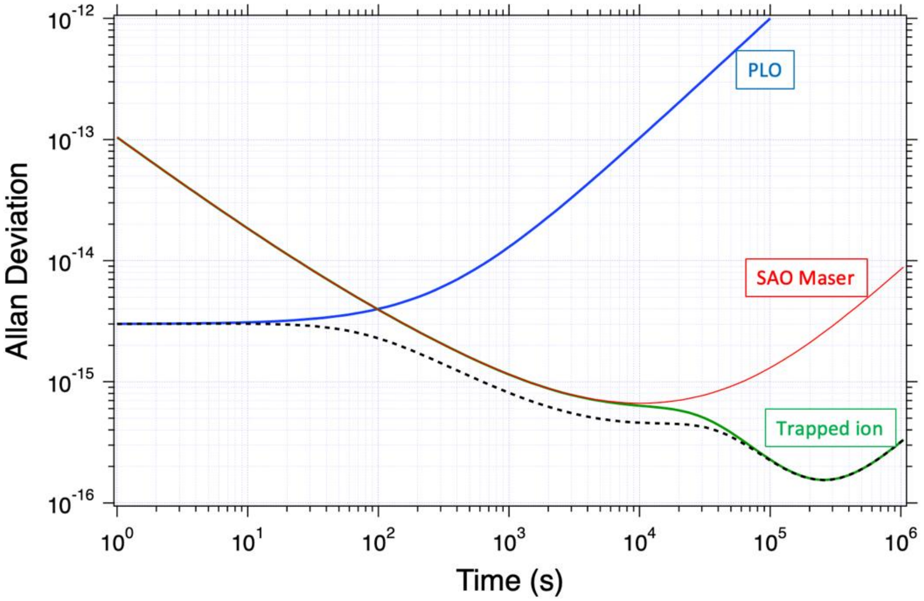


Figure 8. Ultra-stable clocks in the FSTL: Cryogenic and/or photonic local oscillators (blue), hydrogen masers (red), and trapped ion standards (green). The dashed black line conceptually shows the level of stability that the ensemble of all three might reach.

JPL's ultra-stable trapped ion frequency standards drift at $< 3 \times 10^{-17}$/day [111], which is among the best in the world for continuously running atomic clocks. Most metrology laboratories maintain an ensemble of hydrogen masers to obtain this level of stability and thereby provide a local and continuous representation of UTC. JPL's frequency standard can do this with a single clock.

6.1.3.2 The Deep Space Network Frequency and Timing System

JPL-supported frequency standards used in the DSN Frequency and Timing System (FTS) [90] must have 99.999% up time and for the most demanding applications, have a stability of $< 3 \times 10^{-13}$ at 1 s, $< 5 \times 10^{-14}$ at 10 s, and $< 5 \times 10^{-15}$ at 1000 s. The hydrogen maser is one of the few frequency standards that can do all of these and is therefore the primary frequency standard at all DSN sites. The main applications of frequency standards in the DSN are satellite navigation, radio link science, such as radio occultation [112], and gravity mapping [113] and radio astronomy, in particular VLBI [114]. As shown in Figure 9, the frequency standard is a

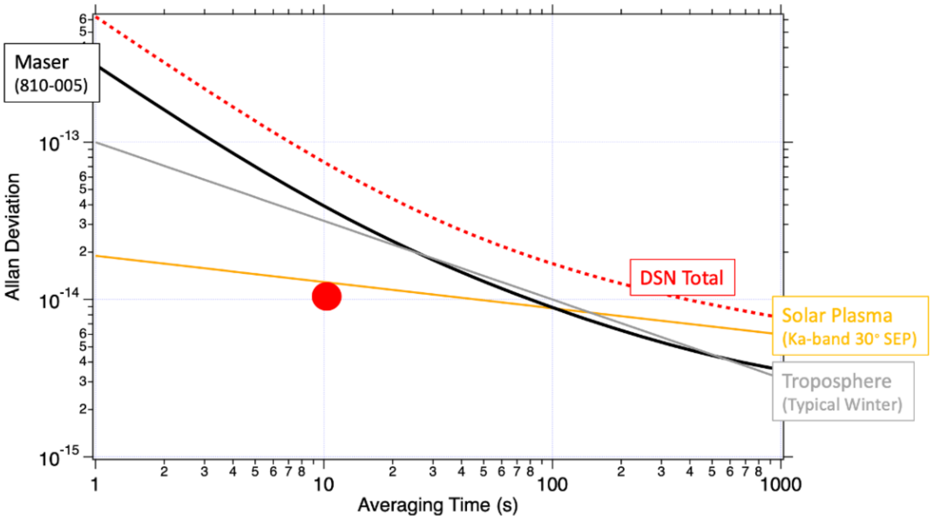


Figure 9. The DSN FTS radio astronomy error budget showing the hydrogen maser frequency standard as a significant component. The red dot is a recent flight project FTS stability request.

significant part of the overall DSN radio science error budget. Furthermore, the red dot indicates a recent flight project request for even better performance, emphasizing the importance of maintaining this level and working towards improving it.

6.1.3.3 The Deep Space Atomic Clock

6.1.3.3.1 Pre-DSAC space clocks

The operational space atomic clocks that currently exist comprise the rubidium cell [28], cesium beam [29], and passive hydrogen maser clocks [30] used in GNSS. Add to this the Chip Scale Atomic Clock (CSAC), which has very low SWaP, but significant instability compared to the others and the Ultra-Stable quartz Oscillator (USO), which has high drift in the long term. As can be seen from Figure 10, the rubidium and hydrogen clocks have Allan deviations of about 10^{-12} at a second of averaging time and drifts of about 10^{-14}/day. The cesium beam GNSS clocks have lower drift, but higher instability at 1 second. This level of performance is sufficient for GNSS as long as clock frequency corrections from the ground can be made several times per day. Future space clocks based on trapped atoms and/or ions will have much lower drift (the Deep Space Atomic Clock – DSAC – based on trapped ions, demonstrated a drift almost two orders of magnitude lower than standard GNSS clocks during its two-year mission – see below) and therefore better autonomy. For future space clocks, one can consider many clock technologies in development on the ground, but calculations show that for GNSS applications, a stability of $10^{-13}/\sqrt{\tau}$ and 10^{-15} at a day is sufficient [31]. Stability below this

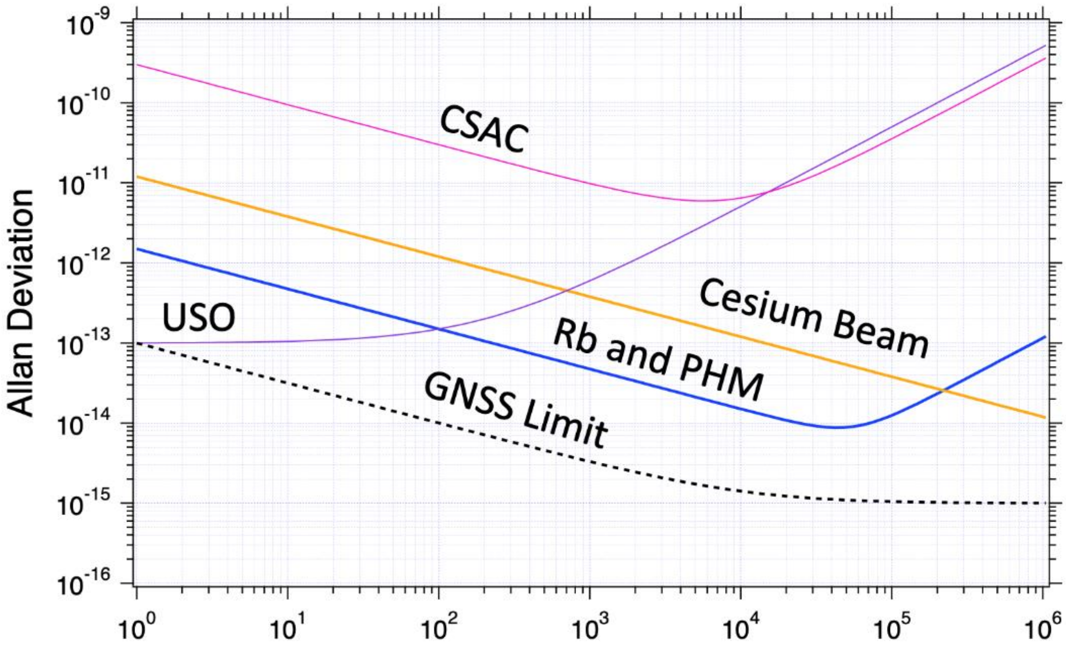


Figure 10. Current operational space clock Allan deviations: the Chip-Scale Atomic Clock (pink), the cesium beam tube GNSS clock (orange), and the rubidium and passive hydrogen maser GNSS clocks (blue). For reference also shown is the limit below which clock performance no longer provides benefit to GNSS (dashed black).

level gives little benefit for that application. This is likely to be true of lunar PNT as well since the application is very similar to current terrestrial GNSS applications.

Methods to electromagnetically trap and cool ions have revolutionized atomic clock performance [32][33][34] because these technologies for confining and slowing the relative motion of ions offer the possibility of reducing and in some cases even eliminating many systematic effects that can lead to clock instability. Terrestrial trapped ion clocks operating in the optical domain have achieved orders of magnitude improvements in performance over their predecessors and have become a key component in national metrology laboratory research programs [35]. However, robust long-term operation and transporting this new technology into space has remained challenging.

6.1.3.3.2 Development of DSAC

In 2019 NASA launched the Deep Space Atomic Clock (DSAC), the first trapped ion atomic clock to operate in space [36]. The DSAC design did not include cryogenics, a sensitive microwave cavity, nor lasers. Instead, it operated at near room temperature, used simple travelling wave microwave components, and used a plasma discharge deep UV light source. The high maturity and robust operability of each of these enabled launch into and operation in space. On the ground, DSAC demonstrated a short-term fractional frequency stability of $1.5 \times 10^{-13}/\tau^{-1/2}$ [37]. DSAC operated for two years in space where it achieved a stability of 1.5×10^{-13} at one second, a long-term fractional frequency stability of 3×10^{-15} and a time deviation of only 4 ns at 23 days (no drift removal), and an estimated drift of

$3.0(0.7) \times 10^{-16}$ per day. Each of these exceeds current space clock performance by at least an order of magnitude [38][39][40]. The DSAC clock was also amenable to the space environment, due to low sensitivities to variations in radiation, temperature, and magnetic fields. It is expected that this level of space clock performance will enable one-way navigation whereby signal delay times are measured in situ making near-real-time deep space probe navigation possible [41].

