Preliminary Design of Intuitive Machines' Lunar Data Network Constellation

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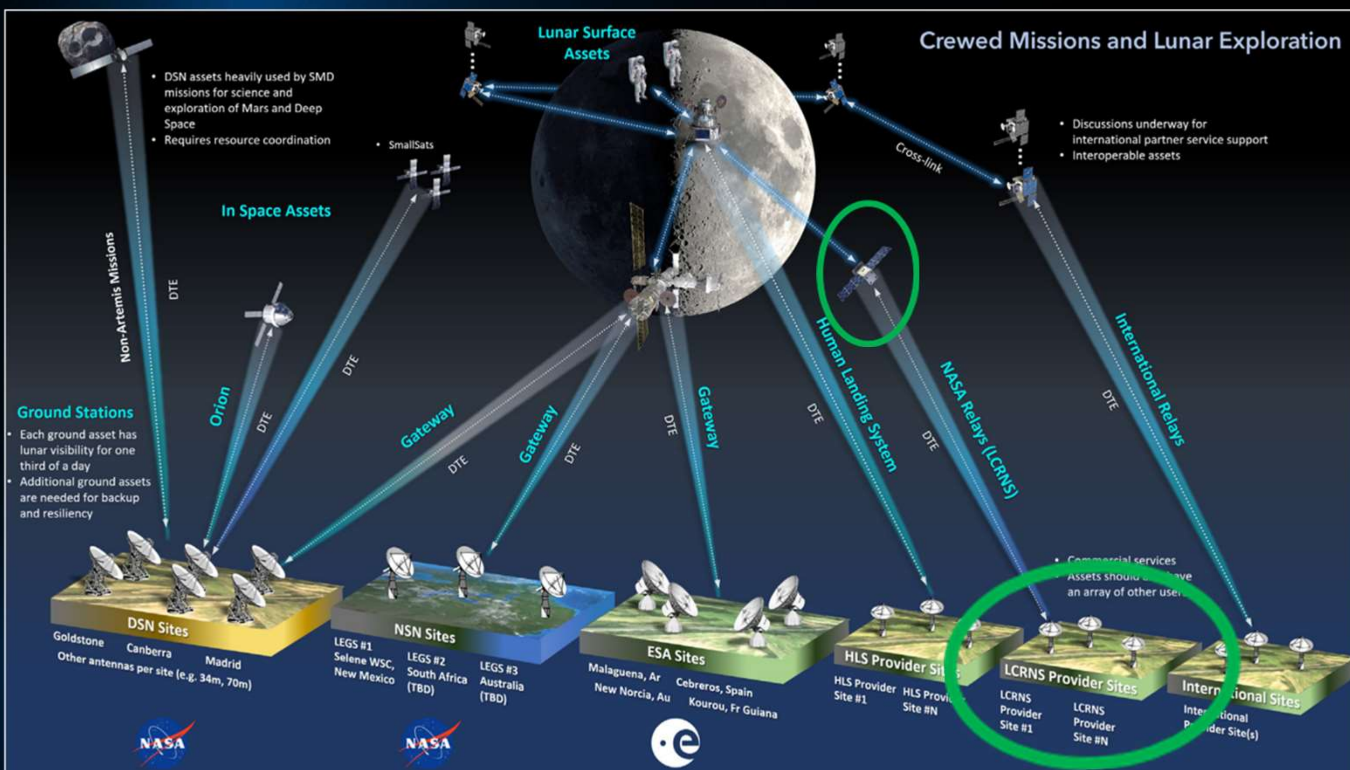
Space Resources Round Table
2-5 June, 2025

IM Lunar Data Network



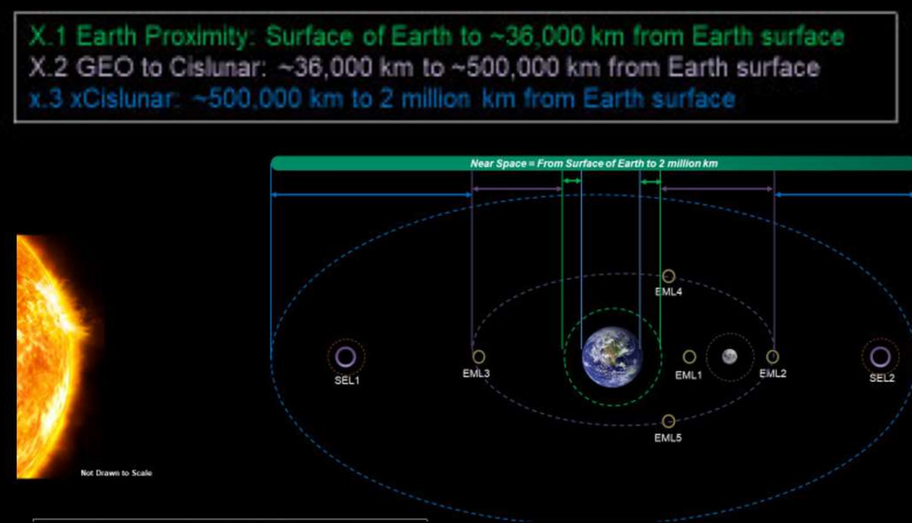
- IM's commercial Lunar Data Network (LDN) is part of NASA's *Lunar Communications Relay and Navigation Systems* (LCRNS) capability
- The LDN includes:
  - Lunar comm/nav satellites
  - Ground network infrastructure to enable satellite operations and mission/network traffic
  - Mission operations to "fly" the constellation
  - Network operations providing customer service delivery and engagement

IM Lunar Ground Network

Note: Additional Ground Station Network capabilities in work

IM Lunar Ground Network

PNT Service	Performance Levels
Ranging	Systematic error ≤ 4.5 m Random Error ≤ 5 m 1σ at 1 s integration interval Time Tagging ≤ 1 µs (UTC)
Doppler	S-band 1-way ≤ 3 mm/s 1σ at 1 s S-band 2-way ≤ 1.5 mm/s 1σ at 1 s X-band 1-way ≤ 0.7 mm/s 1σ at 1 s X-band 2-way ≤ 0.35 mm/s 1σ at 1 s Ka-band 1-way ≤ 0.2 mm/s 1σ at 1 s Ka-band 2-way ≤ 0.1 mm/s 1σ at 1 s Time Tagging ≤ 25 ns (UTC)



IM Lunar Relay Constellation

LDN Performance Capabilities for the NASA Lunar Relay SRD and LNIS

INCREMENT A PERFORMANCE – Increment A capability by Q4 2026

Service	IM Capability
Ka-band	2 – Forward + Return
S-band	2 – Forward + Return (HGA) 1 – Forward + Return (MGA)
AFS	1 (>90% coverage)
Service Volume	South pole up to -80 deg; 125 km
Coverage of an Earth Day	>90%
Service Availability	**Nominal >90%**

INCREMENT B PERFORMANCE – Increment B capability by Q4 2027

Service	IM Capability
Ka-band	6 – Forward + Return
S-band	6 – Forward + Return (HGA) 3 – Forward + Return (MGA)
AFS	2 (>90% coverage) 3 (>80% coverage)
Service Volume	South pole up to -80 deg; 125 km altitude
Coverage of an Earth Day	Ka-band – 100% S-band – 100% AFS (2) – >98%; AFS (3) – >45%
Service Availability	**Nominal >90%; Critical >90%**

INCREMENT C (FULL IOC) PERFORMANCE – Full IOC by Q4 2028

Service	IM Capability
Ka-band	10 – Forward + Return
S-band	10 – Forward + Return (HGA) 5 – Forward + Return (MGA)
AFS/LANS	4-5 (25-45% - GDOP<6)
Service Volume	South pole up to -75 deg; 200 km altitude
Coverage of an Earth Day	Ka-band – 100% S-band – 100% AFS (w/LANS) – >50%
Service Availability	**Nominal 95%; Critical 98%**

