National Aeronautics and Space Administration

# Lunar Node – 1: Initial Flight Results and the Role of Surface Pseudolites in Lunar Navigation

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# Outline

- Lunar-Node 1 Payload
  - Design
  - Operational Expectations vs Reality
  - Results and Takeaways
- Path Towards Lunar Node - X
- Role of Pseudolites in Lunar Navigation Architecture
  - Coverage
  - Interoperability Approach
  - Potential Implementations

# Lunar Node-1 Overview

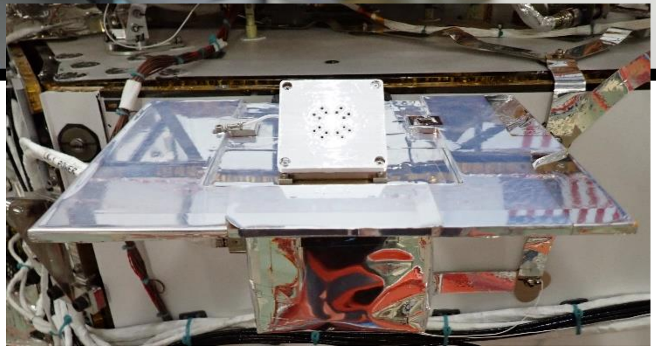
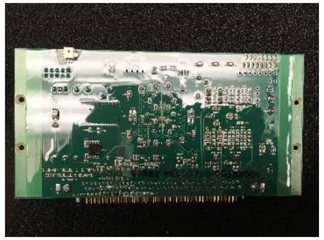
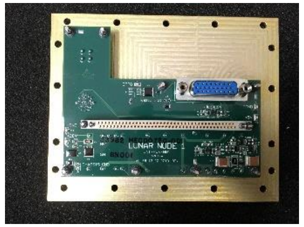