The DSAC mission demonstrated record space clock performance and the ability to achieve a higher degree of autonomy than other space clocks, however, the design was not readily manufacturable and the SWaP, while relatively low at 58 W and 19 kg, was still larger than desirable.

6.1.3.4 DSAC Follow On

6.1.3.4.1 DSAC Follow On technology maturation

With the conclusion of the DSAC mission in 2021, the DSAC Follow-On Technology Maturation Task (TMT) was started to mature the DSAC technology into a lower SWaP manufacturable package. The size comparison between DSAC and DSAC-FO TMT can be seen in Figure 11. In addition, the task was charged with investigating ways to extend the DSAC extrapolated lifetime of seven years to greater than ten years. The TMT SWaP goal is 34 W and 10 kg and is designed to fit into a GPS clock slot. This form factor would also be easily adaptable to a 3U rack-mount package as well. The SWaP reduction while maintaining and even improving performance along with improved manufacturability, makes this development attractive for commercialization for both space and ground-based applications.

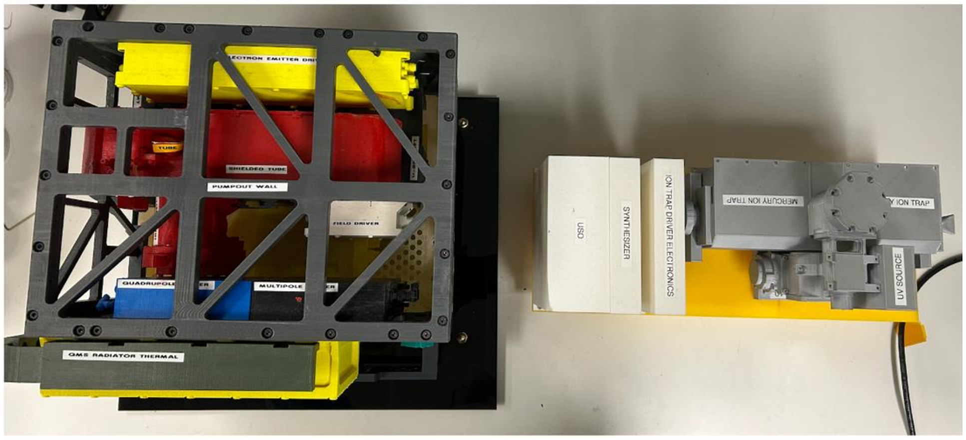
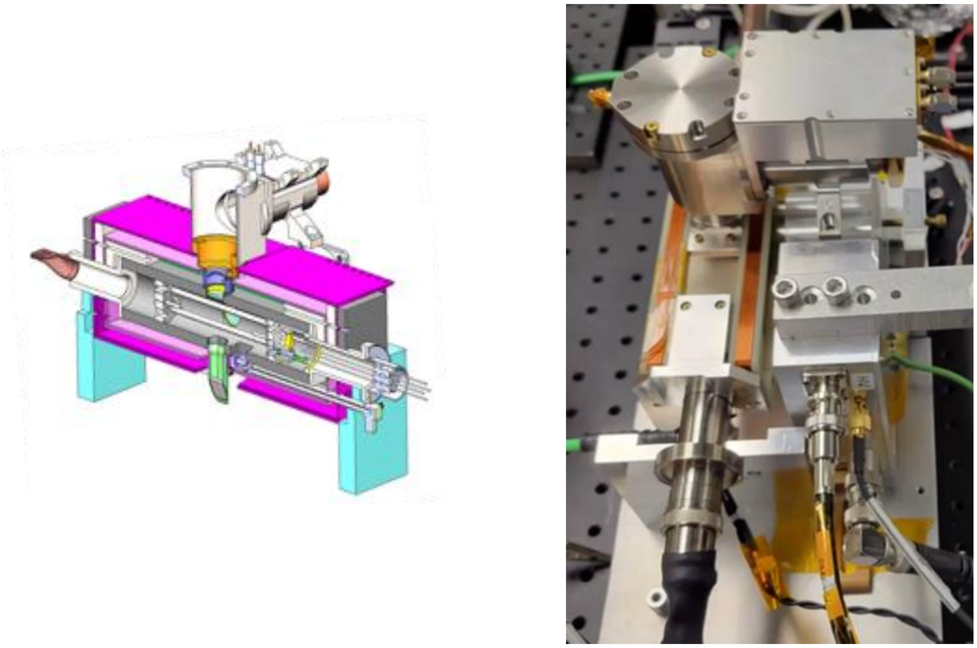


Figure 11. A top view size comparison of the DSAC (left) and DSAC FO TMT (right) models

The TMT SWaP goals will be achieved by first simplifying the DSAC design to use only one ion trap (DSAC used two to achieve ultimate long-term stability but demonstrated that one trap was sufficient for most envisioned space applications), and by developing well-integrated smaller electronics. The TMT ion trap design and a partially assembled prototype is shown in Figure 12.



(a) **(b)**

Figure 12. (a) A cross section of the TMT vacuum tube showing the single linear ion trap. (b) A partially assembled DSAC FO TMT prototype clock.

There are three factors that limit the current DSAC instrument lifetime: buffer gas depletion, mercury depletion, and plasma discharge DUV light source lifetime. Progress has been made in understanding the depletion mechanisms and are being addressed by investigating alternate vacuum wall and electrode materials. The DUV light source consists of a fused silica envelope back filled with mercury. It is well known that mercury diffuses into the fused silica eventually reducing the mercury vapor pressure below that required to sustain a plasma. Research is underway to determine the best way to incorporate sapphire into the envelope since it is also known that sapphire attenuates this process. A factor of two in lifetime due to each of these effects is anticipated.

As an outgrowth of the TMT task mentioned above, the DSAC-FO instrument will have maser-like performance in a 3U rack mount package. Combined with the inherent low environmental sensitivity, such an instrument could find application in both ground and space applications. Its performance and size make it a candidate for a future H-maser replacement (small market in spacecraft tracking and navigation, VLBI, and UTC level timekeeping) and as a replacement for rack mount commercial cesium beam standards. The later are manufactured in large quantities for the telecommunication industry.

A space variant at the outlined stability performance and SWaP has received large interest from the GNSS clock community [117]. Such a DSAC FO clock, once industrialized, would enable autonomous navigation via one-way tracking, new capability in space-based radio link science, and local realization of UTC-like timescales in future PNT systems at the Moon, Mars, and beyond.

6.1.3.4.2 Application of DSAC Follow On technology

In 2021, a DSAC Follow-on trapped ion atomic clock was selected to be on the VERITAS mission to Venus. This clock was to have improved performance over DSAC at the level of $10^{-13}/\sqrt{\tau}$, 10^{-15} at a day, and <10^{-15}/day drift. At the same time, the new version of the clock was to have a SWaP approximately half that of DSAC and be simpler to fabricate and assemble. For budgetary reasons, in 2022 the new clock was cancelled, but not before significant progress was made on its design as well as analysis of how it could contribute to the VERITAS scientific mission. These included a test of Einstein's general relativity [115], and augmentations to radio science, including radio occultation used to study Venus's atmosphere [116]. For the latter, an on-board autonomous clock makes it possible to reduce the time for re-synchronization on each orbit by a factor of two (one-way light travel time instead of two-way), which increases the amount of the atmosphere that can be studied.

The DSAC-FO clock, while originally oriented towards the VERITAS mission, is intended to have wide applicability. The design has a footprint that can fit into the current GPS rubidium atomic clock slot [117], making it potentially attractive to GNSS applications desiring better autonomy. This footprint also enables the clock to fit into a 3U rack-mount ground-based package. With maser-like stability, the ground-based version could serve as a backup to and potential replacement of hydrogen masers for certain applications and would provide a significant performance enhancement as a replacement for cesium beam tube atomic clocks. There is a large market for the latter in the telecom industry that would make the trapped ion clock commercially viable.

6.1.3.5 Micro-mercury trapped ion clock development

The micro-mercury trapped-ion clock (M2TIC) development leverages the traditional trapped mercury ion microwave clock approach such as it was demonstrated DSAC [36]. To significantly reduce SWaP while maintaining good frequency stability capability, several new technologies for reducing the size and power of Hg ion clocks were developed, including miniature vacuum trap tubes with field-emitter-arrays (FEA) electron sources, 194-nm micro plasma lamps, and 40.5-GHz CMOS-based microwave synthesizers. The use of the FEA reduces the thermionic electron emitter of watts of power to mW of electric power consumption. The micro plasma Hg discharge lamp reduces the lamp power consumption from 5 W to tenths of a watt. Furthermore, a CMOS based sub-harmonic phase locking loop synthesizer is capable of reducing the 40 GHz from watts to less than 0.5 Watt. As a result, the overall size and power consumption of a mercury ion clock can be significantly reduced in general while preserving some of the advantages realized with the 40 GHz Hg clock transition.

Figure 13. M2TIC 1.1-liter clock prototype and the micro physics package trap tube

In a recent DARPA clock development program, JPL integrated these new technologies into the M2TIC clock prototypes, which demonstrated stability of $1 \times 10^{-11}/\tau^{1/2}$, averaging down to the 10^{-14} level within a day, while packaged in a 1.1-liter standalone box and consuming less than 6 W of DC power (see Figure 13). This stability level is comparable to the widely used rack-mount Microchip 5071A cesium frequency standard, which is much larger and consumes more power. The prototypes have also been shipped across North America intact to a government laboratory where they were independently tested and verified [128].

One of the prototypes was able to run 40 days with a drift less than any small vapor-cell based atomic clock in use. The successful demonstration of the M2TIC and the related technologies open possibilities for future miniature Hg ion clocks in terrestrial and space applications. Currently, the M2TIC as demonstrated is in a technology transition program with the US clock commercial industry for a next generation tactical clock for the DoD.

6.1.3.6 JPL optical clock development activity

Optical atomic clocks which operate at optical frequencies for higher quality-factor as compared to their microwave counterparts, can outperform the best microwave cesium clocks in both accuracy and stability. For comparison, a ^{87}Sr optical clock with performance at the level of 10^{-18} in fractional frequency units would outperform the highest-precision cesium clock in space (ACES scheduled for launch to the ISS in 2024-2025) by nominally two orders of magnitude with similar size and weight requirements.