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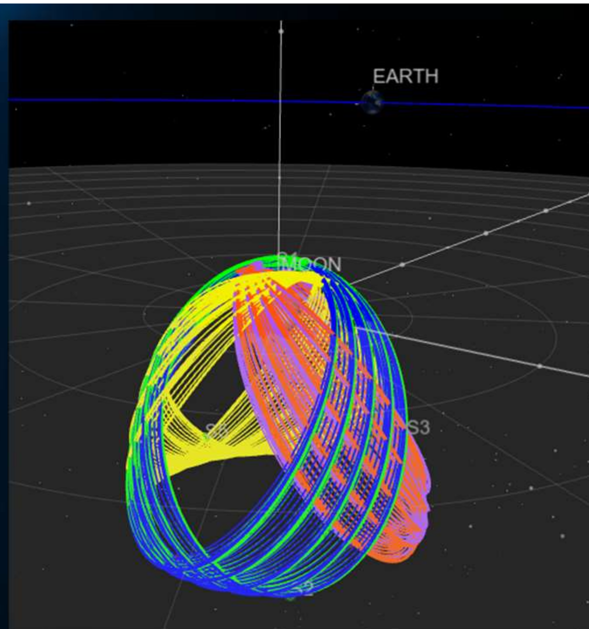
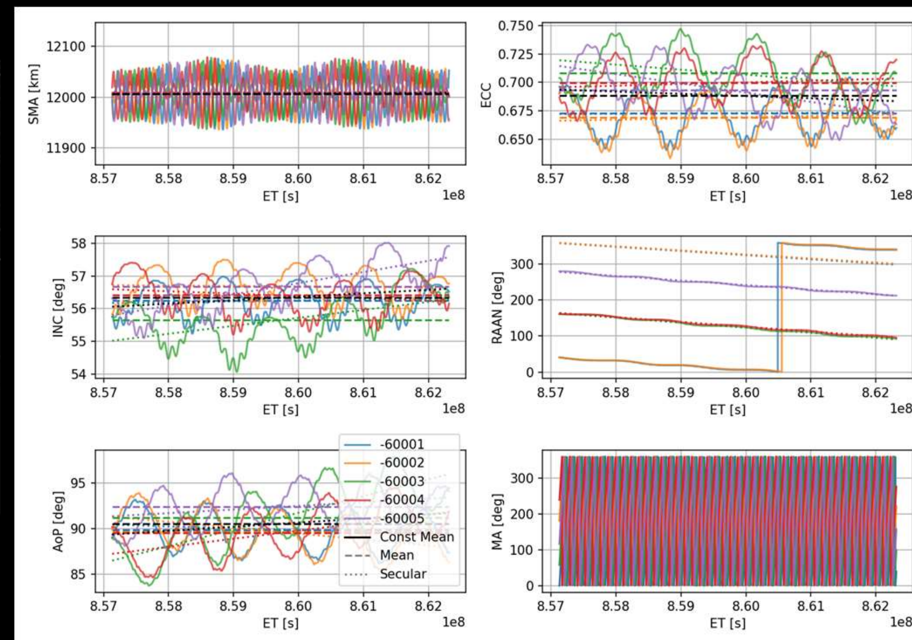
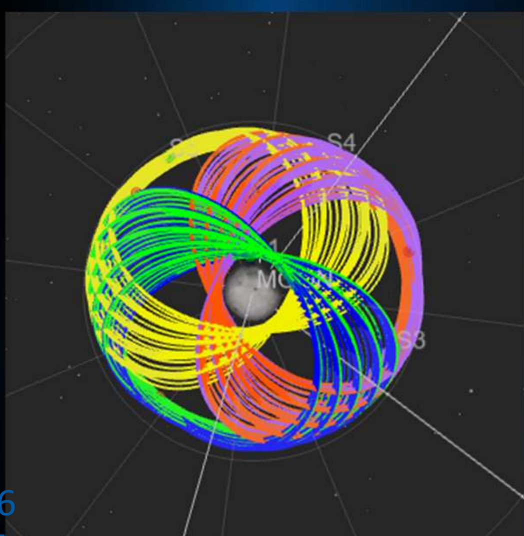
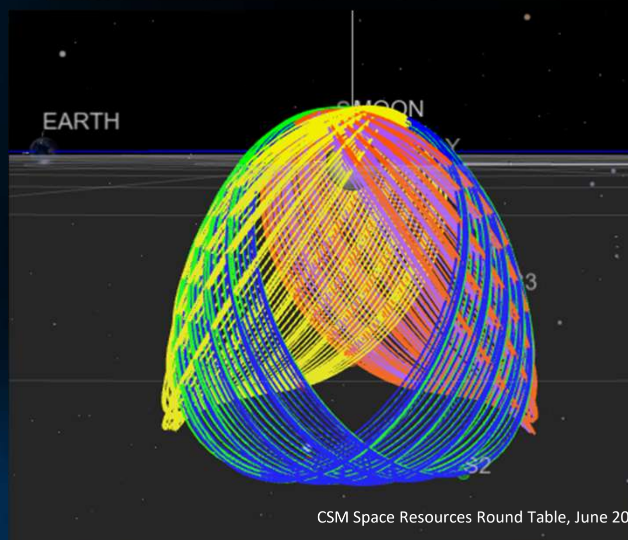
DRC 3.1.0

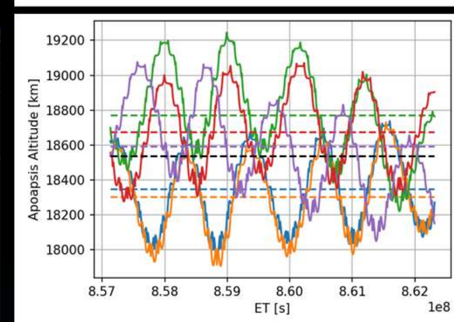
- 3 planes
- SMA 12005 km – Period 32.8 h
- Inclination 56.25
- Eccentricity 0.6968
- Min perilune 1400 km
- Max apolune 19200 km