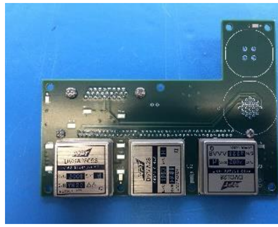
Image Credit: Intuitive Machines

Controller Board with Space CSAC

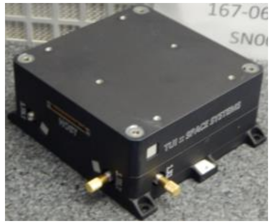



Power Board with Interface

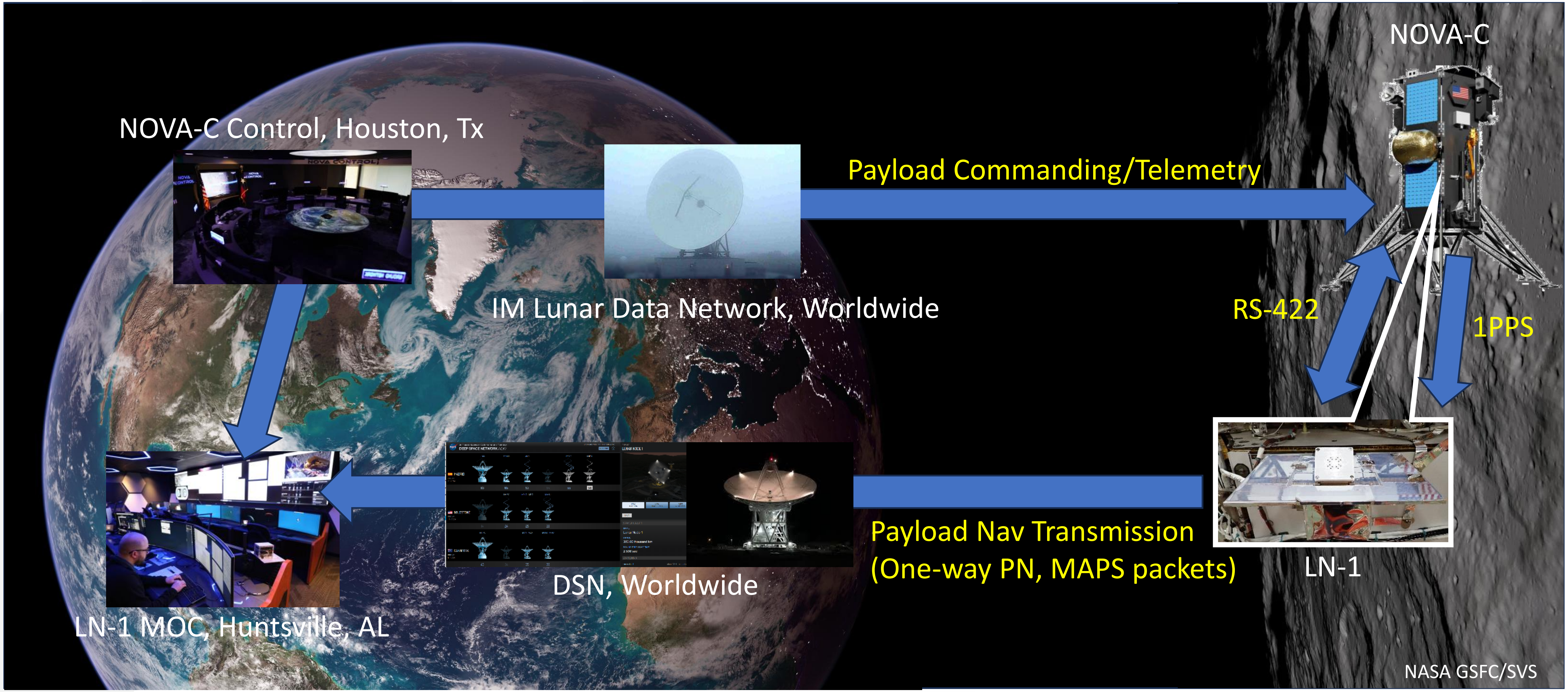




Tethers Unlimited SWIFT-SLX



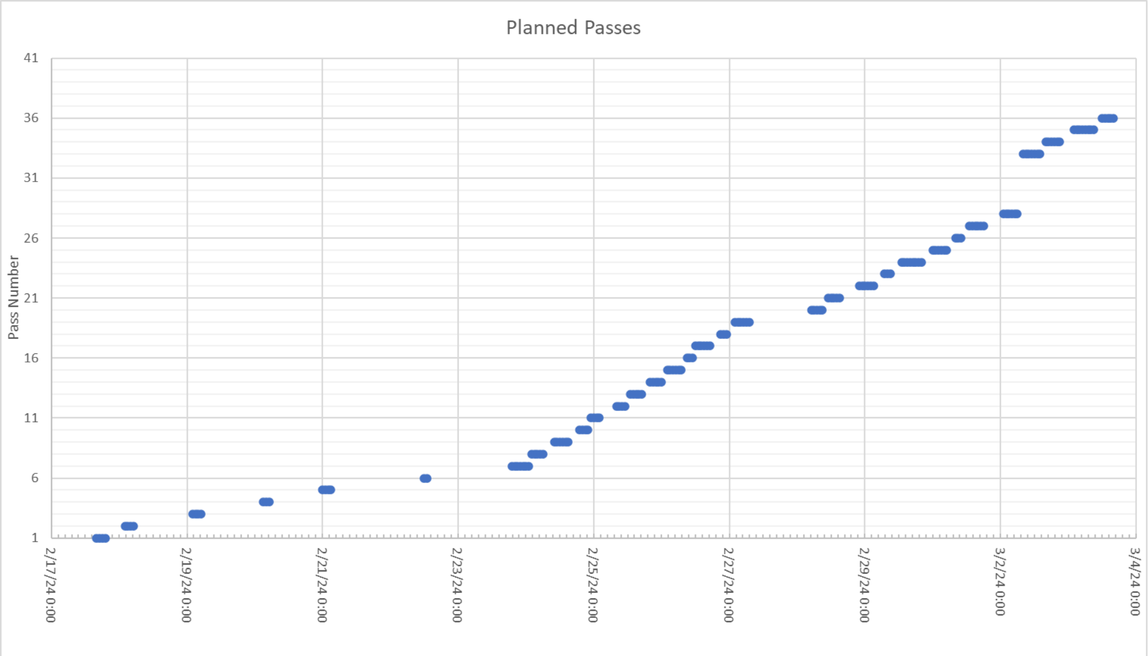
# Operational Approach



# Pass Planning and Execution

- Objectives
  - Daily passes during cruise to checkout hardware
  - Observations in Lunar orbit to capture orbital dynamics
  - Long-term operation from Lunar surface for developing clock calibration and assess hardware survivability
- Achieved most of the cruise passes without issue, surface ops constrained by landing configuration and available power
  - ~4.5 hours of MAPS packets transmission from LN-1 to DSN across 4 cruise passes (>40K one-way MAPS packets)
  - 15 minutes of MAPS packet transmission from Lunar Surface
  - 15 minutes of one-way PN Ranging from Lunar Surface
  - Multiple raw RF recordings of LN-1 transmissions by DSN to assess multipath and data processing
  - One-way Doppler Tracking of LN-1 during all passes