Currently, optical clock technology is mostly aimed at applications for future fundamental physics research and precision measurements, both on ground and in space, where ultimate clock precision is required. These technologies particularly have application in providing very high frequency and time accuracy at national metrology laboratories and providing extremely high sensitivity to relativistic geodesy applications. With significant maturation, other possible applications exist. For example, if optical clocks can demonstrate multi-year continuous and autonomous operation and if their SWaP can be significantly reduced, they will become attractive as the reference for highly autonomous (infrequent updates) timescales on the Moon and planets.

Several laboratories have been working towards ground optical clocks based on trapped Yb ions (see e.g., Figure 7). To reach a frequency stability beyond that of DSAC in a similar size, one will have to simplify implementation approaches and improve reliability.

JPL is researching a miniature space optical clock (mSOC) concept that focuses on reducing the size and power of an optical clock. Specifically, the current development objective is to demonstrate a concept that will have $1 \times 10^{-14}/\tau^{1/2}$ frequency stability with a stability floor less than 1×10^{-16}. Current studies are being performed in an ultra-high vacuum tube that houses nearly perturbation-free laser-cooled and trapped single ions. Currently, $^{171}\mathrm{Yb}^{+}$ is used but other ion species are possible. At this stage, JPL has demonstrated a 16-cc single ion trap tube that is sealed off and without any active pump attached.

JPL is also in the process of establishing a Strontium lattice optical clock ground testbed and developing a critical path to an operating clock instrument by developing and demonstrating a breadboard lattice optical clock prototype with precision on the order of $1 \times 10^{-15}/\tau^{1/2}$ or better.

6.1.4 PNT TECHNOLOGIES

6.1.4.1 GNSS-based PNT

Multiple experimental and theoretical results suggest that both main lobe and sidelobe GNSS ranging signals possess sufficient power to be received in cis-lunar space by a sensitive weak-signal GNSS receiver with a moderately-sized antenna, such as ~1 m diameter parabolic dish. Link budgets, such as Table 5, indicate that such signals support sub-meter ranging.

Table 5. Meter-level GPS ranging observables in lunar orbit are indicated by this link budget, assuming a typical main-lobe GPS L1CA ranging signal, received at the apogee of the lunar orbit around the Earth, using a weak-signal GNSS receiver with a 0.6 m diameter parabolic antenna.

Label	Link Budget Component	Value (raw)	Value (dB)	Description
$\boldsymbol{P_T}$	Transmit Power	26.6 W	14.25 dBW	The spec per the GPS ICD for L1CA
$\boldsymbol{L}$	Wavelength	0.19029 m		GPS L1
$\boldsymbol{L_{RFT}}$	RF Losses in transmitter		-1.25 dB	
$\boldsymbol{G_T}$	Transmitter Gain		13.50 dB	GPS L1 at 14 deg off boresight
$\boldsymbol{E}$	Transmitter EIRP		26.50 dBW	$P_T + L_{RFT} + G_T$
$\boldsymbol{R}$	Range	426000 km		Lunar-Earth distance at apogee (~400,000 km) plus GPS orbital radius (26,000 km)
$\boldsymbol{S}$	Space Loss		-209.34 dB	
$\boldsymbol{A}$	Atmospheric & polarization loss		-0.5 dB	
$\boldsymbol{D}$	Receiver Antenna Diameter	0.6 (m)		Parabolic antenna
$\boldsymbol{G_R}$	Receiver Antenna Gain		17.32 dBi	$10\log_{10}(0.55\pi^2 D^2/L^2)$ (0.55 is efficiency factor)
$\boldsymbol{L_{RC}}$	Receiver Cable Loss	0.8	-0.97 dB	
$\boldsymbol{L_{RP}}$	Processing Efficiency Scale	1	0 dB	
$\boldsymbol{L_{RPB}}$	Processing Loss 1Bit	0.6366199	-1.96 dB	
$\boldsymbol{P_{RA}}$	Received Signal Power at antenna		-166.34 dBW	$E + S + A + G_R$

Label	Link Budget Component	Value (raw)	Value (dB)	Description
$\boldsymbol{P_R}$	Received Signal Power		-169.27 dBW	$P_{RA} + L_{RC} + L_{RP} + L_{RPB}$
$\boldsymbol{N_{temp}}$	Receiver Noise Temperature	267 K		238 K from receiver + 28 K from antenna
$\boldsymbol{N_0}$	Receiver Noise Power Density		-204.33 dBW/Hz	$-228.6 + 10\log_{10}(N_{temp})$
$\boldsymbol{C/N_0}$	**Carrier-to-Noise Density Ratio**		**35.06 dB-Hz**	$\boldsymbol{P_R - N_0}$ **⇒ meter-level positioning**

There are more than a 100 GNSS transmitters in Earth orbit, most in MEO, and some in GEO or inclined GEO orbits**.** The GPS receiver on NASA's Magnetospheric Multiscale Spacecraft (MMS) mission was able to track up to five concurrent GPS L1CA signals near the apogee of its Earth orbit over ranges that are nearly a third of the Earth-Moon distance [42]. With other GNSS satellites numbering three to four times those of the GPS constellation alone, some featuring more powerful signals than GPS L1CA, there is an abundance of GNSS ranging signals to exploit in cis-Lunar space.

The need to carry a ~1 meter diameter dish, however, limits the utility of GNSS-based navigation for some small landed and mobile assets on the Moon. Another limitation of GNSS-based navigation is the poor geometry, with a Geometric Dilution of Precision (GDOP) factors in the hundreds. That translates to poor instantaneous position and timing solutions. However, if GNSS range measurements can be effectively accumulated and combined over time, the instantaneous errors can be averaged down significantly to highly useful values. This can be accomplished, for example, for a fixed landed asset, for a mobile asset with an IMU, or, most importantly and effectively, for an orbiter. All of these would benefit greatly from having a stable clock on board. Receivers that can track the GNSS phase, such as the JPL Cion, will also realize important benefits in averaging down the ranging noise. Orbiters carrying a stable atomic clock could accurately propagate their orbital and clock states, determined with GNSS, to the far side of the Moon, always providing seamless navigation services.

The most flexible and effective exploitation of GNSS signals for cis-lunar navigation, including to the far side of the Moon is, therefore, to navigate a small constellation of spacecraft in lunar orbit with GNSS, and have this constellation produce its own navigation signals for local usage. Even though GNSS-based navigation does not apply to Mars, the concept of navigating an orbiting infrastructure with special signals from Earth (or from the Earth's vicinity), and then having these orbiters generate their own navigation signals (now tied to a terrestrial timescale) optimized to the local environment and needs, does carry over to Mars. Having a remote timescale will be essential for PNT at the Moon, Mars and beyond. Differences between this timescale and Earth UTC must be continuously monitored to enable interoperability.

JPL has significant, unique capabilities related to GNSS-based lunar navigation, including the Cion multi-GNSS weak-signal software receiver, with TRL 9 expected in early 2024; GNSS integrity monitoring and augmentation services with the Global Differential GPS (GDGPS) System; GNSS modeling and data analysis expertise; and new information on GNSS Space Service Volume (SSV) signals, to be obtained by the upcoming Cion missions of NTS-3 and SunRISE.

6.1.4.2 PNT using terrestrial transmitters

The work in [43] extends the concept of weak-signal GNSS in cislunar space to a set of dedicated transmitters on Earth. In contrast to the idea of opportunistically receiving sidelobe signals of GNSS satellites, this concept proposes to transmit the GNSS ranging code from fixed, high-power transmitting stations on Earth's surface. The main intuition behind this idea can be explained as follows. Firstly, GNSS transmitters, being situated on Earth-orbiting platforms, are power-limited. Conversely, a dedicated network of transmitters positioned on the surface of the Earth would have the capability to transmit ranging signals at significantly higher power levels compared to GNSS satellites, and point the main lobe directly at the assets. Since the pseudorange error is influenced by various factors, including the carrier-to-noise-spectral-density-ratio C/N_0, it is expected that this passive PNT (PPNT) service would yield pseudorange estimates of superior quality. Secondly, another factor contributing to pseudorange error is the uncertainty associated with the knowledge of the transmitting stations. In this context, a PPNT system holds an advantage over a weak GPS-based system since the transmitting stations are stationary on the Earth surface rather than being mounted on moving orbital platforms.

The study assumed a vehicle in lunar orbit and focused on the quality of the one-shot absolute position estimate computed from four or more pseudorange measurements. The simulation results indeed suggest that the increased transmit powers and fixed transmitter positions lead to a significant reduction in the pseudorange error experienced by the receiver.

However, a purely Earth-based scheme exhibits a unique set of drawbacks when compared to the weak-signal GPS concept. Firstly, unless a relatively large number of transmitting stations are deployed (i.e., twenty or more stations), the period in which four or more transmitters are visible is relatively low. For example, a scenario with four transmitting stations results in a period of roughly four hours per day of full visibility. Secondly, a purely Earth-based system suffers from worse dilution of precision than the weak-signal GNSS system. This is because the maximum inter-transmitter distance is limited by the diameter of the Earth in the best case. Since the DOP is a multiplicative error term, the degradation of the quality of the one-shot position estimate due to the DOP is substantial.

The final aspect studied in [43] is the very practical issue of antenna pointing. The simulation results suggest that the relatively narrow beam patterns of commercially available parabolic dish antennas result in a severe degradation of the quality of the position estimate outside of the main lobes of the transmitters. If, for example, a naïve pointing strategy of simply tracking the Moon position is employed by the transmitting stations, the position estimate will suffer whenever the target falls out of the main lobe of the transmitters. This suggests that a purely passive Earth-based system will require a more sophisticated antenna pointing scheme.

However, it is to be noted that this study focused exclusively on the once-shot position estimation error and merely provides a baseline for more advanced averaging and tracking methods. Targets which filter and average these estimates will obtain higher-quality position information, making Earth-based schemes a potentially cost-effective option for passive PNT in cislunar space

6.2 RADIOS

JPL has developed many transponders used for both near-Earth and deep space applications. The deep-space transponders include:

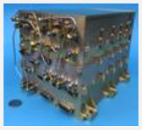
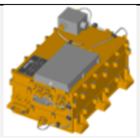
- The Small Deep Space Transponder (SDST)
- The Iris CubeSat Transponder
- The Universal Space Transponder – Deep Space (UST-DS)
- The Universal Space Transponder – Lite (UST-Lite)

JPL also develops relay radios for specific missions, and these include the Mars relay network. The relay-oriented radios include:

- The Electra radio (orbiter side)
- The Electra-lite radio (lander/rover side)
- Ingenuity short-range radio (Ingenuity/Perseverance)

Finally, JPL has also developed a near-Earth transmitter for high throughput (specifically for the NISAR mission) called the Universal Space Transponder – Ka Modulator (KAM). The only transponder listed above that is not software-defined is the SDST, whose function has mostly been superseded by the UST line of transponders.

