NASA Mission Needs at the Moon: Communications, PNT, and Observability

I. EXECUTIVE SUMMARY

Expanded cislunar Communications, Positioning, Navigation, and Timing (C&PNT) and observation capabilities are necessary to enable an increased mission cadence and accelerate the establishment of a sustained U.S. presence in the lunar South Pole region. This white paper defines the C&PNT and observation needs of future lunar surface and cislunar missions commensurate with the phased build-up of the Moon Base Program, annual crewed Artemis missions to the lunar surface, and expanded lunar science missions. The user needs defined here facilitate the critical role of commercial industry in NASA's lunar exploration efforts. This demand signal will serve as context for future Space Communications and Navigation (SCaN) market research efforts and public solicitations.

II. BACKGROUND

NASA's lunar objectives will be achieved through a variety of missions and elements, including science orbiters, crewed landers, and critical surface infrastructure. To define the time-phased C&PNT and observation needs of these missions, this white paper will follow the Moon Base Program timeline,[1,2] which will build a sustained lunar presence through a three-phase approach:

1. Phase 1 (Now-2028): Build, Test, Learn
2. Phase 2 (2029-2032): Establish Early Infrastructure
3. Phase 3 (2033-Beyond): Sustained Human Presence

Traffic to the Moon in these three phases grows progressively, with an increasing number of launches delivering a combination of Artemis missions,[3] landers, orbiters, supplies, and other assets to cislunar space and the lunar surface. NASA will leverage industry to deliver the C&PNT and observation capabilities necessary to enable a sustained lunar exploration effort.

III. LUNAR MISSION NEEDS

The following sections combine details from a variety of planned lunar missions and their corresponding C&PNT requirements to characterize the overall architecture capabilities necessary to support missions and elements across each consecutive Moon Base phase.

Table 1: Service Regions

	Phase 1	**Phase 2**	**Phase 3**
Lunar South Pole Region: Latitude	-84 to -90 degrees latitude		
Lunar South Pole Region: Altitude	125 km	200 km	200 km
Moon Base Operational Region	Volume around centralized lunar surface site(s)		
Number of Centralized Lunar Surface Sites	1	3	3-5+
Assets per Centralized Lunar Surface Sites	Up to 3	3-5	5+

COMMUNICATIONS

As lunar infrastructure is established, launches to the Moon will become more frequent, mission objectives will increase in complexity, and user communications needs will evolve. During Moon Base Phase 1, lunar missions will initially rely on Direct-with-Earth (DWE) links as the primary communications pathway until lunar relay capabilities achieve operational readiness. Expanded terrestrial ground station capabilities will be required to support surface users and downlink data from relays, support large science orbiters, and provide redundant communications paths for critical assets.

In Moon Base Phases 2 and 3, centralized surface communications station(s) will be erected to provide surface proximity communications (Wi-Fi, 3GPP) services and alternative return link pathways, enabling additional lunar surface missions and higher data throughput alongside a reduced number of concurrent DWE or relay links. Throughout all three Moon Base phases, NASA intends to proliferate HD/UHD cameras across the lunar surface to observe astronaut extravehicular activities and infrastructure construction. This will continue to grow the number of concurrent users and overall return data throughput. While early missions will rely on Radio Frequency (RF) communications links (S-, X-, Ka-Band),[4] Moon Base Phases 2 and 3 may incorporate optical communications terminals to deliver higher data throughput capabilities.

Table 2: Lunar Communication Needs

	Phase 1	**Phase 2**		**Phase 3**
Service Availability[a] (Per Earth Day)				
Relay Coverage and Availability	50%	> 90%		99%
Ground Station Availability	99%	99%		99%
Concurrent Users (Combined Real-Time and Non-Real-Time Services)				
		2030	2032	
Concurrent Relay Users *Without lunar surface aggregation*	Low Rate: 1+ High Rate: 1+	Low Rate: 2+ High Rate: 6+	Low Rate: 4+ High Rate: 10+	Low Rate: 4+ High Rate: 20+
Concurrent Relay Users *With lunar surface aggregation*	Limited/ Demonstration	Low Rate: 2+ High Rate: 4+	Low Rate: 4+ High Rate: 6+	Low Rate: 4+ High Rate: 10+
Concurrent Ground Station Users *Lunar User to Earth (DWE),* *Does not include relays as users*	Low Rate: 3+ High Rate: 3+	Low Rate: 3+ High Rate: 4+	Low Rate: 4+ High Rate: 6+	Low Rate: 4+ High Rate: 9+
Peak Instantaneous Throughput for Real-Time Service (Return)				
Relay *Lunar Users to Relay*	50 Mbps (2028)	300 Mbps (2030) 550 Mbps (2032)		850 Mbps (2034) 1250+ Mbps (Goal)
Ground Station *Relays to Earth*	50 Mbps (2028)	300 Mbps (2030) 550 Mbps (2032)		850 Mbps (2034) 1250+ Mbps (Goal)
Ground Station *Lunar Users to Earth (DWE)*	50 Mbps (2027) 100 Mbps (2028)	200 Mbps		300 Mbps
Peak Instantaneous Throughput for Real-Time Service (Forward)				
Aggregate (DWE & Relay) Forward	25 Mbps	200 Mbps		300 Mbps
Non-Real-Time Data Service (Return)				
Small Mission Data Volume *CLPS, etc. (balanced DWE/Relay)*	5 GB/day per mission, 5+ missions	5 GB/day per mission, 10+ missions		5 GB/day per mission, 10+ missions
Large Mission Data Volume *LRO replacement, Orion, etc.* *(primarily DWE)*	100 GB/day per mission	650 GB/day per mission		3100 GB/day per mission