Pre-flight: ~one hr/day cruise/orbit, ~8 hrs/day from surface

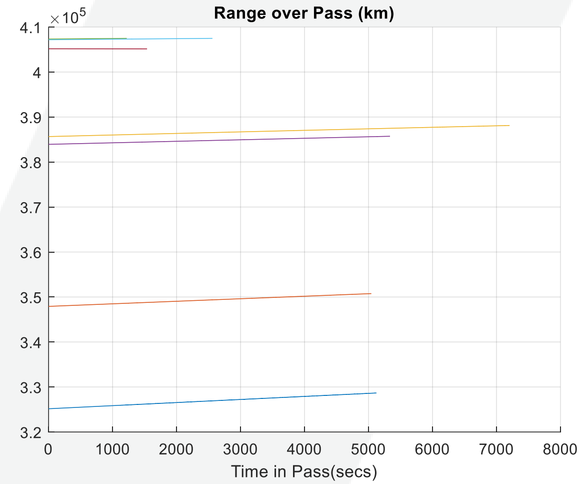


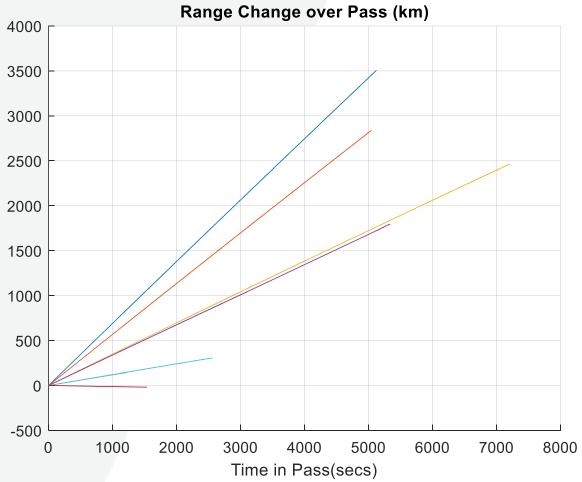

Actual: ~one hr/day cruise/orbit, ~30 minutes from surface

| BOT (UTC) | EOT (UTC) | FACILITY | ACTIVITY | LN-1 Mode |
|---|---|---|---|---|
| 2024-048T16:30:00 | 2024-048T18:30:00 | 56 | L3 INITIAL ACQ | MAPS |
| 2024-049T02:30:00 | 2024-049T04:30:00 | 54 | TKG PASS | MAPS |
| 2024-049T21:30:00 | 2024-050T03:00:00 | 56 | IM1 Support | MAPS |
| 2024-050T02:40:00 | 2024-050T04:40:00 | 24 | TKG PASS | MAPS |
| 2024-050T21:25:00 | 2024-051T04:45:00 | 54 | IM1 SUPPORT | MAPS |
| 2024-051T03:50:00 | 2024-051T04:45:00 | 56 | IM1 SUPPORT | MAPS |
| 2024-058T02:55:00 | 2024-058T06:55:00 | 56 | IM1 SUPPORT | MAPS (Surface) |
| 2024-059T11:50:00 | 2024-059T14:45:00 | 36 | IM1 SUPPORT | PN 1-way (Surface) |

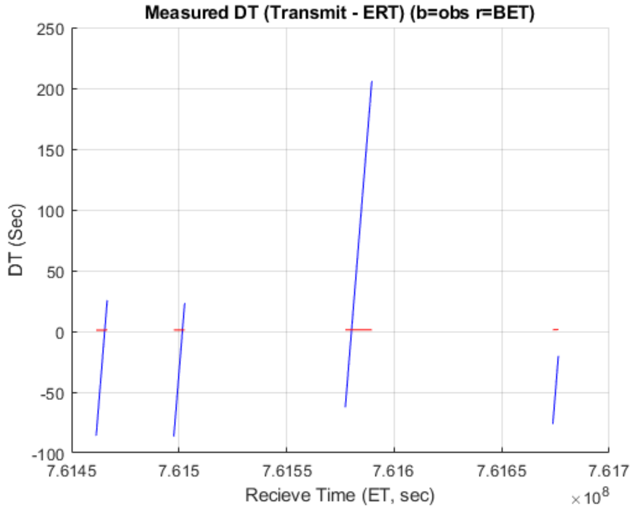
# Raw and Calibrated Results

## Motion over Pass (BET)



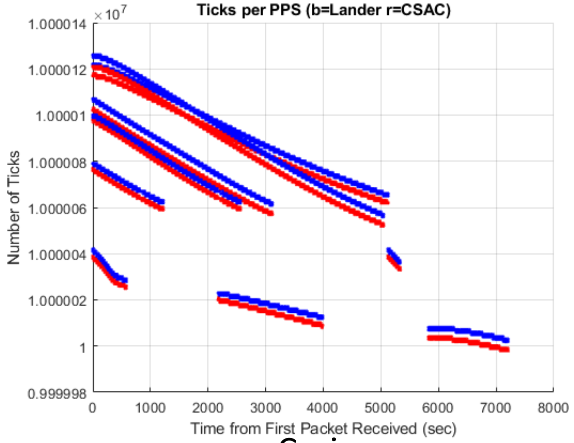




## Range via Time Transfer (raw)




| Drift per pass |
|---|
| 0.0217593 |
| 0.0217487 |
| 0.0217598 |
| 0.0217539 |
| 0.0216795 |
| 0.0217464 |
| 0.0216956 |