Table 6. JPL software-defined radios and transponders

	Iris	**Electra-Lite**	**UST-DS**	**UST-Lite**	**UST-KAM**
Image					
Spacecraft Size Class (kg)	< 10	> 50	> 50	< 50	>50
Link	Direct with Earth	Mars Relay Network	Direct with Earth Mars Relay Network	Direct With Earth, Lunar Relay	Direct To Earth
Frequency Bands	X up, X down, UHF up	UHF up, UHF down	UHF/S/X/Ka up, UHF/S/X/Ka down Simultaneous dual band	UHF/S/X/Ka up, UHF/S/X/Ka down Simultaneous quad band	Ka-Band down (25.5 – 27 GHz)
Synthesizable Bandwidth (MHz)	50	38	144	2500 (single band, assumes external modulator) 426 (quad band, per band)	1500
Mass (kg)	1.1 (X band only)	3	5.4	3.0	4.5

	Iris	Electra-Lite	UST-DS	UST-Lite	UST-KAM
DC Power (W)	35 (Includes 4W X band RF Amp)	65 (Includes 9W RF Amp)	45	30	40
Radiation Tolerance (TID) (krads)	23	>20	50	300	50

The Iris transponder was included as the main payload of the first interplanetary CubeSat pair, the Mars Cube One (MarCO) A/B. MarCO was launched on May 5, 2018 and accompanied the InSight lander. The main purpose of the MarCO spacecraft was to relay the signal from InSight's Entry-Descent-and-Landing (EDL) back to Earth. This required that MarCO include the ability to receive UHF transmissions from InSight during its EDL and the ability to receive and transmit X-band signals from and to Earth. Since then, the Iris radio has been licensed to the Space Dynamics Laboratory (SDL) and around twenty additional Iris radios have been produced in support of the Artemis-1 mission and other missions including LICIACube (used to capture images of the crash of DART with asteroid Dimorphos) and CAPSTONE. All of these missions only utilized its X-band capability. Iris has been involved in performing first in space demonstrations of many features including PN-DDOR with two simultaneous 8-MHz channels [CITE], One-Way Ranging and Doppler with a CSAC, among others. Other software defined features included on Iris include over the air (OTA) update capability, beacon mode, spectrum filtering, and up to 12.5 Msps downlink and 6.25 Mbps uplink rates. Future features in development and testing include open-loop recording, GMSK modulation, among others. The Iris transponder targets Class D CubeSat missions.

The UST-Lite transponder is the next generation transponder aimed to support the near-Earth and deep space missions. The main missions that this transponder targets are Class B/C SmallSat missions with the need for high data rates. This transponder supports the highest downlink and uplink rates. Currently, the transponder is expected to support up to 187.5MHz I/Q bandwidths. This transponder can also synthesize up to 1.5Gbps QPSK downlink signals at its highest rate. Finally, it is the only transponder that can synthesize the Ka-Band PN-DDOR waveform due to its high synthesizable bandwidth. The UST-Lite uses mezzanine cards with high-speed digital samplers to directly sample and synthesize waveforms. With such direct waveform sampling approach, component counts can be drastically reduced while avoiding the use of baseband and intermediate frequency (IF) waveforms. The higher digital processing capability, coupled with expandable access to multiple high-speed samplers, allows the UST-Lite to support up to four simultaneous communication bands. The UST-Lite's first version is designed to support a quad-band link: S/Ka-band proximity and simultaneous X/Ka-band Earth communications. The current plan is to achieve TRL 5/6 by end of 2023. The transponder can optionally also host a Qualcomm Snapdragon co-processor module that can aid in processing tasks when necessary. This module can aid in the processing of radiometric or radar data.

The UST KaM was developed to support the NISAR mission, which is a near-Earth radar mission. Due to NISAR's vast amount of generated data, the mission required a radio capable of transmitting at an extremely high rate (up to 1.74 Gbps with rate 7/8 LDPC encoding and OQPSK modulation). This covers almost the entire near-Earth spectrum allocation at Ka-band (within 1.5GHz), which required RF filtering to contain the sidelobes within the spectrum mask. Note, however, that the UST KaM does not include a receive slice, which means that it is only a modulator and cannot receive data.

Finally, JPL has also developed ultra-low SWaP radios (approximately 3 grams) for the Ingenuity-Perseverance link at the 900-MHz band. However, these radios are based on the 802.15.4 protocol and do not support radiometric features. However, the radio can support up to 1 Mbps, depending on the link budget between the two point-to-point entities. The radios can transmit up to 31 dBm of RF power and can implement mesh network capability for distributed low-SWaP sensors and users.

6.3 RANGING TECHNOLOGIES

This section describes technologies to perform ranging measurements between a spacecraft and a ground station. Some of these technologies are mature and have been in operation for decades. Some others are standards that have either been used by a handful of missions or are still being developed and standardized.

At their core, all ranging technologies are based on the same concept: Estimate the time it takes for an electromagnetic wave make one round trip to the spacecraft. This is achieved by designing the ranging signal in such a way that, at a given epoch, the phase of the transmitted and received signal can be measured and compared to obtain a pseudo-range measurement. This value can then be corrected to account for time synchronization offsets and other environmental offsets (e.g., troposphere-induced delays), as well as any range ambiguity, to yield a true range observable with an associated time tag.

The way pseudo-range measurements are turned into range measurements depends on the ranging system. For example, in space applications, it is common to take all phase observables at the ground station, which is assumed to have a common stable time and frequency reference for the uplink and the downlink. Therefore, time biases due to lack of clock synchronicity are avoided by design, while ambiguity and environmental factors are solved in post-processing using information external to the ranging system. The downside, however, is that a limited number of spacecraft can be tracked simultaneously per antenna (less than ten in the short to mid-term), thus limiting the scalability of the system for lunar applications.

Alternatively, GNSS systems perform phase measurements at both the transmitter (the satellite) and receiver (the user) and recover range information without requiring time synchronization between them. This is achieved by broadcasting information on the state and clock of the GNSS satellites and solving for time bias at the receiver. This allows the system to scale to a potentially unbounded number of users but requires a complex infrastructure to ensure GNSS satellites have knowledge of their position and time.

Next, we describe several ranging technologies in use today by the DSN and other space communication networks. These include well-known methods such as sequential ranging, PN ranging and Delta-DOR (DDOR), as well upcoming methods such as RF telemetry ranging, and optical ranging.

6.3.1 SEQUENTIAL RANGING

Sequential ranging has been used on many space missions, going back several decades [54]. In sequential ranging, the ground station transmits a repeating pattern of subcarriers which are modulated sequentially in time onto a carrier. This signal is received by the spacecraft, which coherently turns it around and sends it back to the ground station. The ground station receiver then correlates the received subcarriers with local copies to estimate the phase difference, modulo the subcarrier period. The phase differences are then combined to generate the final phase offset measurement, which is then corrected for environmental effects and ambiguity to result in the final range measurement.

6.3.2 PN RANGING

PN ranging follows the same principle of operation as sequential ranging, but the signal sent from the ground station to the spacecraft, and back, is a pseudo-noise (PN) code [55][56]. This code is designed as a linear combination of several shorter PN codes, which allows the ranging system to acquire phase measurements quickly (even if the entire PN code has not been received) and, at the same time, ensure the PN sequence is long enough to avoid range ambiguity problems.

PN ranging can be operated in either turn-around or regenerative mode. In turn-around mode, the spacecraft receives the PN sequence on the uplink and coherently modulates it on downlink carrier. This simplifies the receiver implementation, but the overall system performance is impacted by both uplink and downlink noise. Alternatively, in regenerative PN ranging, the spacecraft receiver regenerates the received PN chips using a tracking loop and then provides the reconstructed signal to the receiver for transmission on the downlink. This effectively decouples uplink and downlink, improving noise conditions and allowing the technology to operate satisfactorily at lower SNR conditions.

The performance advantage of the regenerative PN ranging technique over the turn-around sequential ranging technique has been known for some time [57][58], but was not used on a NASA mission until the New Horizons mission [59]. Recently, JPL has developed radios that incorporate the PN ranging technology (e.g., the Iris radio).

6.3.3 RANGING WITH HIGH DATA RATE LINKS

An important consideration when using PN ranging is bandwidth occupancy, more specifically and the coexistence of the ranging signal with high data rate data transfer in bandwidth-constrained links. To overcome this problem, two techniques have been proposed, one combining PN ranging and GMSK-modulated data, and another known as RF Telemetry Ranging.

6.3.3.1 PN ranging plus GMSK

In PN ranging plus GMSK data, a PN sequence is transmitted by the ground station and tracked by the spacecraft receiver [60]. This recovered PN sequence is then phase modulated together with GMSK-modulated telemetry on the downlink. To separate them at the station's receiver, data is first demodulated and subtracted from the received signal to obtain a clean copy of the PN-modulated waveform. This copy is then sent to the range recovery mechanism, which measures the phase of the transmit and receive signal and uses their difference to recover range estimates.

Using appropriate modulation indices for the data and ranging portions of the signals, the loss of performance of the data demodulation due to the in-band ranging signal can be made less than 1 dB; and conversely, the loss of ranging performance due to the interference of the data modulation can also be made less than 1 dB [61].

6.3.3.2 Telemetry ranging

Another variation of PN ranging suitable for operation with high-rate downlink is known as RF Telemetry Ranging and allows range estimates to be recovered even if the spacecraft transponder neither turns around nor regenerates the PN sequence on the downlink. This, in turn, allows mission designers to use all but a small fraction of the downlink bandwidth for data transmission.

In RF Telemetry ranging, the uplink station sends a PN sequence and periodically measures the phase of the transmit signal [61][62][63][64]. At the spacecraft, the phase of the received PN sequence is latched whenever a downlink frame departs (or a constant offset thereafter) and the value is then placed inside of downlink frames and telemetered back to Earth. Finally, the station measures the time of arrival of the downlink frame and associates that time tag with the phase value measured onboard the spacecraft, effectively recovering all the necessary information for a range computation. Also note that by measuring the two required time tags on the ground, the spacecraft clock need not be synchronous with the ground.