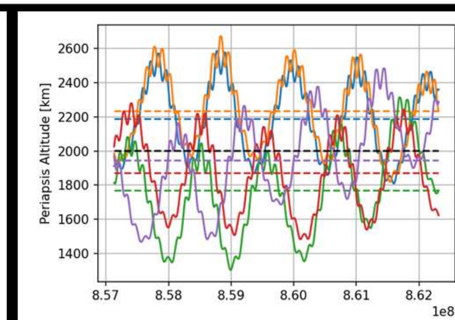












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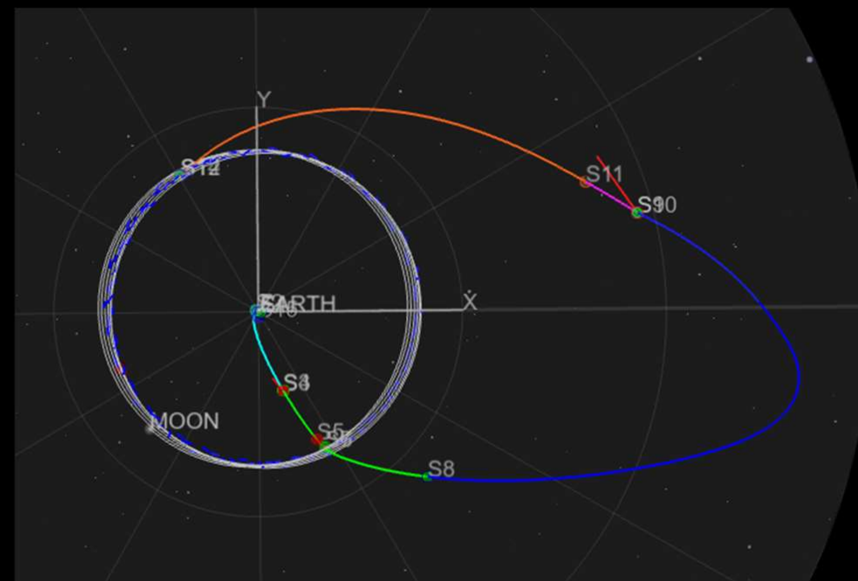
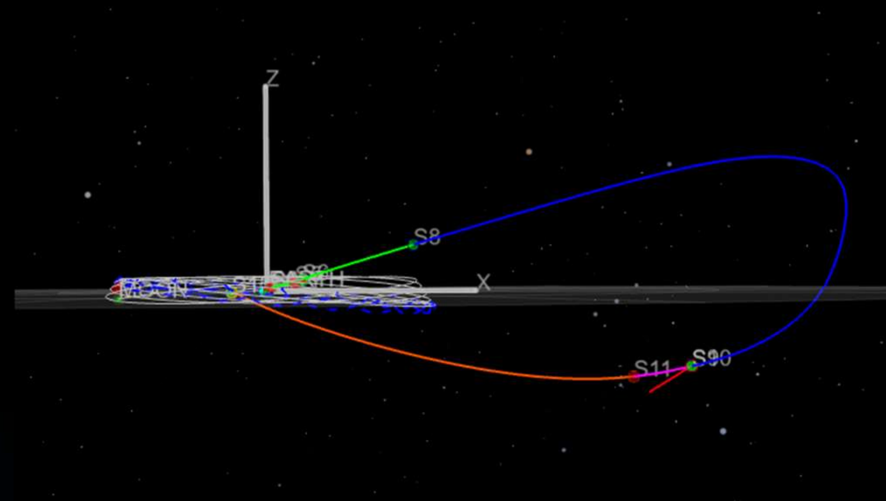
LDN-1 Trajectory

Event	Time	dV	Notes
Launch	L+0		
Course Maneuver	L+1 day	16.65 m/s	
TCM-1	Flyby-1 day (L+4.6)	Statistical	
Lunar flyby	L+5.6 days		Perilune alt 950 km
Apogee	L+45 days		Apogee at 1.3Mkm
DSM-1	LOI-26 days (L+83)	79.45 m/s	
TCM-2	LOI-5 days (L+104)	Statistical	
LOI	L+109 days	157.97 m/s	
Total	**110 days**	**254.08 m/s**	





LDN Constellation Evolution

Each incremental deployment operationally ready to provide services approximately 3 months after launch.

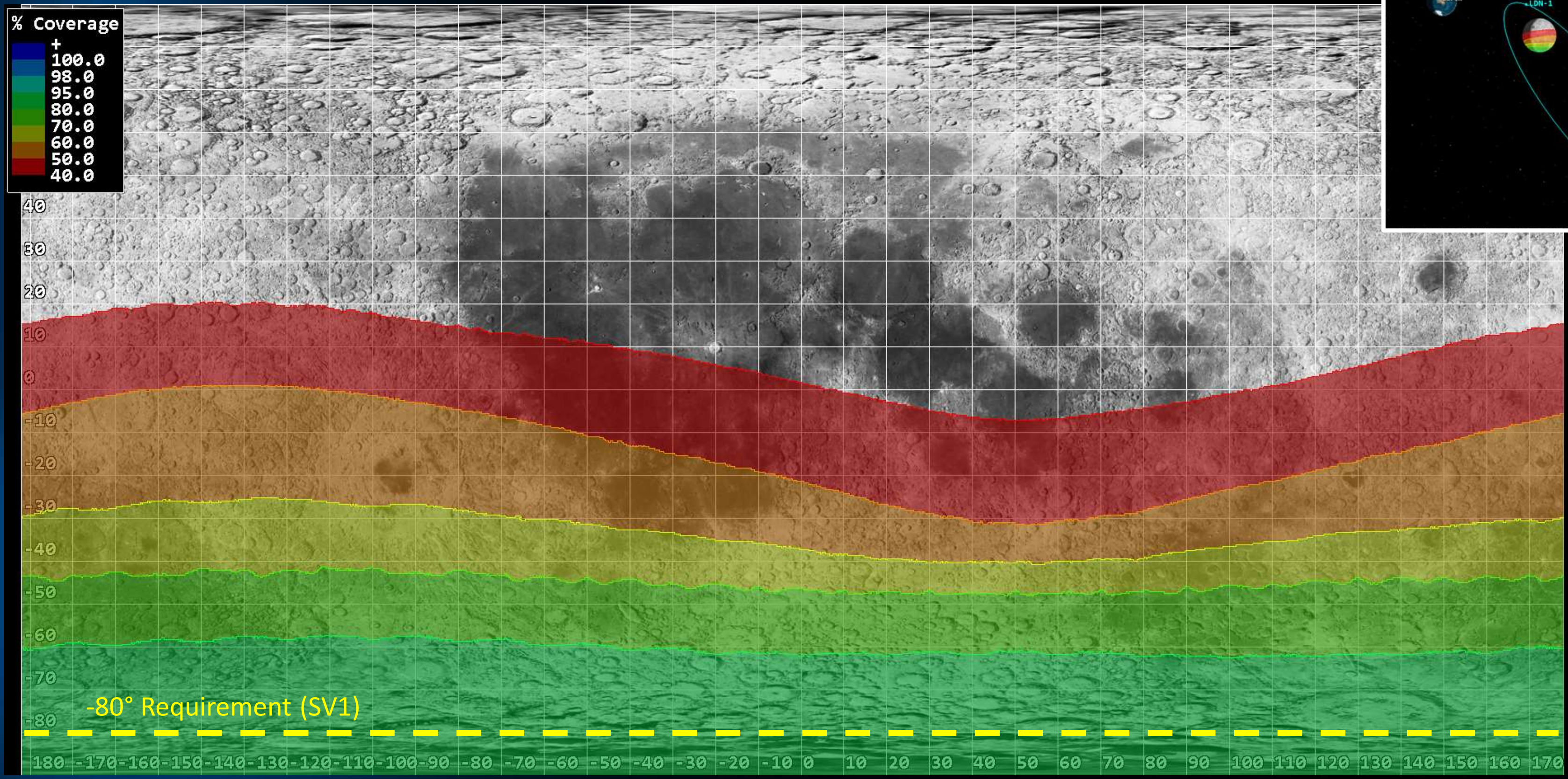
Increment	Operational Date	Satellites & Deployment Approach	S-Band Services	Ka-Band Services	X-Band Services	AFS Services
Alpha	Q4 2026	 LDN-1 (Launch on IM-3, 2026) (On Mission, Q4 2026)	2x HGA, Tracking 1x MGA, Fixed Nadir	2x HGA, Tracking	1x MGA, Fixed Nadir	1
Bravo	Q4 2027	 LDN-1 (on mission) LDN-2 LDN-3 (Launch on IM-4, Q4 2027)	6x HGA, Tracking 3x MGA, Fixed Nadir	4x HGA, Tracking	3x MGA, Fixed Nadir	3
Charlie	Q4 2028	 LDN-1 LDN-2 LDN-3 (on mission) LDN-4 LDN-5 (Launch on IM-5, Q4 2028)	10x HGA, Tracking 5x MGA, Fixed Nadir	10x HGA, Tracking	5x MGA, Fixed Nadir	5

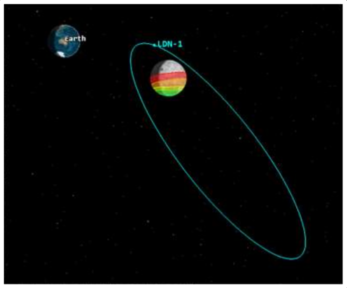
Service Coverage, Increment A

1x S-F/R (70%), 1x Ka-R (70%), 1x AFS-F (70%)