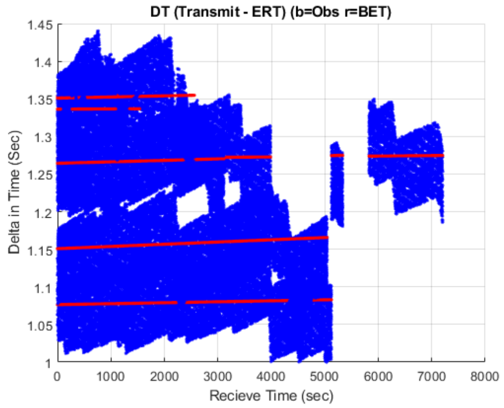
## Onboard Clock Drift



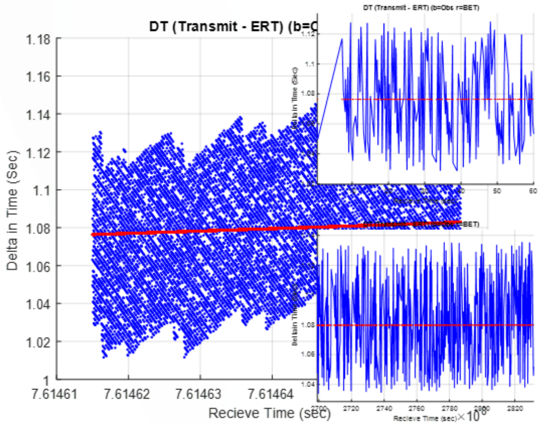

Cruise

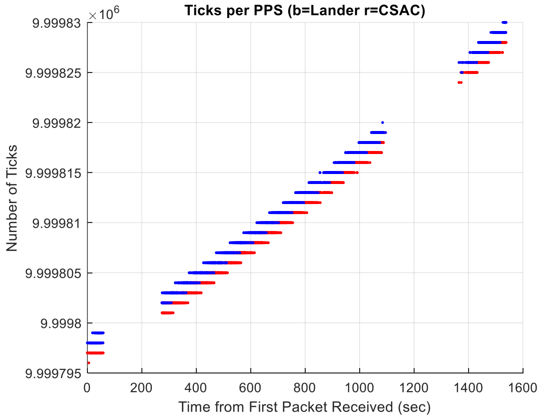
## With Bias and Drift Correction via BET

### All Passes (time since start)




### Pass 1



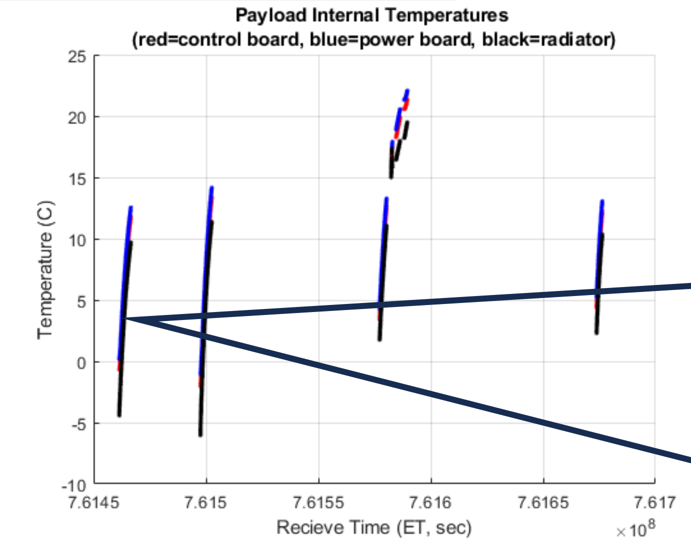



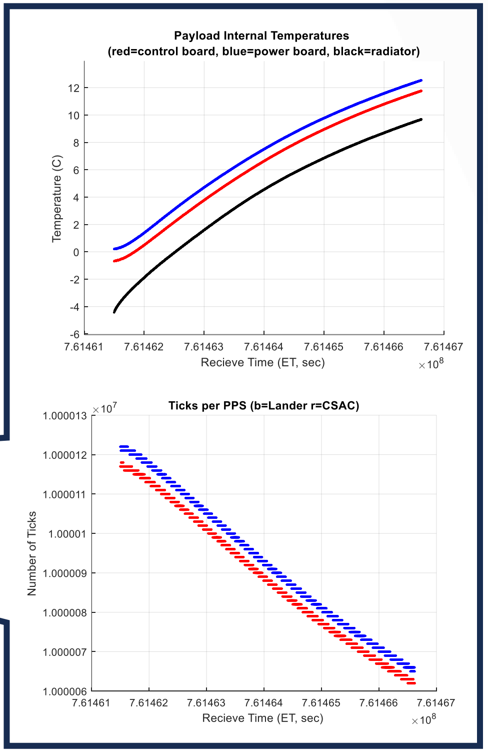

Surface

# Takeaways

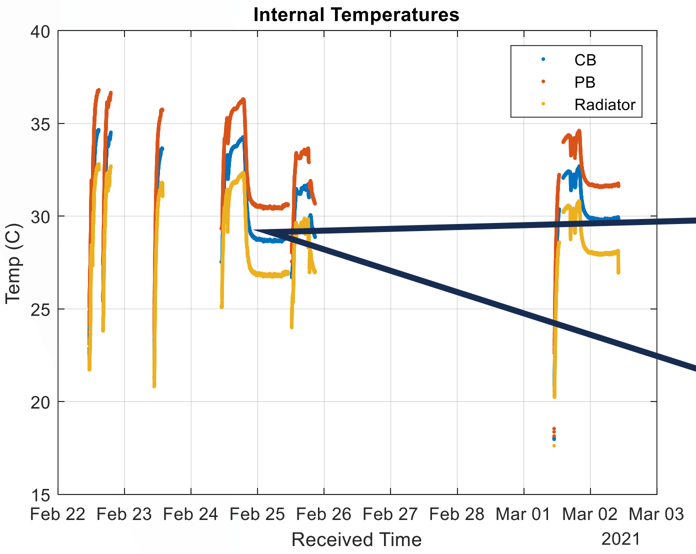
- Primary science was planned for lunar surface
- Cruise checkouts were opportunistic to ensure payload operational and capture additional data
- Internal oscillators (CSAC and XTAL) and radio had known thermal stabilization time requirements
- Thermal drift directly correlated to poor timing and frequency stability