6.3.4 OPTICAL RANGING

Optical ranging is currently being standardized in CCSDS for use in non-coherent optical modulations such as Pulse Position Modulation (PPM) or Optical On-Off Keying (O3K). Two modes of operation are being standardized: the synchronous mode, which is based on the Time-of-Flight experiment conducted by the LaDEE mission [65]; and the asynchronous mode, which is based on RF telemetry ranging.

In the synchronous mode of operations, ranging is obtained in a manner analogous to PN ranging, but the uplink and downlink signals are normal commanding and telemetry modulated onto an optical carrier [66]. The phase measurements at the ground station transmitter and receiver are made from the start of a ranging frame, which is identified by special synchronization markers known as Range Synchronization Markers (RSMs). Further, to achieve continuous time transfer between the uplink and downlink, the duration of an uplink and downlink frame is made equal on board the spacecraft by synchronizing the uplink and downlink clocks, and by spacing the RSMs in such a way that the duration of an uplink and downlink ranging frame is equal.

On the other hand, in the asynchronous mode of operations phase measurements are performed at the uplink subsystem of the ground station and on board the spacecraft, referenced to the start of ranging frames (rather than a PN sequence as in the RF case) [67]. Like RF telemetry ranging, phases measured on board the spacecraft are associated with time tags measured at the station's downlink subsystem, thus avoiding the need for high precision clocks on board the spacecraft. Furthermore, because the system only makes phase measurements on the uplink, the optical system can operate asymmetric operational scenarios where a mission has an RF uplink and an optical downlink.

The performance of optimetric systems for ranging in lunar scenarios has been evaluated in [68]. Results show that ranging accuracies of less than 1 m are possible given reasonable assumptions on the performance of tracking loops.

6.3.5 DELTA DIFFERENTIAL ONE-WAY RANGING (DDOR)

Delta Differential One-way Ranging is an Earth-based tracking technique that uses radio interferometry to directly measure spacecraft position in the plane of the sky. Large antennas of the DSN and other supporting space agencies receive signals from spacecraft and angularly nearby natural radio sources that define the International Celestial Reference System (ICRS) used for navigation. The difference in signal arrival time at two stations is measured. To enable this type of measurement, the spacecraft must transmit wideband ranging signals commonly known as "DOR Tones." DDOR complements line-of-sight range and Doppler; these data used in combination provide robust and highly accurate determinations of spacecraft trajectories. Measurements made at X-band for several dozen spacecraft over the past twenty years have shown angular accuracy in the range of 1-2 nrad. 1.5 nrad corresponds to plane-of-sky position accuracy of 0.6 m at lunar distance or 225 m at 1 AU distance [69][70][71].

The most demanding application of DDOR has been targeting the arrival at the top of the Martian atmosphere for landers on direct Earth to Mars trajectories. To ensure reference frame consistency, the ephemeris of Mars is also maintained in the ICRS by DDOR measurements of Mars orbiters. Improved tracking efficiency is possible for missions with multiple spacecraft through simultaneous or near-simultaneous measurements of several spacecraft. This was most useful in 2018 for targeting of the InSight Lander and the MarCO-A and MarCO-B CubeSat relay spacecraft.

While range and Doppler already provide line-of-sight coordinates at the 1-m level, navigation analyses have shown that plane-of-sky coordinates using Earth-based techniques can only be further improved by reducing DDOR measurement errors below their current small values. Work to improve DDOR is ongoing in two directions. The current dominant measurement error is due to the dissimilarities in the spacecraft sinusoidal ranging signal spectrum and the quasar broadband noise spectrum. Recent transponder developments include the spreading of DOR tones by a pseudo-noise (PN) code. This reduces the spectrum dissimilarities and has both operational and performance advantages. [72] Iris, UST, and UST-Lite all offer this service. “PN DOR” is currently being demonstrated with the Lunar Flashlight mission. Accuracy at the sub-nrad level is likely achievable at X-band.

Advantages of using the 32 GHz band for DDOR measurements have long been anticipated. Errors due to charged particles are reduced by the higher RF frequency and thermal noise errors can be reduced by taking advantage of the wider spectrum allocation for deep space research at 32 GHz. UST-lite now offers a wide bandwidth PN DOR service in the 32 GHz band. Accuracy at the sub-nrad level is likely achievable.

7 ADVANCED PNT CONCEPTS FOR THE MOON, MARS, AND BEYOND

With the recent exploration initiatives for robotic and human missions to the Moon and Mars, it is desirable to establish a scalable orbiting and surface architecture that provides accurate and autonomous PNT services for orbiting and surface users at the Moon, Mars, and other planetary bodies. In this section, we consider two PNT concepts that can be enabled by a high-grade frequency and timing reference: 1) lunar surface station for orbiting and surface spacecraft, and 2) deep space relay network that provide PNT services to spacecraft in the Mars vicinity and inner planet region.

7.1 LUNAR SURFACE STATION THAT ENHANCES PNT SERVICES FOR ORBITING AND SURFACE SPACECRAFT

NASA began the Communication Relay and Navigation System (LCRNS) project in 2022 to develop the long-term communications and navigation infrastructure at the Moon to meet the needs of the Artemis missions and other lunar missions. ESA, JAXA, other space agencies, and commercial entities may contribute additional lunar relay orbiters that are compatible with the NASA’s orbiters via the LunaNet Interoperability Specification [1]. The lunar relay network is expected to build up incrementally starting with a few relay orbiters that focus on the lunar south pole region, and to evolve to provide global coverage of the Moon. As part of the PNT services, LCRNS adopts the Earth’s GNSS approach with orbiters broadcasting unique spread spectrum signals in S-band, and users simultaneously measuring the time-of-arrivals of signals from multiple orbiters to estimate their own states.

To ensure sustained human presence at the Moon, NASA plans to deploy surface infrastructure elements that can survive the lunar nights. This includes lunar fixed or mobile surface towers that provide terrestrial communications for astronauts and rovers in the vicinity of the landing sites [118][119][120]. The same tower can be used to augment the LCRNS relay network to greatly enhance the PNT services and their performance. The lunar surface station is envisioned to include the following PNT capabilities:

- Provide short-range time distribution to orbiting and surface spacecraft.
- Transmit a GNSS signal to augment the orbital determination (OD) schemes of lunar spacecraft for fast OD convergence. The transmitter can also act as a surface beacon that guides lunar spacecraft during dynamic events like decent and ascent.

- Receive lunar relay orbiters' S-band GNSS signals. This enables accurate relative navigation of users on lunar surface. The Joint Doppler Ranging (JDR) method [118] requires as little as one orbiter to perform real-time position fix of a surface user. This is particularly useful during the early stage of lunar relay network deployment when the number of orbiters is small.

The lunar surface station architecture is directly applicable to the Mars relay network, and this supports the NASA Moon-to-Mars initiative [2].

7.1.1 SHORT-RANGE TIME DISTRIBUTION TO LUNAR ORBITING AND SURFACE SPACECRAFT

In the human exploration era, lunar orbiting and surface spacecraft are expected to work collaboratively to achieve their mission goals. Both the infrastructure elements as well as the users need to be time-synchronized and must collectively maintain a precise globally referenced time. The time reference can come from Earth's ground station, or from Earth's GNSS constellations [122]. In both cases, the range of transfer is of the order of 400,000 km. The range between the lunar surface station and the lunar orbiting and surface spacecraft is much closer, of the order of a few thousand km or less. In-situ time-transfer from a lunar surface station equipped with a good clock can be more accurate due to much shorter range and higher clock stability.

The clocks at the lunar surface station need to be time-synchronized with Earth's reference time. In the case of the lunar South Pole, due to the Earth-Moon geometry and long lunar night due to tidal-locking, many landing site candidates do not see Earth for an extended period in each lunar cycle. Figure 14 shows the rise and set trajectories of Earth as viewed from the Connecting Ridge that Earth spends many days below the lunar terrain.

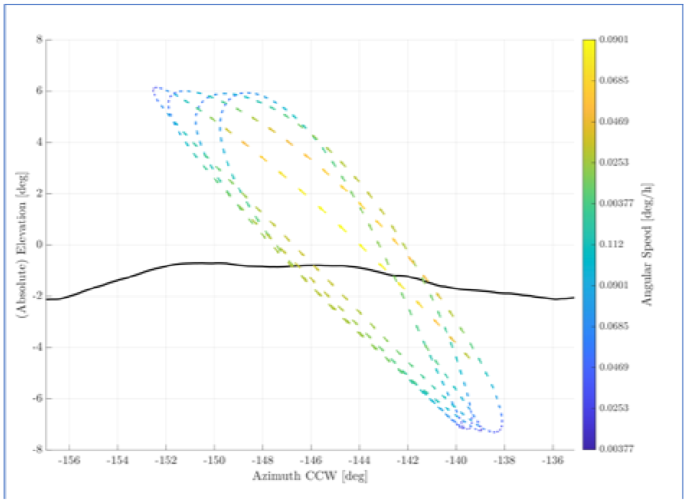


Figure 14. Earth Visibility as Viewed from Connecting Ridge

For the lunar surface station equipped with a clock like DSAC2 with long-term stability, frequent contact with Earth is not required to continue to provide accurate timing and frequency references during the long gap when Earth is below the horizon.

7.1.2 GNSS TRANSMITTER ON LUNAR SURFACE

Equipped with a good clock, the lunar surface station can broadcast a strong and stable GNSS or LNSS signal to the users, and the users can measure the Doppler and range of this link as additional observables to perform OD and/or trajectory estimation. This effectively provides an additional GNSS or LNSS node that is fixed on the lunar surface and acts like a pseudolite similar to Earth's GPS/GNSS applications. This approach is particularly useful to improve the OD and decent trajectory estimations using the Earth's GPS/GNSS signals at lunar distance as proposed by [24][26].

As the lunar surface ground station ephemeris can be measured to high-accuracy with respective to the Moon-centered Moon-fixed inertial frame, measurements of signals generated from the lunar surface ground station can be used to minimize the conversion errors between the Moon-centered Moon-fixed coordinate system and Earth-centered Earth-fixed coordinate system.