Coverage of Earth Day, SV1

LCRNS.3.0095 (SRD Table 3-3)
One Satellite (LDN-1)
One Month Analysis Period





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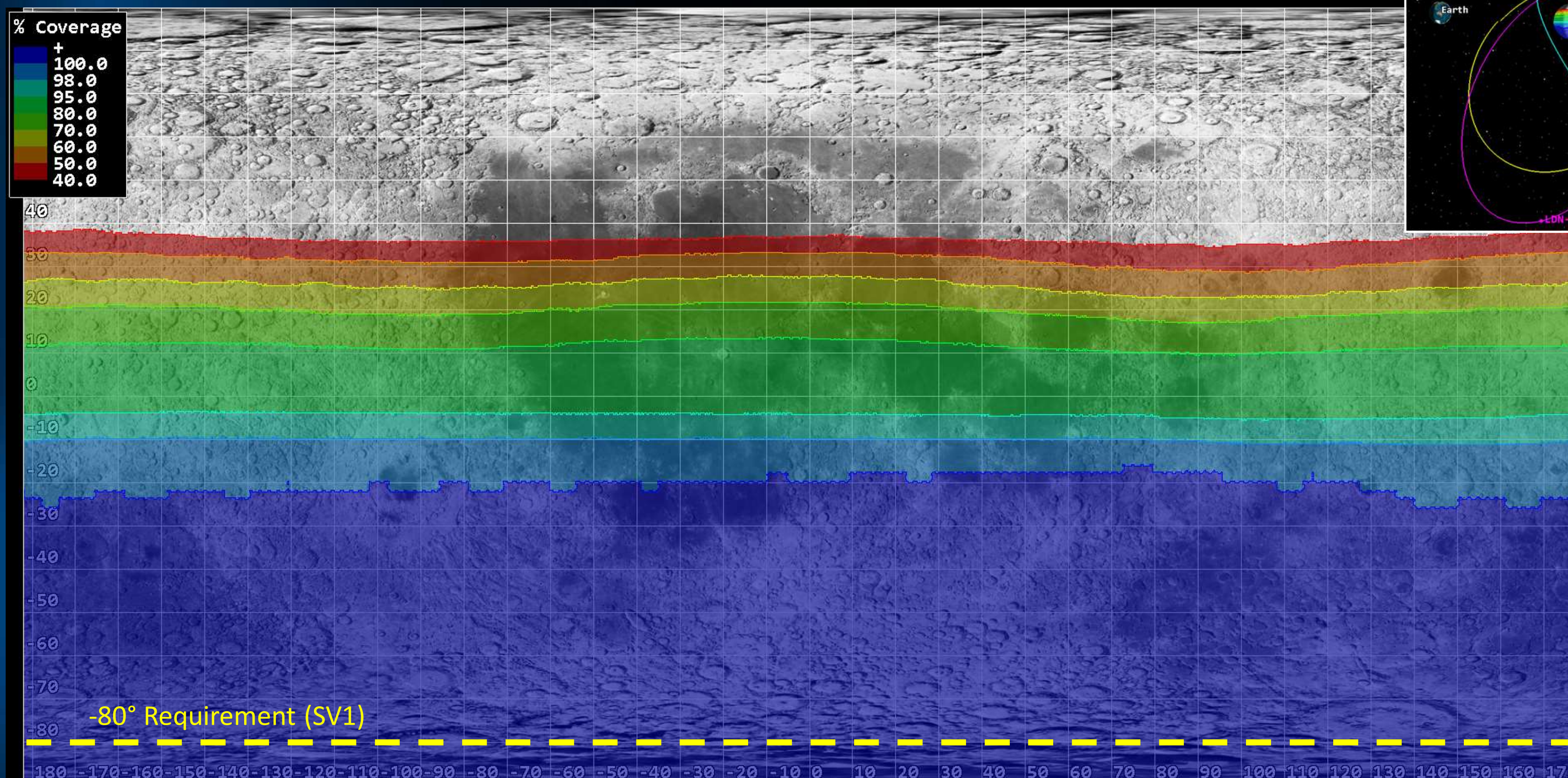
INTUITIVE MACHINES

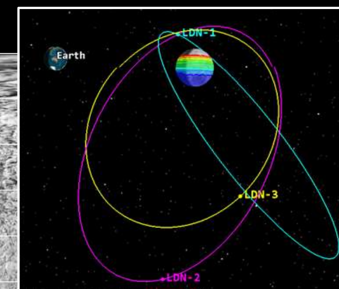
Service Coverage, Increment B – Proximity Links

1x S-F/R (90%), 1x Ka-F/R (75%)

Coverage of Earth Day, SV1

LCRNS.3.0095 (SRD Table 3-3)
Three Satellites (LDN-1,2,3)
One Month Analysis Period



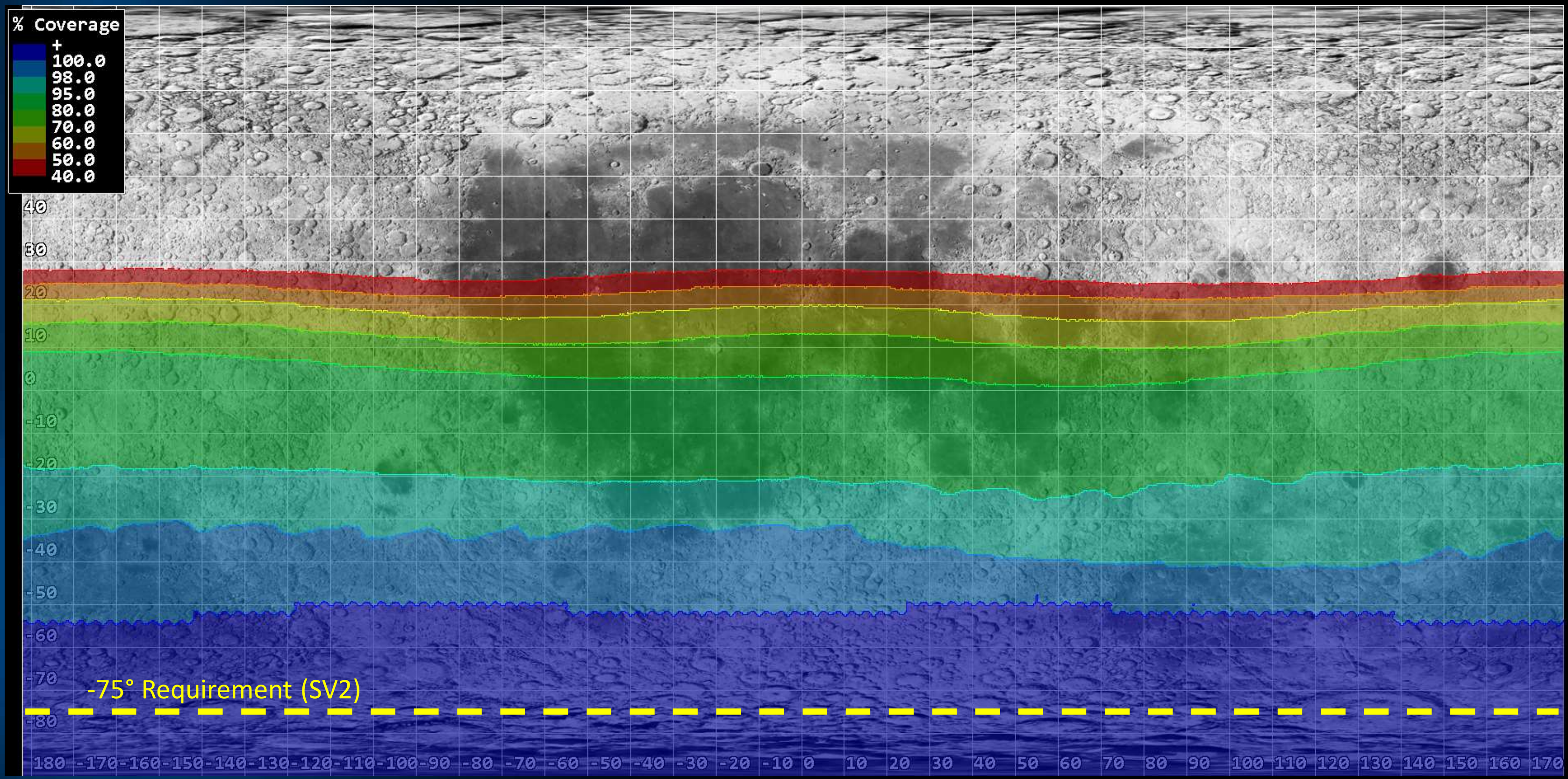


Service Coverage, Increment C – Proximity Links

2x S-F/R (90%), 2x Ka-F/R (75%)