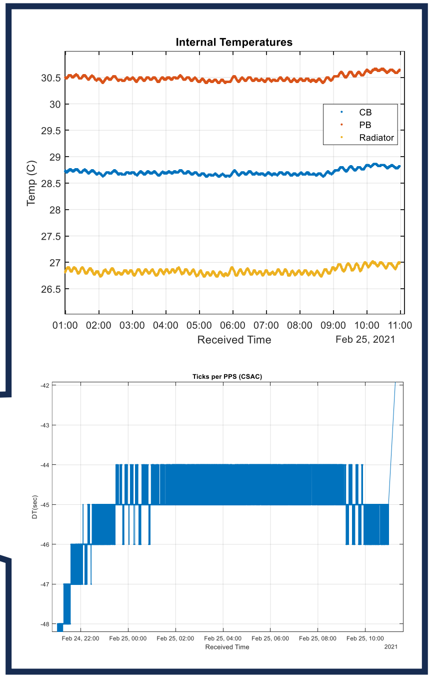
In-flight



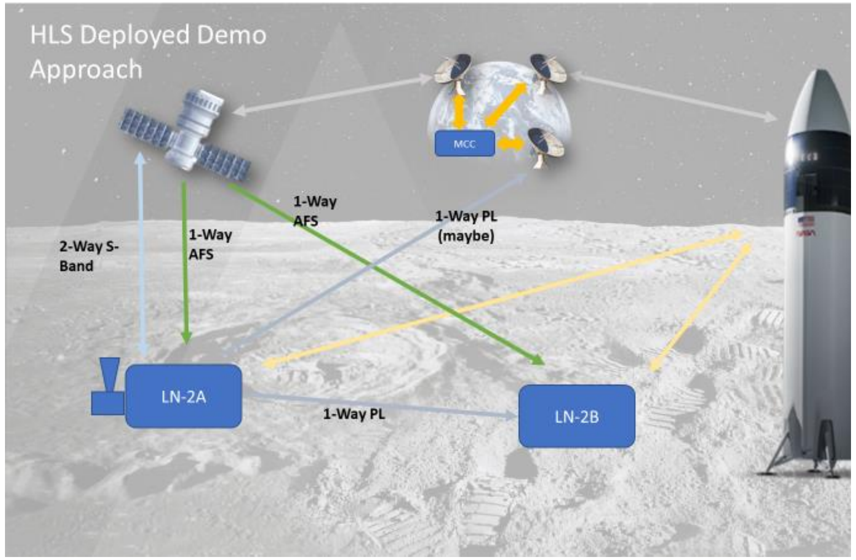

During Compat Testing



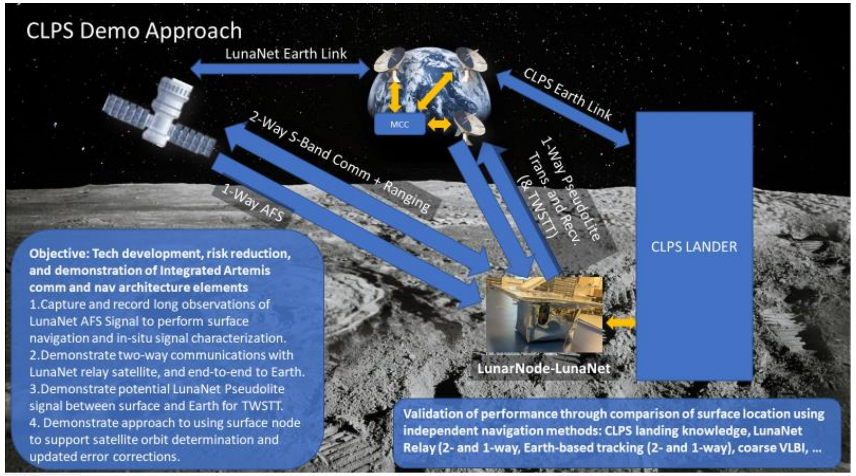



# Lunar Node: Next Steps

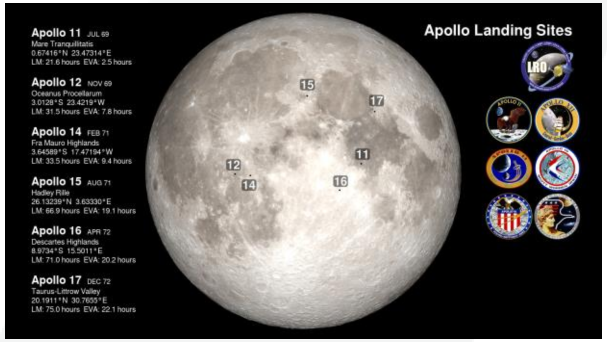
- Key Planned Upgrades
  - Inclusion of receiver to enable peer-to-peer ranging in alignment with LunaNet Specifications
  - Updating one-way ranging code from JPL to LunaNet
  - Inclusion of higher stability timing source
  - Potential operation as early LunaNet AFS user receiver and implementation of Two-way Time Transfer
- Hardware Development
  - Internal SDR-based implementation to support field testing for a localized infrastructure
  - Implementation of LunaNet PN receiver (and transmitter potentially) into upgraded radio by CesiumAstro
  - Procurement of support hardware (i.e. power capture and storage)
- Continued Testing
  - Long-term testing with LN-1 Flight Spare and Flight-like Radio to capture timing and frequency stability over extended periods
  - Evaluation of other clock sources (OXCO, TCXO)
  - Field testing with limited deployment of ground sensors
- Continued evaluation of role in architecture
  - Monitor station, early testing, augmentation