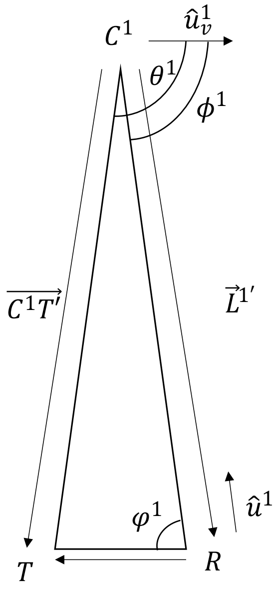
7.1.3 GNSS RECEIVER ON LUNAR SURFACE

The lunar surface station is stationary on the lunar surface and its ephemeris is known to a high degree of accuracy. It can receive relay orbiters' GNSS-like signals, broadcast the range and Doppler measurements to the users, and enable the users to perform real-time position, velocity, and time (PVT) estimations relative to the station's location. This relative navigation approach reduces some of the common measurement biases in the station link and the user link, thus provides more accurate PVT estimations.

Joint Doppler and Ranging (JDR) [123] is one relative navigation scheme that uses range and Doppler measurements between one or more relay orbiters and a user and the lunar surface station to perform real-time PVT estimations for the user relative to the nearby lunar surface station.

Unlike GPS/GNSS-style trilateration schemes which only measure ranges between a user and the orbiters, the JDR scheme uses both range and range-rate (Doppler) measurements by the user and the lunar surface station. The range-rate measurements are first converted to "Doppler-adjusted" pseudo-ranges and are then incorporated mathematically into the range measurements using the law of cosines, as shown in Figure 15. The additional Doppler observables together with the range measurement enable the user to perform real-time position fix with as little as one orbiter, assuming the user's altitude is known.

Like many Doppler-based methods, JDR is sensitive to the range-rate measurement errors. Depending on the number of relay orbiters in-view there are various variations of JDR schemes that generate single-differencing and double-differencing data types to eliminate the common biases in measurements. [123] provides detailed discussion on the PVT performance of the JDR schemes as a function of the clock's characteristics.



Visual description of Doppler localization with law of cosines. T is the user, R is the reference station, and C^1 is the satellite. $\hat{u}_v^1$ is the unit vector of the satellite's velocity vector and $\hat{u}^1$ is the unit vector from the reference station to satellite 1.

$$\left\|\vec{L}^{1\prime}\right\| = \frac{\vec{L}^{1\prime} \cdot \hat{u}_v^1}{\cos\phi^1}$$

$$\left\|\overrightarrow{C^1T'}\right\| = \frac{(\vec{L}^1 + \vec{P})\ \cdot \hat{u}_v^1}{\cos\theta^1}$$

$$\cos\varphi^1 = \frac{\vec{P} \cdot \hat{u}^1}{\|\vec{P}\|}$$

$$\left\|\overrightarrow{C^1T'}\right\|^2 = \left\|\vec{L}^{1\prime}\right\|^2 + \left\|\vec{P}\right\|^2 - 2\left\|\vec{L}^{1\prime}\right\|\left\|\vec{P}\right\|\cos\varphi^1$$

Figure 15. Outline of the JDR method.

7.2 DEEP SPACE RELAY ARCHITECTURE FOR COMMUNICATIONS AND NAVIGATION

This section discusses an evolvable deep space relay architecture that provides communications and navigation services for spacecraft in deep space [124]. The relay orbiters are placed in strategic inclined Mars heliocentric orbits, one Mars-leading and inclined with respective to the Mars orbital plane and one Mars-trailing and inclined in the opposite direction. The inclined geometry of the architecture ensures that there is sufficient geometric diversity of measurements in both the planar and the normal directions of the Mars orbital plane. This deep space relay architecture is illustrated in Figure 16.

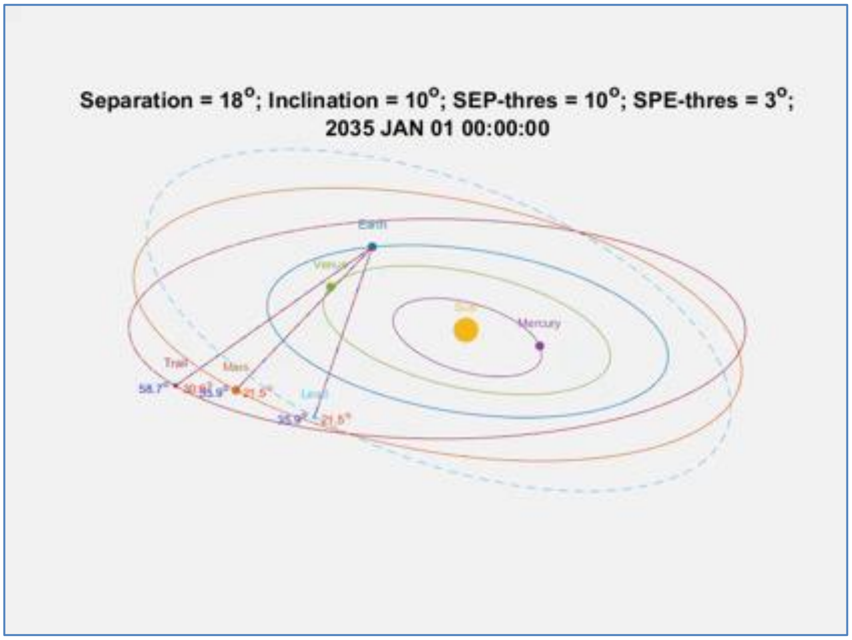


Figure 16. Deep Space Relay Network

The two deep space relay orbiters together with Earth they form a space-based Deep Space Network (SDSN) for the space service volume that covers the Mars vicinity and the inner-planets region. They provide range and Doppler measurements to user for PVT estimations in deep space. Additional relay orbiter(s) can be put in other location(s) in the solar system to enhance the deep space relay architecture. One possible candidate is to place an orbiter in a halo orbit around the Sun-Mars Lagrange point L2 [125]. This provides good coverage for the Mars polar regions, and near-continuous coverage for the hemisphere of Mars during Mars night. This third orbiter also improves the accuracy of the PNT services. The JPL Solar System Dynamic website includes 925 Southern L2 and 925 Northern L2 halo orbits, which are mirror images of each other [126]. The choice of halo orbit depends primarily on the desired coverage of the backside of Mars. Examples of the Sun-Mars L2 halo orbits are shown in Figure 17.

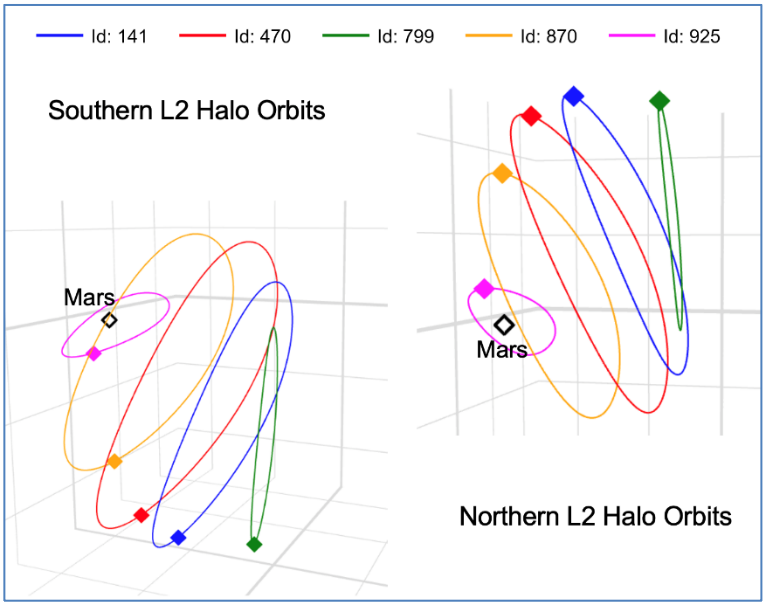


Figure 17. Examples of Sun-Mars L2 Halo Orbits

Depending on the relative geometry between Earth, relay orbiters, and the user, either the GNSS-like trilateration scheme [15] or the JDR scheme can be employed to provide PNT services to the user. For deep space communications and navigation at Mars distance, one-way light-time delay of signal transmission can be as high as twenty minutes. If the infrastructure nodes and the user carry high-quality clocks, the radiometric links can then maintain long-term stability beyond the one-way light-time delay, and one-way tracking methods (Doppler and ranging) can be used instead of 2-way. This allows real-time in-situ PVT estimation, and the relay network can provide PNT services to multiple users simultaneously.

8 CONCLUSIONS

This white paper describes architectures for PNT at the Moon, consistent with LNIS and NASA’s Moon-to-Mars initiative. The most efficient way to meet the long-term goal of providing PNT services at Mars is to invest in needed technologies now and incorporate them into the lunar PNT system.

Investments needed to enable a fully capable Lunar PNT system include the development of high-performance space atomic clocks; high-performance software-defined radios such as UST-lite and Iris capable of advanced communications and navigations techniques with multiple frequencies; navigation autonomy; ground stations; and a terrestrial beacon service. In critical aspects, technologies that work at the Moon will not work at Mars. System engineering studies and architecture trades to identify the differences between the lunar and Mars operational scenarios should begin immediately. The outcome of these studies will inform appropriate technology investments to make and test (to the extent possible at the Moon and with precursor missions to Mars) so that they are ready for Mars exploration beginning in the 2030s.