Coverage of Earth Day, SV2

LCRNS.3.0095 (SRD Table 3-3)
Three Satellites (LDN-1,2,3,4,5)
One Month Analysis Period



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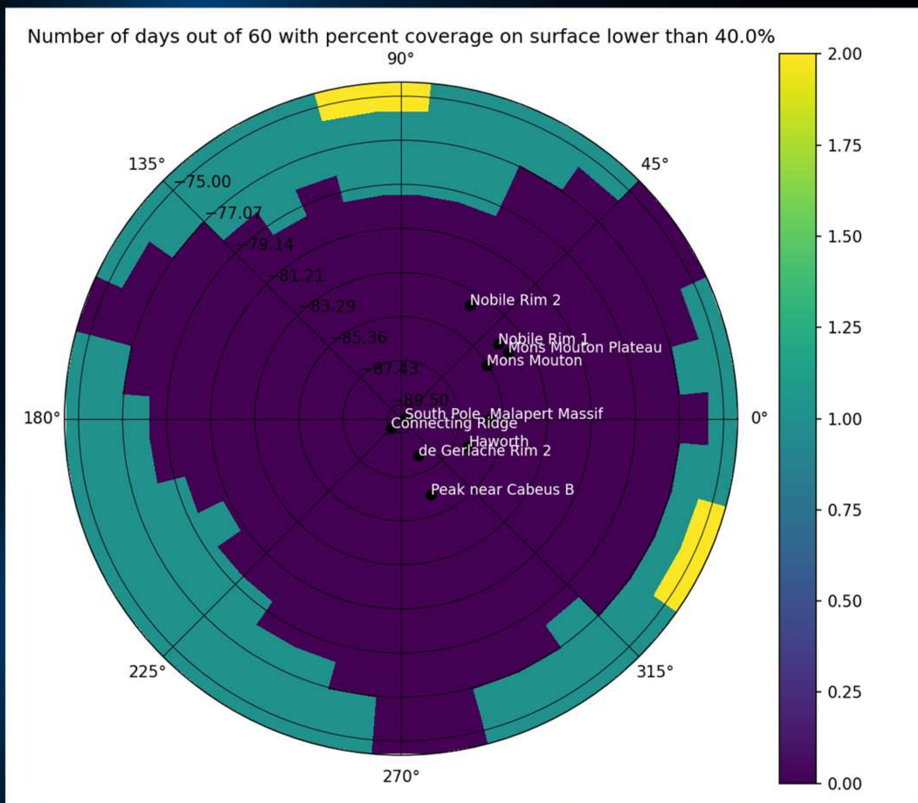
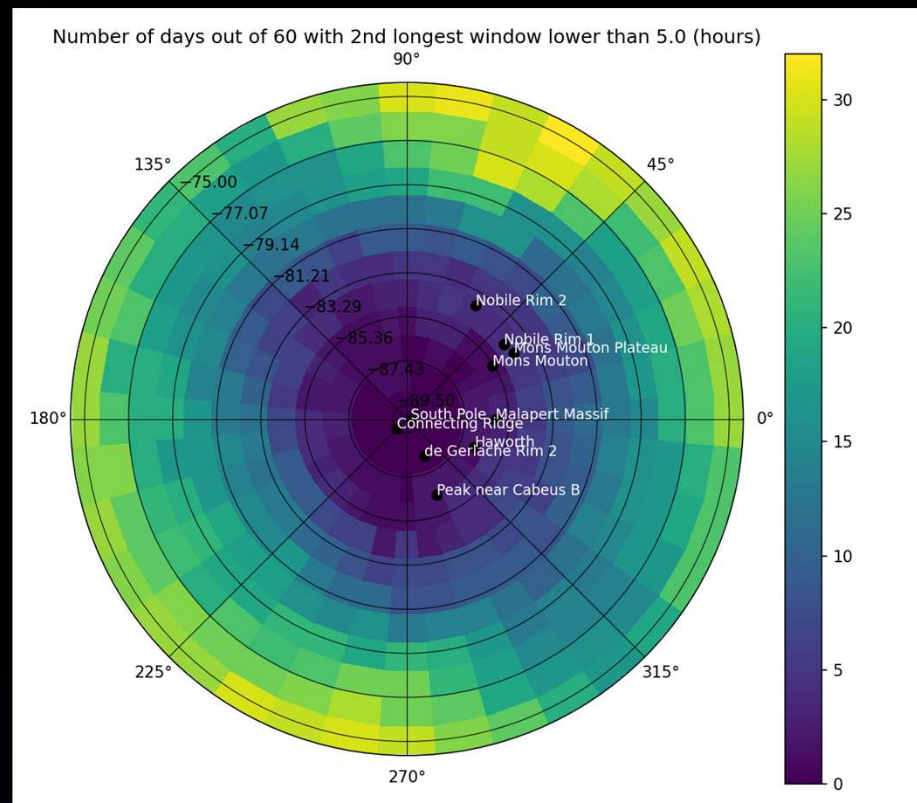
DRC 3.1.0 – AFS/LANS Coverage

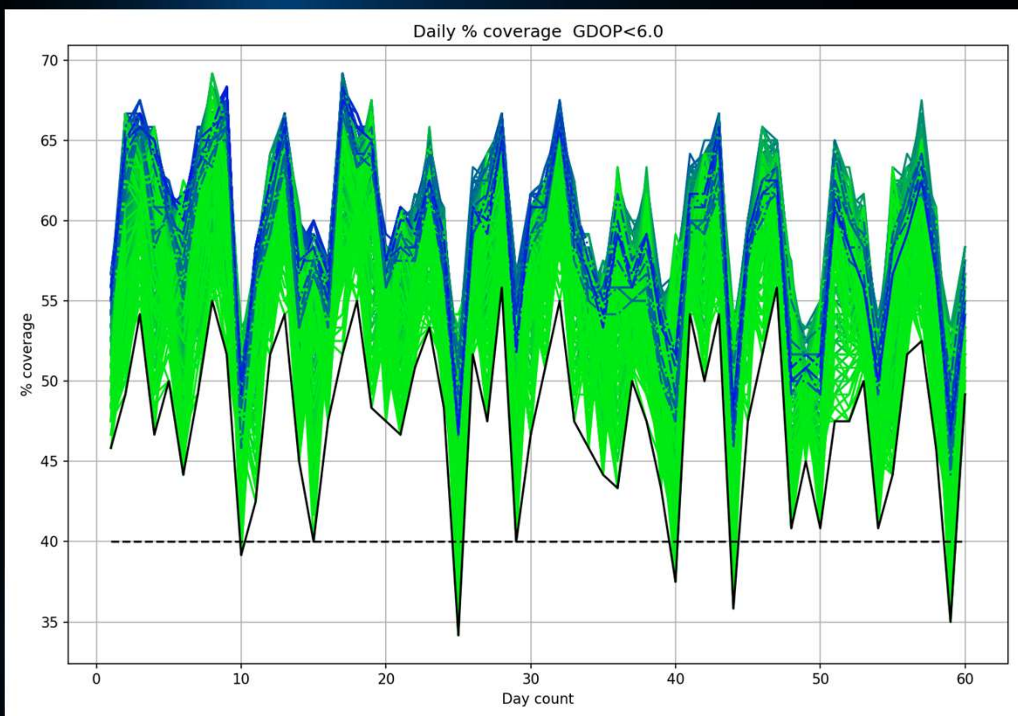
- Total Coverage % < Target (days x surface points) – 0.36%
- Daily Continuous Windows % < Target (days x surface points) – 19.3%