[a] *Availability* refers to percent time a service is operational; *coverage and availability* refers to the percent time a line-of-sight exists to the full service volume (see Table 1) and service is operational. Usage may be less than availability.

POSITIONING, NAVIGATION, & TIMING

Positioning, Navigation, and Timing (PNT) capabilities are integral to ensuring lunar missions can safely and successfully execute mission objectives. During the initial portion of Moon Base Phase 1, users will be largely reliant on terrestrial PNT sources and onboard sensors. As lunar relays become operational, the baseline navigation and timing approach for Moon Base will leverage the Lunar Augmented Navigation Service (LANS),[5] which consists of Augmented Forward Signals (AFS)[6] transmitted continuously by multiple relay nodes. LANS is comparable to terrestrial Global Navigation Satellite Systems (GNSS), wherein four or more signals observed simultaneously by a user can be processed to form a complete position, velocity, and time (PVT) solution. Note that LANS must be tied to an established reference clock system representing the Coordinated Lunar Time (LTC) time scale.

A combination of LANS signals and an onboard inertial measurement unit (IMU) should be sufficient to enable lunar surface positioning to within 10 m. Higher fidelity needs, such as hazard avoidance or proximity operations with position knowledge requirements of less than 10 m will require users to augment LANS radiometric observables with additional sensors, such as LiDAR, cameras, etc. Throughout the Moon Base timeline, PNT capabilities will evolve primarily by expanding the number of relay assets and reliable reference clock sources to deliver increased availability and navigation accuracy throughout the service volume.

Table 3: LANS-Based PVT Estimation Needs

	Phase 1[a]	**Phase 2**	**Phase 3**
Positional Knowledge[b]	50 m (surface) 100 m (ascent/descent)[c] 100 m (orbit)	25 m (surface) 50 m (ascent/descent)[c] 100 m (orbit)	10 m (surface) 50 m (ascent/descent)[c] 100 m (orbit)
Velocity Knowledge[b]	Limited	0.1 m/s	0.1 m/s
PNT Service Availability (e.g. LANS/AFS)	Limited / Demonstration	80%	99%
Time Knowledge	1 μs	0.1 μs	0.1 μs
Time to First Fix	600 s	600 s	600 s
LTC Trace to UTC	1000 ns	100 ns	100 ns

[a] *During the early portion of Phase 1, there will be insufficient (< 4) relays to establish a LANS. The knowledge/availability requirements only apply once there are sufficient relay assets to establish LANS with acceptable geometric distribution.*[7]
[b] *State estimate knowledge needs are absolute, 3D, RSS, 3σ.*
[c] *Ascent/descent requirement is per axis until landing and assumes user has hazard detection systems.*

OBSERVABILITY FROM ORBITAL PLATFORMS

Observability for Moon Base is driven by the need to characterize and continually monitor the lunar surface in support of mission planning, operational safety, and long-term infrastructure development.[8] Effective observability encompasses both pre-mission reconnaissance and ongoing operational awareness. Sustained high-resolution surface imagery enables mission planning through the generation of photomosaics, stereo imagery, and digital elevation models that can be used for detailed assessments of natural terrain features and site topography. Unique challenges of the lunar South Pole, including extreme lighting conditions, permanently shadowed regions, and varied terrain slopes, drive to a sub-half-meter imaging requirement to ensure small-scale hazards can be effectively characterized, with 30 cm preferred. Observability capabilities will also include real-time video monitoring to bring the world along with NASA at Moon Base while enhancing crew situational awareness, telerobotic performance, and engineering assessments of events such as plume surface interactions.

For Phase 1, passive RF sensing capabilities complement the operational picture provided by imaging. RF sensing for the surface and orbital regimes provides basic space situational awareness (SSA) and enables safety of navigation. Other activities enabled by RF sensing include the validation of surface wireless coverage areas and the identification of RF interference sources. For crew and mission safety, continuous space-based monitoring of ionizing radiation is also needed in Phase 1.