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Acronyms

APL	Applied Physics Laboratory
BIPM	Bureau International de Poids et Mesures (in English, the International Bureau of Weights and Measures)
BW	Bandwidth
CBT	Cesium Beam Tube
CCSDS	Consultative Committee on Space Data Systems
CDMA	Code Division Multiple Access
CGPM	General Conference on Weights and Measures
CLPS	Commercial Lunar Payload Services
CSA	Canadian Space Agency
CSAC	Chip Scale Atomic Clock
DC	Direct Current
DDOR	Delta Differential One-way Ranging
DLR	German Aerospace Agency
DOD	Department of Defense
DOR	Differential One-way Ranging
DSAC	Deep Space Atomic Clock
DSN	Deep Space Network
DTE	Direct To Earth
DTF-21	DSN Test Facility 21
DUV	Deep Ultraviolet
ELFO	Elliptical Lunar Frozen Orbits
EOC	Extended Operating Capability
ESA	European Space Agency

EVA	Extravehicular Activities
FSTL	Frequency Standards Test Laboratory
GaN	Gallium Nitride
GDGPS	Global Differential GPS
GDOP	Geometric Dilution of Precision
GEO	Geostationary Earth Orbi
GMSK	Gaussian-filtered Minimum Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HLS	Human Landing System
ICRS	International Celestial Reference System
ICSIS	International Communication System Interoperability Standards
IERS	International Earth Rotation and Reference Systems
IMU	Inertial Measurement Unit
IOAG	Intenational Operations Advisory Group
ION	Interplanetary Overlay Network
ITU	International Telecommunication Union
JPL	Jet Propulsion Laboratory
LANS	Lunar Augmented Network System
LCRNS	Lunar Communication Relay and Navigation System
LM	Lockheed Martin
LNA	Low-Noise Amplifier
LNIS	LunaNet Interoperability Specification
LNSP	LunaNet Service Provider
LNSS	Lunar Navigation Satellite System

MAC	Miniature Atomic Clock
MEO	Medium Earth Orbit
MMS	Magnetospheric Multiscale Spacecraft
NENS	Nanoenergy and Nanosystems
NRHO	Near Rectilinear Halo Orbit
O2O	Optical to Orion
O3K	Optical On-Off Keying
OCXO	Oven-Controlled Crystal Oscillator
OD	Orbit Determination
PN	Pseudo-Noise
PNT	Positioning Navigation and Timing
PPNT	Passive PNT
PPP	Public Private Partnership
RAFS	Rubidium Atomic Frequency Standard
RF	Radio Frequency
RFP	Request for Proposal
RSM	Ranging Synchronization Marker
RX	Receiver
SDL	Space Dynamics Laboratory
SLS	Space Launch System
SNR	Signal-to-Noise Ratio
SSPA	Solid-State Power Amplifier
SSV	Space Service Volume
SWaP	Size, Weight, and Power
TAI	International Atomic Time

TBD	To Be Determined
TDM	Technology Demonstration Mission
TDMA	Time Division Multiple Access
TMT	Technology Maturation Task
TX	Transmitter
UHF	Ultra-High Frequency
USO	Ultra-Stable Oscillator
UST	Universal Space Transponder
UTC	Coordinated Universal Time

Appendix A - Background

A.1 Stakeholder stakeholders/sponsors

A.1.1 DSN

The Deep Space Network (DSN) is NASA’s international array of giant radio antennas that supports interplanetary spacecraft missions, plus a few that orbit Earth [89]. The DSN also provides radar and radio astronomy observations that improve our understanding of the solar system and the larger universe [89].

The DSN provides communications and navigation services to space missions using three DSN complexes located in the United States, Spain, and Australia. It both transmits and receives signals.

Each DSN complex contains a Frequency and Timing system. A frequency reference is derived from one of at least four, redundant atomic frequency standards [90]. At each complex, a single (prime) atomic frequency standard serves as the source for all coherent, precision, station frequencies and provides the reference for the station Master Clock [90]. Among other things, this system is an important part of determining the range and range-rate of spacecraft.

A.1.2 CONSULTATIVE COMMITTEE FOR SPACE DATA SYSTEMS (CCSDS)

The Consultative Committee for Space Data Systems (CCSDS) is a multi-national forum for the development of communications and data systems standards for spaceflight. Space communications experts from 28 nations collaborate in developing space communications and data handling standards.

CCSDS is organized into six areas, each with three to six working groups in specific topics, including systems architecture, mission planning and scheduling, service management, onboard wireless, coding and synchronization, optical communications, and delay tolerant networking.

The goal of CCSDS is to enhance governmental and commercial interoperability and cross-support, while also reducing risk, development time & project costs. More than 1,000 space missions have chosen to fly with CCSDS-developed standards.

Two CCSDS working groups most relevant to PNT applications at the Moon, Mars, and beyond are described in more detail here

A.1.2.1 Time Management Working Group

The CCSDS Time Management Working Group is developing standards for time transfer, clock correlation, and clock synchronization. Also, it is working on a standard for time dissemination in a space network. These standards have relevance for cross-support of NASA, ESA, and other missions which may implement either stand-alone space missions or operate within a network at the Moon or Mars.

The first deliverable of the Time Management working group is an informational report [4] describing how civilian space agencies currently manage and historically have managed time for their space missions. The report includes a description of frequency and timing standards, including types of frequency references, atomic clocks, the definition of the second, timescales, network considerations, and international organizations for timing standards. The report also describes the global navigation satellite systems (GNSSs) of the U.S., Europe, Russia, and China.

The report then describes clock correlation, as practiced by NASA, ESA, DLR, JAXA, ROSCOSMOS, and CAST. Clock correlation is a method of transferring a clock counter value from space to the ground, considering the one-way light time between the two, in order that a timescale on Earth may be correlated with the onboard clock. The report discusses clock synchronization, and concludes with a survey of mission time management requirements.

A.1.2.2 Navigation Working Group

The CCSDS Navigation Working Group concentrates on developing technical flight dynamics standards (orbit/trajectory, attitude, tracking, maneuver, pointing, orbital events, conjunction assessment, satellite re-entry, etc.). The aim is the increase flight dynamics interoperability of space missions among the space agencies.

The current goals of the working group are to:

1. Establish the content and format required for the exchange of orbit/trajectory descriptions for use in tracking spacecraft, mission planning, conjunction assessment, and other space applications.
2. Establish the content and format required for the exchange of spacecraft tracking data and navigation sensor data for use in orbit determination applications.
3. Establish the content and format required for the exchange of spacecraft attitude/orientation data and attitude sensor data for use in attitude determination applications.
4. Establish the content and format required to facilitate the transmission of requests related to pointing spacecraft instruments and/or onboard antennas, which require ephemeris and attitude knowledge to process.
5. Establish the content and format required to exchange spacecraft maneuver information, both predicted and reconstructed, related to intentional changes to the spacecraft orbit and attitude using spacecraft actuators.
6. Establish the content and format required to exchange warnings related to conjunctions of space objects and re-entry of space objects.
7. Establish the content and format required to facilitate the exchange of predicted orbital events which affect spacecraft operations.
8. Establish a structure and format that allows the creation of an integrated message combining data from the Blue Books in the Navigation Working Group charter.
9. Develop informational reports that provide explanatory information regarding the published and in progress flight dynamics standards.

Explore additional opportunities for standardization in the area of flight dynamics.

A.1.3 ITU

The International Telecommunication Union (ITU) is the United Nations specialized agency for information and communication technologies. To facilitate international connectivity in communications networks, the ITU allocates global radio spectrum and satellite orbits and develops the technical standards that ensure networks and technologies seamlessly interconnect. The ITU-R and other organizations are currently working to define a new process for accommodating differences between atomic based and Earth-rotation based timescales.

A.1.3.1 UTC and Leap-Seconds

Coordinated Universal Time (UTC) [5] is a global time standard calculated by the Bureau International des Poids et Mesures (BIPM). It is based on a network of more than 450 atomic clocks maintained in 85 national time laboratories worldwide. These clocks not only provide regular measurement data to the BIPM but also offer local real-time approximations of UTC, known as UTC(k). The General Conference on Weights and Measures (CGPM) holds the authority to define and establish the unit of time, the second, and the reference timescale, UTC.

The International Earth Rotation and Reference Systems Service (IERS) plays a vital role in determining and publishing the discrepancy between UTC and the Earth's rotational angle indicated by UT1. When the difference between these two approaches 0.9 seconds, a leap second is introduced and applied simultaneously across all time laboratories. Several time and frequency services, regulated by the ITU Radiocommunication Sector (ITU–R), broadcast UTC and the UT1-UTC difference.

To obtain International Atomic Time (TAI), BIPM calculates a weighted average of all the designated atomic clocks. The process involves a complex algorithm that incorporates estimation, prediction, and validation for each type of clock. Additionally, measurements comparing clocks at a distance rely on techniques such as global navigation satellite systems (GNSS) or two-way satellite time and frequency transfer. These measurements need to be processed to compensate for delays caused by the ionosphere, gravitational field, or satellite movement. UTC is derived from TAI by adding or removing leap seconds as necessary while maintaining the consistent ticking of the atomic second.

During the atomic clock era in the 1970s, it was agreed that UTC should remain aligned with the Earth's irregular rotation, allowing an estimation of the Earth rotational angle UT1 within a 0.9-second tolerance. This alignment was particularly important for navigation systems based on celestial observations. Initially, UTC was corrected in small time and frequency steps, but since 1972, entire leap seconds have been used. Currently leap seconds are only added (or subtracted) at the end of the day on June 30th or December 31st. When a leap second is added, e.g., in the NASA Deep Space Network clock, the precise clock rate remains untouched and the additional second is labeled as 23:59:60.

The introduction of an additional second labeled as 23:59:60 was not anticipated in some modern digital systems. This discrepancy has resulted in the implementation of alternative low precision methods by some tech companies. For instance, Google "smears" the additional second over the previous 24 hours, Facebook spreads it over the subsequent 18 hours, and Microsoft adjusts it in the last two seconds.

From the perspective of managing complex systems, the simultaneous application of a leap second to all satellite clocks and users poses risks. Most global navigation satellite systems, except GLONASS, chose to synchronize their clocks and timescale with UTC without adding leap seconds. Consequently, GPS time and Galileo time is currently ahead of UTC by 18 seconds. BeiDou time is ahead by four seconds. This situation can cause confusion among users on the day a leap second is applied and raises concerns about potential anomalies that could compromise the reliability of critical infrastructure.

Future UTC alignment with Earth's rotation: During the 27th meeting of the General Conference on Weights and Measures in November 2022, it was decided to maintain the existing process of aligning UTC with the Earth's rotation. However, the decision envisions a larger tolerance limit than the current 0.9 seconds. This adjustment would become less frequent to ensure continuity of UTC for at least the next 100 years. BIPM is currently collaborating with ITU–R and other organizations to develop a new process, expected to be implemented by 2035. This process will incorporate a newly identified tolerance value for the UT1-UTC offset, ensuring the efficiency and effectiveness of UTC in current and future timing applications.

A.1.3.2 Future Redefinition of the Second

The General Conference on Weights and Measures (CGPM) holds the authority to define and establish the unit of time, the second [91]. In 1967 the CGPM defined the second as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom". This was revised at the 26th meeting of the CGPM (2018) to be defined by taking the fixed numerical value of the cesium frequency $\Delta\nu_{Cs}$ which is the unperturbed ground-state hyperfine transition frequency of the cesium 133 atom, to be 9,192,631,770 when expressed in the unit Hz, which is equal to s^{-1}.