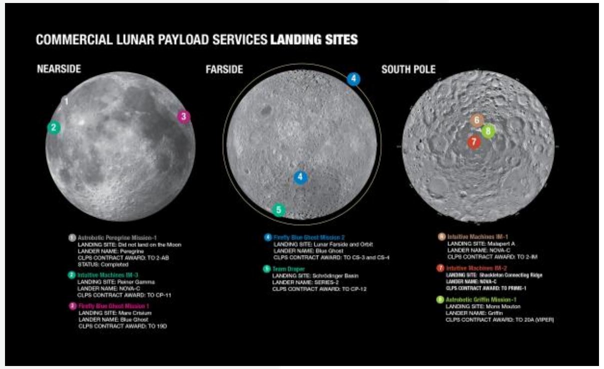

Possible flight follow-on configuration as a deployed surface payload (above) or hosted on a CLPS lander (below)



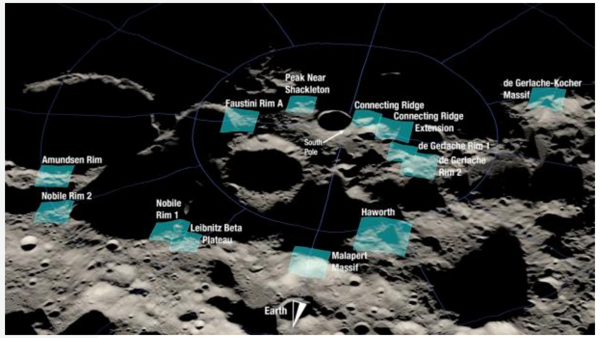
# Need: Focused Augmentation of Constellations




Apollo Landing Sites (NASA/GSFC/SVS)

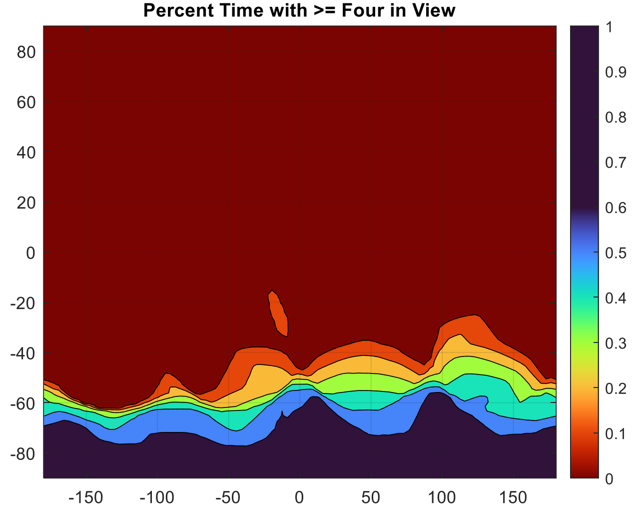



Initial CLPS Landing Sites (NASA/CLPS)

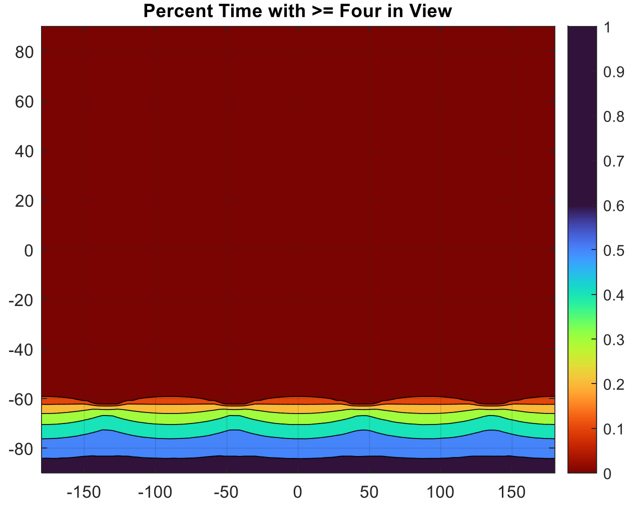



13 Candidate Artemis III Landing Sites (NASA/GSFC/SVS)

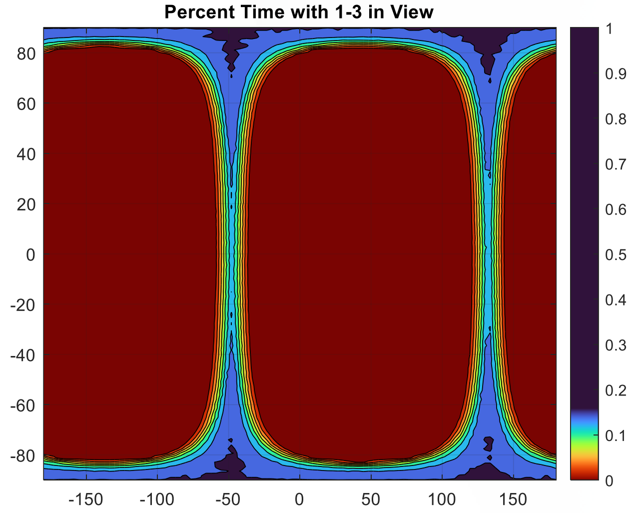
## Coverage over 12 hours w/ 30 Deg Elev Limit