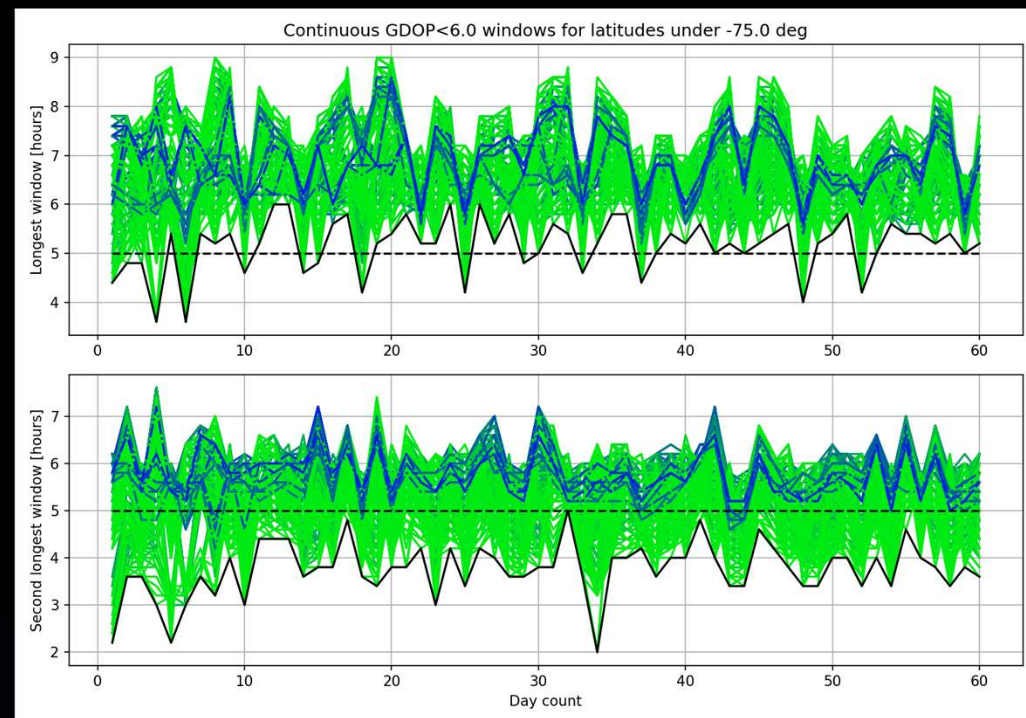




DRC 3.1.0 – EVA Window Coverage

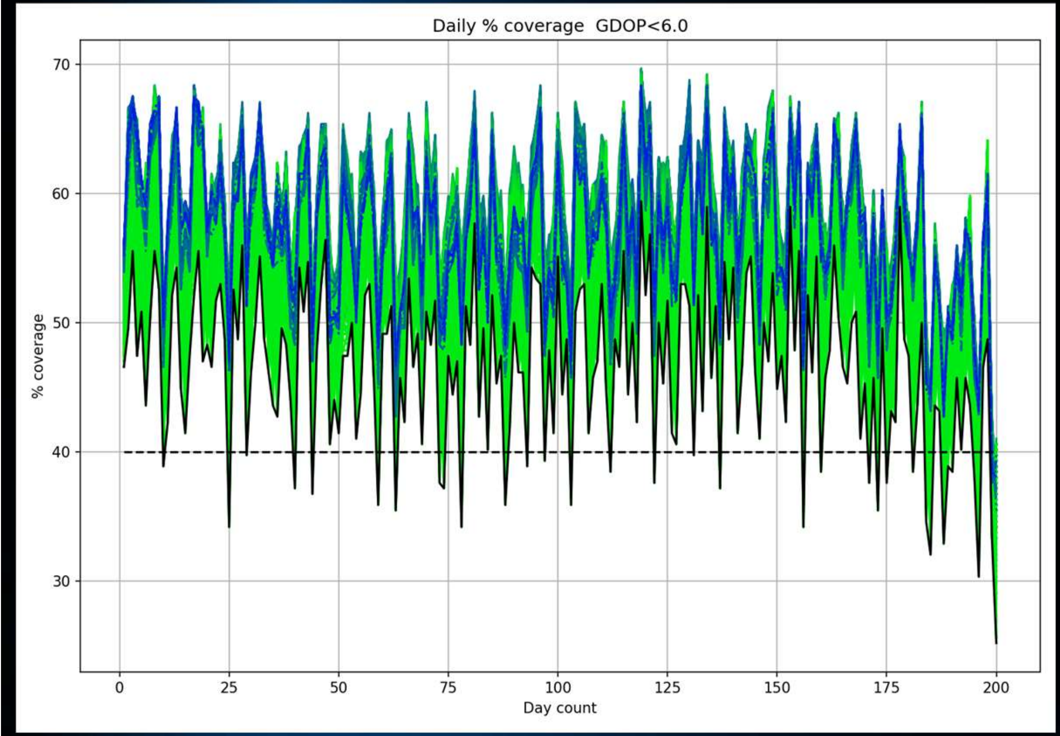
- Total Coverage % < Target (days x surface points) – 0.36%
- Daily Continuous Windows % < Target (days x surface points) – 19.3%