Optical frequency standards based on different species and transitions in many National Metrology Institutes have now surpassed the realizable accuracy of the current definition by a factor of up to 100. The reliability and uncertainty of related time and frequency transfer methods between standards at distant locations are improving. The Consultative Committee for Time and Frequency (CCTF) is working to identify the best candidate species or ensemble of species that could serve as the basis for a new definition. They have prepared a roadmap of the actions and timings needed to decide on a new definition of the second and has established criteria towards such a new definition. The International Committee for Weights and Measures (CIPM) has been encouraged to bring proposals to the 28th meeting of the CGPM (2026) for the choice of the preferred species, or ensemble of species for a new definition of the second, and for the further steps that would need to be taken for a possible new definition to be adopted at the 29th meeting of the CGPM (2030).

A new, higher accuracy redefinition of the unit of time, the second, will have relevance to overall metrology and will offer new levels of reference precision in future science measurements. But a future redefinition should have little or no consequence to PNT implementations at the Moon or Mars.

A.1.3.3 Timescales for the Earth, Moon, Mars, and beyond

Any timescale consists of an origin of time and an accurate statement of time elapsed since then based on the definition of the second. UTC is such a system developed around atomic clocks operating on Earth. Time scales that support PNT normally do not require an accurate time origin (relative to other timescales such as UTC). For example, in mid Earth orbit, GPS time is only syntonized modulo 1 s [94]. Earth-based GNSS timescales are steered to UTC (without the leap seconds), but with only modest precision. For example, GPS time is only required to be within 1 µs of UTC, though in practice it is held within 10 ns. However, for interoperability of multiple GNSS systems (e.g., GPS and Galileo), it has been shown that the bias between systems must be kept below 10 ns [95]. Requirements on the stability of GNSS timescales are more stringent. GNSS atomic clocks are constantly monitored and updated several times a day to stay within 1 ns. This is done so that positioning errors due to on-board clocks remain 10x less than those due to ephemeris errors [96].

Most space missions to the Moon and beyond currently operate with local time knowledge obtained with dedicated two-way radio links from Earth based tracking stations and time references (such as the DSN). With the expected large increase in the number of missions to the Moon, Mars, and beyond that require a degree of autonomy from Earth, there will be a need for more easily accessible local time references. This will require new locally based timescales maintained by very stable space qualified atomic clocks and the ability to monitor differences of these new timescales to Earth defined UTC.

A.1.4 INTERNATIONAL OPERATIONS ADVISORY GROUP (IOAG)

There are two active Working Groups within the Interagency Operations Advisory Group (IOAG) that are relevant to this white paper: the Lunar Communications and Navigation Working Group (LCNWG), co-chaired by S. Lichten (NASA/JPL) and M. Cosby (UKSA), and the Mars and Beyond Communications Architecture Working Group (MBCAWG), co-chaired by S. Lichten (NASA/JPL) and M. Lanucara (ESA).

These two working groups produced reports in early 2022 summarizing recommendations for architectures for lunar and Mars communications [92][93].

The two 2022 reports focused on recommendations for lunar and Mars communications networks, but only lightly touched on position, navigation, and timing (PNT). The lunar 2022 report served as the basis for the LunaNet specification that is now guiding lunar network development by NASA and multiple other space agencies. In 2023 and 2024, both IOAG working groups are putting increasing focus on the PNT aspects of the network architecture for Cislunar and Mars environments, to support future space exploration.

The working groups have representations from all the major space agencies.

The focus of the IOAG and its working groups continues to be interoperability in a space exploration environment where multiple space agencies and commercial entities are operating and would all greatly benefit from interoperability based on common agreed upon and followed standards for communications and PNT.

This white paper will eventually be shared with both working groups and more broadly, with the IOAG. It is expected to influence the path forward for PNT in Cislunar and at Mars, through consideration by organizations like the IOAG and CCSDS.

A.1.5 DEPARTMENT OF DEFENSE

Motivated by the strategic interest of the U.S. and its allies in lunar explorations, the U.S. Department of Defense (DoD) has an intense and growing interest in the Moon, as reported recently by a number of media channels [97][98][99]. For example, in 2020 the Space Force Commander, Gen. John Raymond, required in his first planning guidance for the newly created Space Force "an order of magnitude expansion of our ability to sense, communicate and act to protect and defend American interests in cis-lunar space and beyond." This year, the DoD's National Geospatial Intelligence Agency (NGA) was tasked with the formation of a lunar reference frame analogues to the terrestrial reference frame [100]. NGA declared its intent to extend this responsibility to other planetary bodies.

While DoD agencies appear to take leadership from and coordinate with NASA, their interests and applications may be less Mars-looking than NASAs, and consequently, they might be more amenable to use efficient lunar-specific technologies, including DoD-assets such as GPS. Indeed, future upgrades to GPS specifically to address lunar navigation, such as backside antennas and higher orbits, have been floated within the Space Force community. It is another reason not to overlook the evolving GNSS infrastructure for lunar navigation.

A.1.6 COMMERCIAL ENTITIES

While NASA is committed to led industry lead the design and construction of the lunar navigation infrastructure, subject to its performance and interoperability requirement, it is already clear there is room for commercial entities to pursue their own interest, potentially beyond, or even outside the NASA-developed guidelines and interoperability specification. The scale of the global interest (perhaps a race) in lunar exploration may give rise to international commercial interests that may want to get ahead of NASA. A strong indication of the potential for commercial exploration is Lockheed Martin's spinoff of Crescent Space LLC to deliver communications and navigation services at the Moon, aiming for customers beyond NASA [101]. Other ambitious space-faring corporations may follow suit. Once again, such endeavors may not be interested in Mars, and may seek efficient, Moon-specific technologies, including the use of NASA's unique in-house expertise and capabilities.

A.2 Related activities

A.2.1 NTS-3 AND SUNRISE MISSIONS

Using GNSS signals at the Moon critically depends on the capabilities of a special class of GNSS receivers designed to track these weak and poorly characterized signals. The NTS-3 and SunRISE missions, slated for in 2024, will improve the art of navigation with weak GNSS signal. Both these geosynchronous missions will carry the JPL Cion weak-signal GNSS receiver. Both will be observing and characterizing space service volume GNSS signals that have never been experimentally characterized in space. NTS-3, in particular, will feature a special Cion antenna with the highest gain ever in Earth orbit, and is explicitly targeting the surveying and characterization of as many GNSS signals as its budget and schedule support.

It has already been established that GPS L1CA signals can support sub-meter-level ranging is cis-lunar space with only a moderately large antenna (~1 m diameter dish should be more than enough). But other GPS signals, such as L5, are even more powerful, and so are the signals from the other 5 major global and regional GNSS. NTS-3 has the potential to assess the availability of these multitude of signals for cis-lunar navigation.

NTS-3 is an experimental GPS spacecraft, sponsored by AFRL, and is due to launch in May 2024 for a nominal one year in orbit. SunRISE is a NASA heliospheric science mission, managed by JPL, and is scheduled to launch in September 2024 for a nominal one year in orbit.

A.2.2 DSN STUDIES

A.2.2.1 DSN Futures Study

The DSN Futures Study has been commissioned by NASA's Space Communication and Navigation Program (SCaN), and more specifically by the Program Systems Engineering Division within SCaN, to define the next-generation DSN Architecture for the 2030s through 2050s.

The Study will be conducted in FY23-FY24 and will: identify major future mission drivers and requirements; perform analyses and trades to define the needed DSN architecture in coming decades; identify flight capabilities required to ensure needed end-to-end capabilities; develop a roadmap for critical and key DSN capabilities of the future with linkages to drivers and requirements; and generate rough cost estimates for key roadmap elements and for different business models for deep space services.

Focus Areas for the DSN Futures Study include:

- DSN Next Generation Architecture -- Number and Types of Antennas
- DSN Next Generation -- Optical Communications
- Next Generation Mars Relay
- DSN Next Generation – Smallsats

The DSN Futures Study is led by the JPL IND Chief Engineer and PSE Manager (S. Lichten). There is an Independent Review Team chaired by the SCaN Office of the Chief Engineer (OCE) (N. Mallik). The SCaN point of contact for the DSN Futures study is J. Hayes.

Key questions to be addressed in the DSN Futures Study include how many DSN antennas will be needed and what capabilities they will need to have. The PNT considerations for lunar and Mars environments will have notable impacts to the DSN since the DSN currently provides the ground end of the deep space communications and PNT links, so as new systems are developed to provide or adv ance those services in Cislunar and Mars environments, the DSN will evolve to provide its part of those services. Additionally, the DSN will play a key role in calibrating or transferring time between Earth and deep space locations.

A.2.2.2 DSN Loading studies

SN Capacity and Loading Studies are conducted in the Program Systems Engineering (PSE) area at JPL, funded through SCaN's PSE Division. The DSN Loading Studies are updated 2-3 times per year, constrained primary by funding, as more frequent updates would be desirable. The loading studies look ahead through the 2020s, 2030s, and 2040s to project anticipated demand for DSN-provided services and capabilities. A recent result [102] projects that DSN excess demand – demand above and beyond what the DSN can provide – will grow significantly in the late 2020s and through the 2030s. During upcoming lunar missions, the DSN demand will be more than double the number of antennas that the DSN will have. And further out, in the 2040s when human Mars Exploration commences, these very high levels of excess demand will persist without relief because unlike the lunar crewed missions which are relatively short (~ several weeks), Mars missions will last for several years. In response to these DSN loading studies, NASA has embarked on developing several mitigations, including a new 18m-class subnet of ground antennas (Lunar Exploration Ground System – LEGS) and the Lunar Relay Communications Satellites (LCRNS).

The DSN Futures Study will provide notable enhancements to these ongoing DSN loading studies, by performing deep dives and examining the causes and potential solutions in far more detail.

A.2.3 IOAG STUDIES

Two studies have been published (see Section 3.1.4) by the lunar and deep space IOAG communications and navigation working groups. Those studies, released in 2022, focused mostly on communications and are presently being updated to incorporate additional Position, Navigation and Timing (PNT) technical areas. The lunar study formed the basis for the LunaNet interoperability specification.

Current studies in these two working groups include: review of the LunaNet specification to ensure interoperability; updates to the Mars architecture recommended in the 2022 report; additional studies for outer planets and other non-Mars and non-lunar space exploration destinations, including Lagrange type trajectories; consideration for excess demand being experienced by the DSN and ESA's ESTRACK network, which is expected to grow in future years; incorporation of the DSN Futures Study recommendations and recommendations from other studies being conducted by ESA and others in parallel.

In addition, the IOAG is establishing a new Security Working Group to define and recommend security for interoperable deep space PNT and communication systems. This Security WG will coordinate with its counterpart in CCSDS.