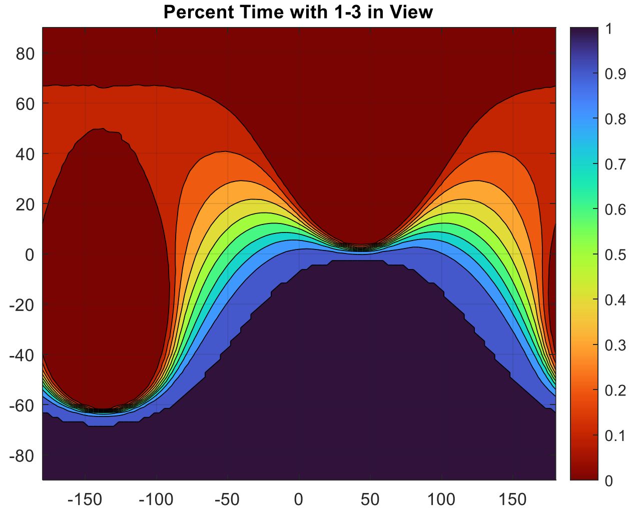

6 Satellites Phased in 12 Hr Frozen Orbits(4)




4 Satellites Phased in 12 Hr Frozen Orbits(4)




4 Satellites Phased in 100x100 Polar Orbit




3 Satellites Phased in 12 HR Frozen Orbit

# Approaches to Navigation via Architecture

- Solution dependent on number of satellites in view
  - 4 satellites in view: real-time (x,y,z,t) solution with accuracy limited by GDOP
  - 3 satellites in view: if have time, can solve (x,y,z), if not time, can solve to location on a surface
  - 2 satellites in view: requires extended observation time, decreased accuracy
  - 1 satellite in view: primary useful for time synchronization
- For less than 3 satellites, increasing dependence on time of observations and change in observation geometry over time
  - Increasingly sensitive to user timing capability
  - Requires a user stay fixed within desired accuracy range
- Ways to augment
  - Provide a local time synchronization for user to LunaNet
  - Surface-based range measurement to fixed asset(s)
  - Assumptions of being fixed to surface (variable fidelity, and impact of uncertainty between DEMS and inertial frame)

# Implementation Approaches and Challenges

## Ultra-wideband Ranging

- COTS solution
- Requires dedicated hardware
- Ability to measure range at cm level from 50 to 500 m dependent on implementation
- Not currently in architecture or specifications
- Small size and power requirements

## Wi-fi Round-Trip Timing

- Specification included in WIFI 5
- Limited implementation
- Measures range using two time transfer over network
- Implemented at firmware level on modems
- Range dependent on implementation (power, firmware, antennas) max ~kms
- Wi-Fi has wide planned usage across surface elements

## LunaNet/Peer to Peer PN Ranging

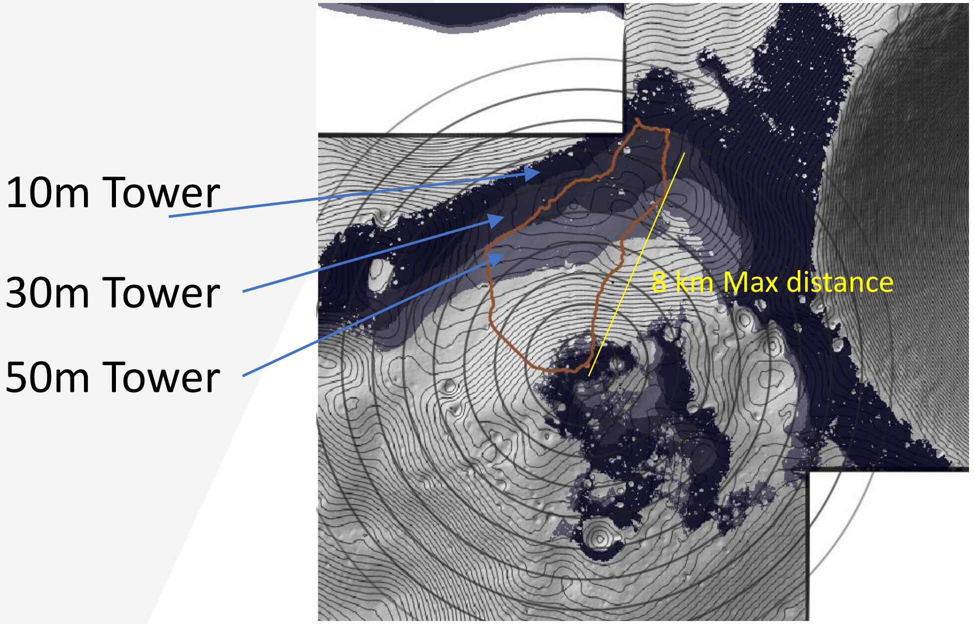
- Requires dedicated use of radio
- Requires scheduling of pass between user and host for frequency selection and operation
- Utilizes two separate frequencies (TX and RX)
- Requires a larger radio element, would likely be part of comm systems