Orbital observation capabilities will follow a phased development alongside Moon Base, with enhanced imaging coverage, resolution, and revisit period. As the number of simultaneous orbital and surface users increases, a growing suite of SSA sensors will also be required. Additional capabilities needed for Phase 2 and Phase 3 operations include thermal imaging, multi-spectral sensors, water ice remote sensing, and permanently shadowed and lunar night imaging. Together, these observation capabilities will enable the long-term operational objectives of Moon Base, including in-situ resource utilization, lunar night operations, and establishing a permanent human outpost.

Table 4: Lunar Observation Needs

For Lunar South Pole Regions	**Phase 1**	**Phase 2**	**Phase 3**
Surface Sample Distance (SSD) *Visible Light Imaging and Video*	50 cm (Threshold) 30 cm (Target)	≤30 cm	≤25 cm
Revisit Period *South Pole Region*	Limited	168 hours	48 hours
Revisit Period *Moon Base Region(s)*	3 hours	3 hours	1.5 hours
Observation Angle	Nadir or Off-Nadir/Oblique		
Additional Capability Needs	• Orbital & Surface Passive RF Detection and Localization • Ionizing Radiation Monitoring	• Space Situational Awareness (e.g. Electro-optical sensors, Active RF sensors) • Surface & Sub Surface Characterization of Geotechnical Properties (e.g. Radar sounding, Microwave Radiometry, Synthetic Aperture Radar) • Thermal Environment Characterization (e.g. Thermal Infrared (TIR) Imaging, Infrared Radiometer) • Volatile Characterization (e.g. Microwave Radiometry, Radar Sounding, Cosmic Ray Radio Frequency Sounding, Infrared Spectroscopy, Far Ultraviolet, Near-Infrared (NIR), Intermediate Infrared (IMIR), TIR Spectroscopy, Neutral and Ion Mass Spectroscopy of Activate Molecules) • Mineralogical Characterization (e.g. Ultraviolet, Visible, NIR, IMIR, TIR image spectroscopy, Active Reflectance Spectroscopy) • Permanently Shadowed & Lunar Night Imaging	

IV. CONCLUSIONS

NASA requires expanded C&PNT and observation capabilities to enable a sustained lunar presence. There are significant challenges to delivering the necessary capabilities, including short timelines, ambitious performance expectations, and a difficult operating environment. However, given the maturity and innovation of the terrestrial space communications and observation marketplace, there are multiple capability gaps that can be closed by potential industry partners:

- Terrestrial Ground Stations:
    - Communications: Increased quantity and throughput of terrestrial ground station communication services.
    - Navigation: Increased accuracy/precision of navigation services, including timing.
- Relay Providers: Additional C&PNT relay constellation satellites to provide increased availability, data throughput, and simultaneous user links.
- User Terminals:
    - Communications: Widely available and space-rated RF transceivers and optical communications terminals.
    - PNT: Systems capable of AFS signal acquisition and tracking, peer-to-peer radiometric generation, navigation sensor fusion, and accurate position, velocity, and time estimation.
- Lunar Surface C&PNT Node: Resilient and durable proximity (Wi-Fi/3GPP/PNT signal) transceivers, data aggregation capabilities, DWE/relay communications systems, and/or atomic clocks/timing systems to help establish a Coordinated Lunar Time (LTC).
- Observation: Lunar surface observation instruments and spacecraft buses.

Please monitor the SCaN website[9] and SAM.gov[10] for upcoming opportunities to engage with NASA, partner with SCaN, and contribute to the next age of lunar exploration.

V. REFERENCES

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VII. APPENDIX A: ACRONYMS AND ABBREVIATIONS

Acronym	Definition
3GPP	3rd Generation Partnership Project
AFS	Augmented Forward Signal
C&PNT	Communications and Positioning, Navigation, and Timing
CLPS	Commercial Lunar Payload Services
DWE	Direct-with-Earth
FWD	Forward
GB	Gigabyte
GNSS	Global Navigation Satellite Systems
HD	High Definition
IMU	Inertial Measurement Unit
LANS	Lunar Augmented Navigation Service
LiDAR	Light Detection and Ranging
LRO	Lunar Reconnaissance Orbiter
LTC	Coordinated Lunar Time
m/s	Meters per second
Mbps	Megabits per second
ns	Nanosecond
PNT	Positioning, Navigation, and Timing
PVT	Position, Velocity, and Time
RF	Radio Frequency
RSS	Root Sum Square
RTN	Return
SCaN	Space Communications and Navigation
SSA	Space Situational Awareness
SSD	Surface Sample Distance
UHD	Ultra-High Definition
UTC	Coordinated Universal Time
μs	Microsecond
σ	Standard Deviation