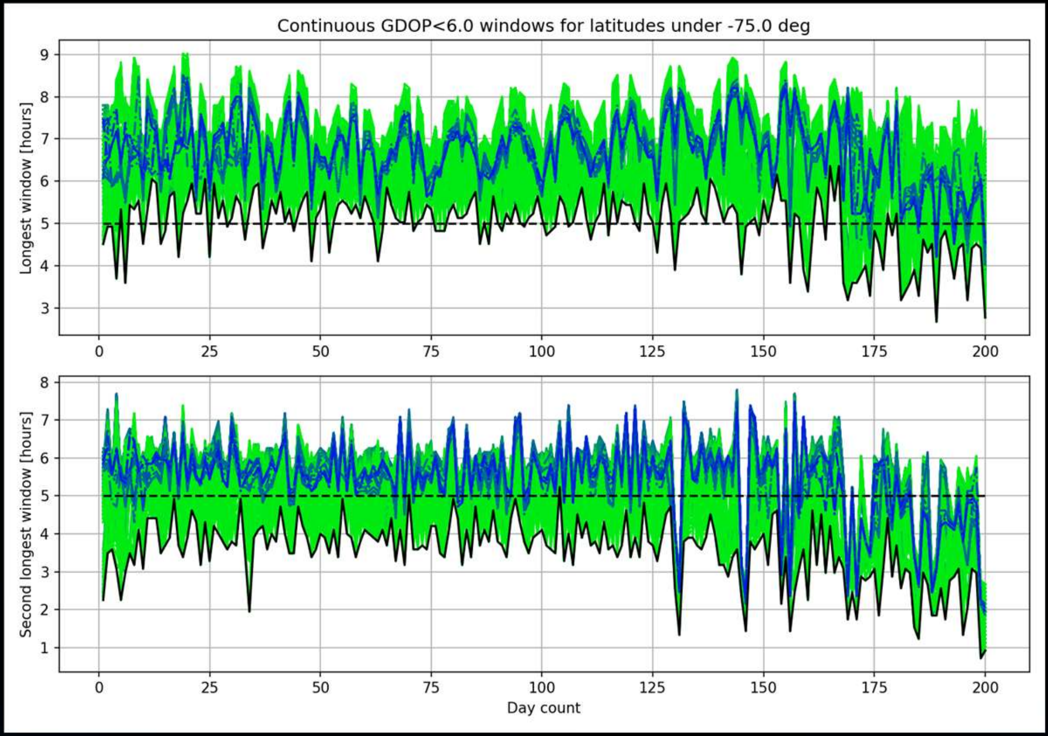




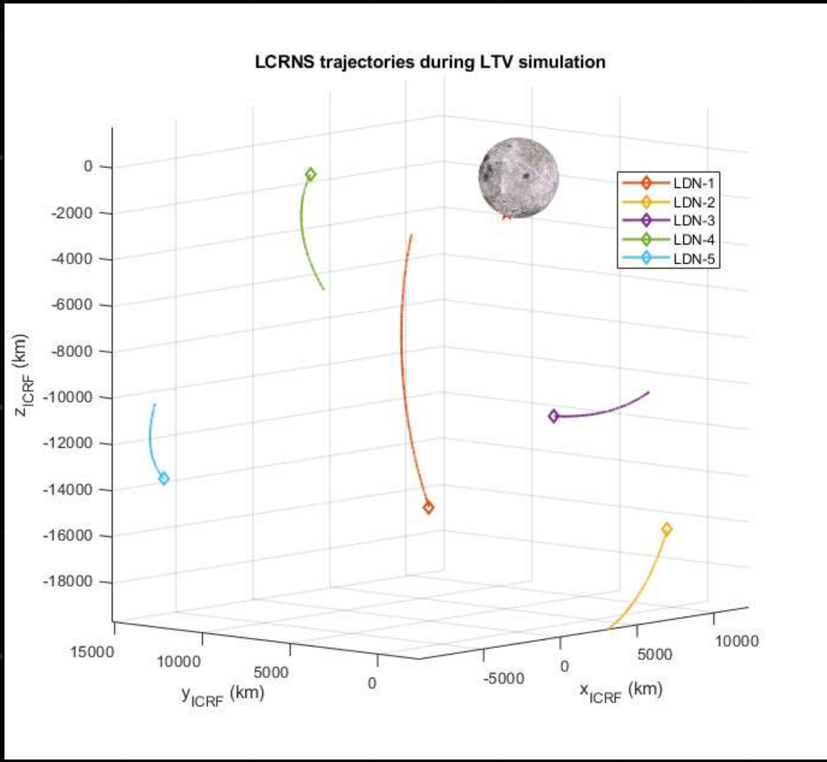
DRC 3.1.0 – Long Term Stability

- Long term drift effects (without station-keeping) can be seen starting at day 125
- Total Coverage % < Target (days x surface points) for 200 days – 1.32%
- Daily Continuous Windows % < Target (days x surface points) for 200 days – 39.9%





LCRNS PERFORMANCE SIMULATION



- Operates similarly to terrestrial GNSS
  - Time-of-flight based code division multiple access signals
- Adheres to NASA Lunar Relay Service Provider requirements [2]

Error	Value
SISE Position	13.43 m (3-sigma)
SISE Velocity	1.2 mm/s (3-sigma) @ 10 sec

Measurement uncertainty requirements from NASA[2]

$$\mathrm{UERE}^2 = \mathrm{SISE}_{pos}^2 + \mathrm{UEE}_{pos}^2$$
$$\mathrm{UERRE}^2 = \mathrm{SISE}_{vel}^2 + \mathrm{UEE}_{vel}^2$$

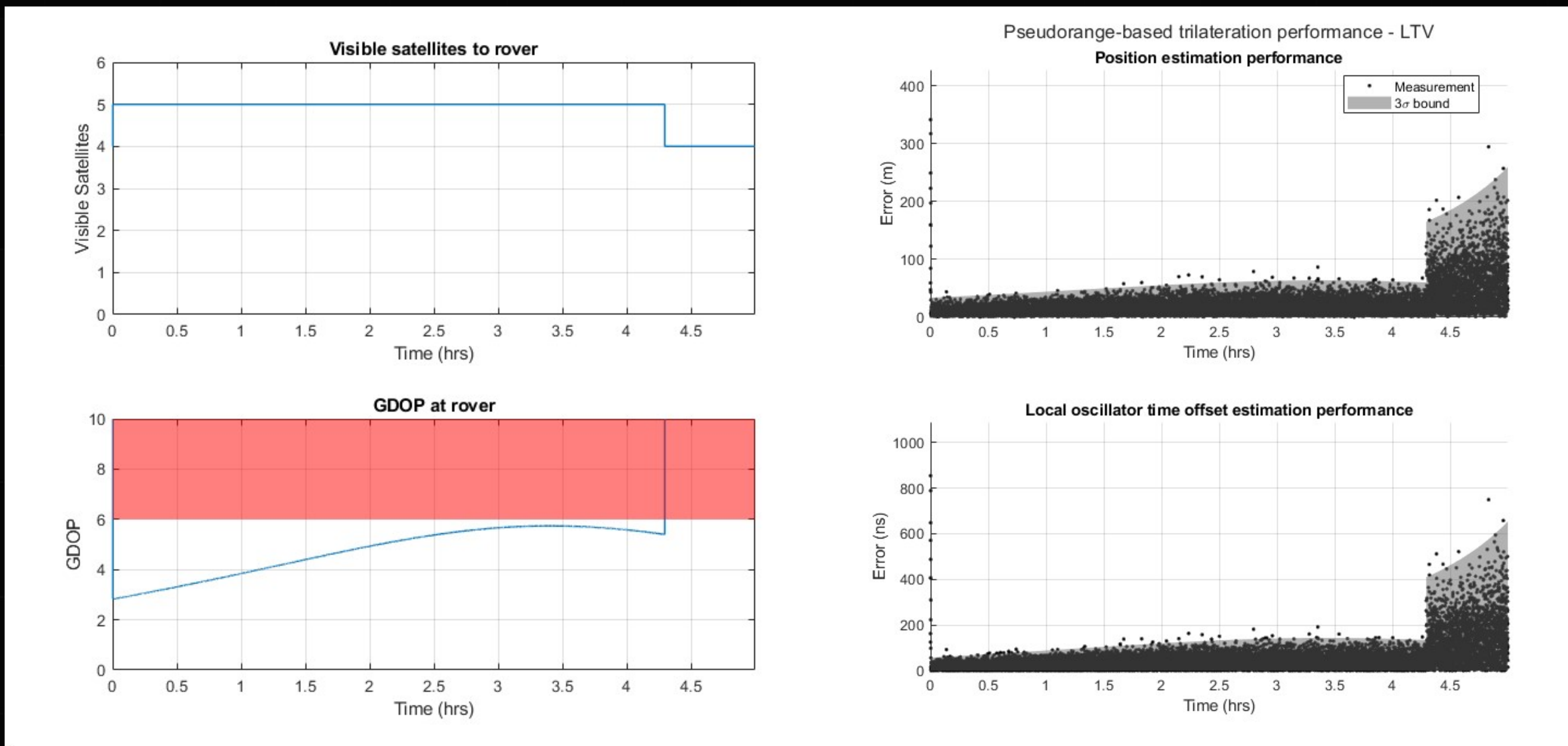
LUNAR USER TERMINAL (LUT) RECEIVER

INTUITIVE MACHINES

- 2nd order PLL-assisted DLL
- 100 MHz front-end bandwidth
- Assuming tracking the pilot (Q) channel, $f = \mathbf{2492.028}$ MHz, 5.115 Mcps
- DLL noise bandwidth of 0.1 Hz (carrier-aided), PLL noise bandwidth of 20 Hz
- DLL E/L spacing 0.5 chips
- DLL predetection integration time (PIT) 1s, PLL PIT of 10ms
- Thermal, phase, and dynamic stress errors modeled using equations from Kaplan and Hegarty (2017)