## LunaNet/One-way PN Ranging

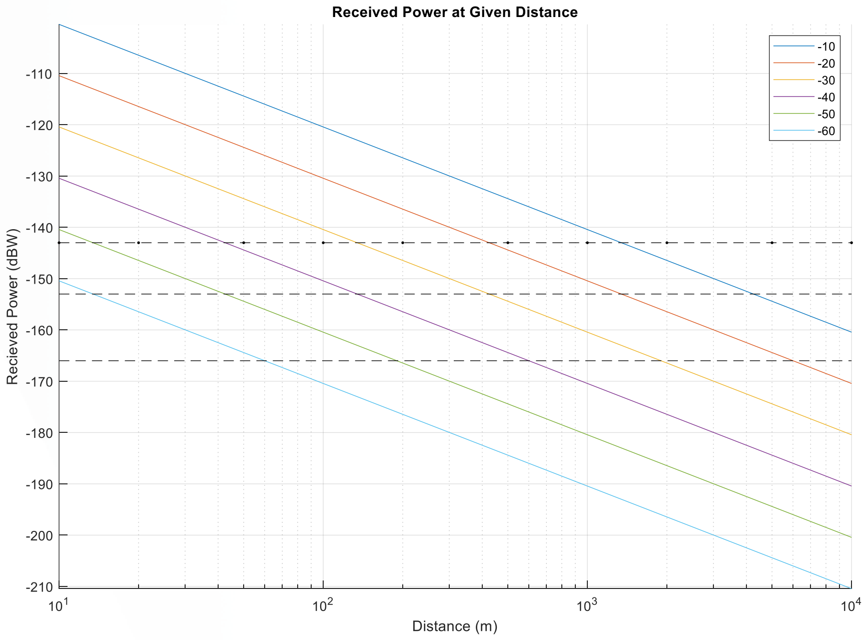
- Aligns with signals being deployed by orbital assets
- Allows for seamless integration of additional measurements
- Operational range limited by power constraints
- May require very low power transmission (or intentional signal degradation at cost of increased noise)
- Will need to customize use of ephemeris messages to match fixed location
- Can operate in mixed mode to switch between user and provider of services
- May be implemented independently of comm

# Challenges with Deploying Pseudolites to Surface

- If align with LunaNet frequency, must allow follow surface power restrictions (or risk interference with orbital signals)
  - -20 dBm output within spec at 1.5 to 6 km (equivalent to lower end of Bluetooth LE transmission)
  - -30 dBm output within spec at 0.5 to 2 km
- Can select power drop-off to focus on gaps between solutions
  - When near lander (or infrastructure), can consider relaxation of navigation constraints
  - Can turn signal on/off based on operational range (i.e. only when not in comm)
  - Augment longer-range AFS with other network-centric approaches
- Will still be limited by line of sight between PL and user (site dependent)

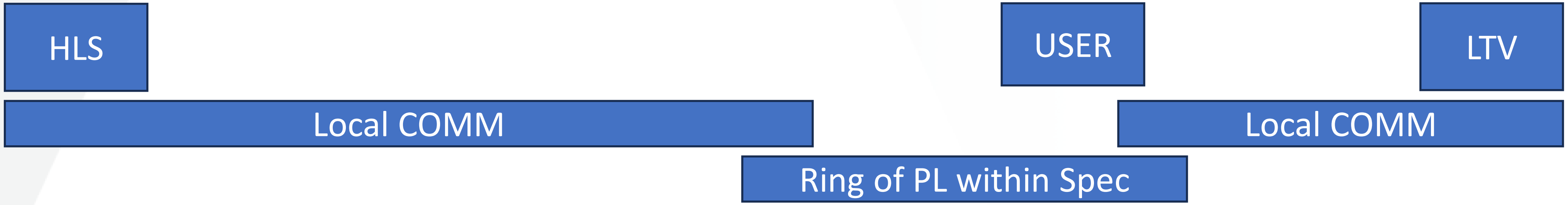



1 km Contours from Hub for Example LTV Traverse



# Forward Work: Towards Deployment of PLs

- Hardware Development and Testing
  - Ground testing to provide inputs to potential interference between local PL and orbital signals using simulator
- Consider Alternate Frequency
  - Similar to GNSS augmentation, consider a secondary frequency for local references with higher noise floor and non-interference
- Multi-mode ground receiver/transmitter with stable clock to transfer between user and provider modes
- Continue to assess as part of larger architecture and balance with other comm-based approaches
  - Balance between all surface elements for common signals
  - Define trusted time sources and distribution network
  - If multiple ground elements, can tune power based on range to create rings of coverage based on focused operations (doesn't work in more general operational scenario)



# Thank you very much!

**Thank you to our partners for supporting this mission:**

- Lunar Node-1 Team at MSFC and program staff at HQ/SMD/GRC
- Intuitive Machines
- CLPS Office
- DSN Team at JPL and Peraton
- Tethers Unlimited