ROVER TRIANGULATION PERFORMANCE

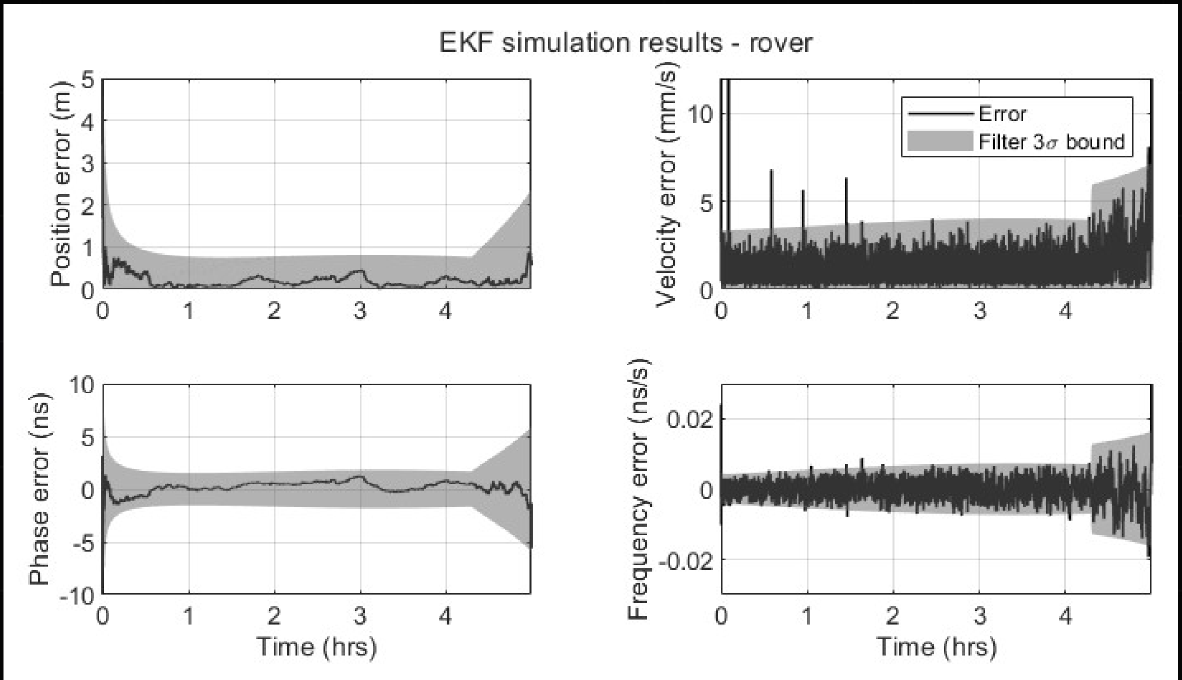
INTUITIVE MACHINES



Simulations are from 2027 MAR 1 02:00:00 UTC to 2027 MAR 1 07:00:00 UTC

ROVER EKF PNT PERFORMANCE

Moon Racer Lunar Terrain Vehicle



Accelerometer measurements, with LCRNS measurements at 1 Hz

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Data Service Volumes

IM's LDN significantly exceeds NASA's requirements for NSNS forward and return data volumes.
Ref: LCRNS.3.0390 (Table 3-7)

- Each Satellite
  - 2x HGAs/satellite, each HGA providing 1 S and 1 Ka-band bidirectional service (S and Ka simultaneous in each HGA) – Supports 2x S-Band users –or- 2x Ka-band users – or- 2x S/Ka dual band users
  - 1x S-Band fixed MGA service independent of HGAs – supports an additional 3rd S-band user
  - 1x X-Band fixed MGA service independent of all NSNS-required services (IM commercial service offering)
  - 150 Mbps "mission downlink" between LDN satellite and each ground station via Space-Ground link
  - 60 Mbps "mission uplink" between LDN satellite and ground stations
  - 12.9 Tbits / day (1.6 Tbytes / day) per satellite
- Total Network
  - Increment A – 12.9 Tbits/day (single satellite)
  - Increment B – 38.7 Tbits/day (three satellites)
  - Increment C – 64.5 Tbits/day (five satellites)

Note: Each satellite is out of view of earth approximately 1 hour per day due to lunar far side transit. Data volume estimates are to the "Service Volume". Specific mission user location on the lunar surface or in lunar orbit will affect actual contact periods.

LDN / NSNS Daily Volumes (in Tb/day)

	IOC-A	IOC-B	IOC-C
NSNS Return Service Volume Requirement	3.1	3.3	6.5
LDN Return Service Capability	12.9	38.7	64.5
NSNS Forward Service Volume Requirement	0.002	0.7	1.4
LDN Forward Service Capability	4.9	14.7	24.5

LunaNet References

- Dafesh, Philip A.,, Crenshaw, Juan, Gramling, Cheryl, et al, "**The Design of a Flexible, Interoperable Navigation Signal for Future Lunar Missions**," Proceedings of the 2025 International Technical Meeting of The Institute of Navigation, Long Beach, California, January 2025, pp. 712-731. https://doi.org/10.33012/2025.19961
- Dafesh, Philip A., Khadge, Gourav K., Wong, Nathan S., Djuknic, Goran, "**Flexible Data and Frame Synchronization Structure for the LunaNet PNT Signal**," Proceedings of the ION 2024 Pacific PNT Meeting, Honolulu, Hawaii, April 2024, pp. 844-866. https://doi.org/10.33012/2024.19661 - LINK
- Dafesh, Philip A.,, Crenshaw, Juan, Gramling, Cheryl, et al, "**The Augmented Forward Signal (AFS).** Defining the Navigation Signal Standard for Future Lunar Missions," InsideGNSS+ November/December 2024, December 2024, pp. 28-42. https://lsc-pagepro.mydigitalpublication.com/publication/?i=836148
- **LunaNet. LunaNet Interoperability Specification**. NASA Baseline Document, Version 5, LNIS V005, January 2025. – LINK
- LunaNet. LunaNet Signal-In-Space Recommended Standard: **Augmented Forward Signal Volume A**. NASA Recommended Standard, Version 1, LNSIS-AF V001, January 2025. - LINK

THANK YOU

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Data Services Delivery Concept Service (API)

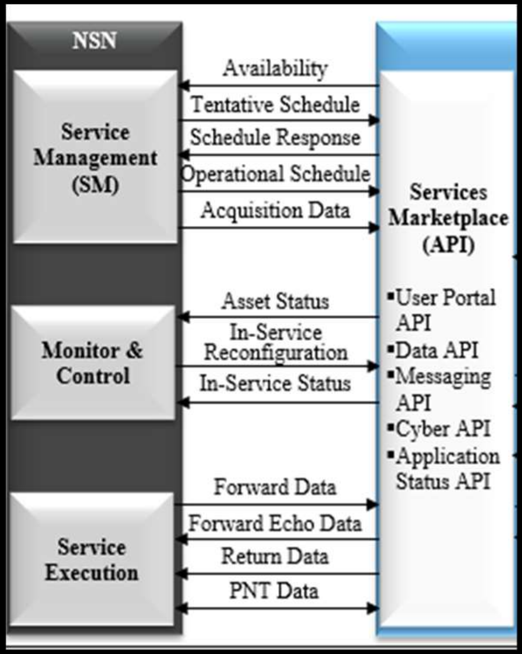
IM LDN Services provide human-operable and automated interface for management, monitoring, and data delivery

- IM's User Services API provides the coordination, scheduling, management, and data delivery capabilities of the LDN to NSNS and commercial users.

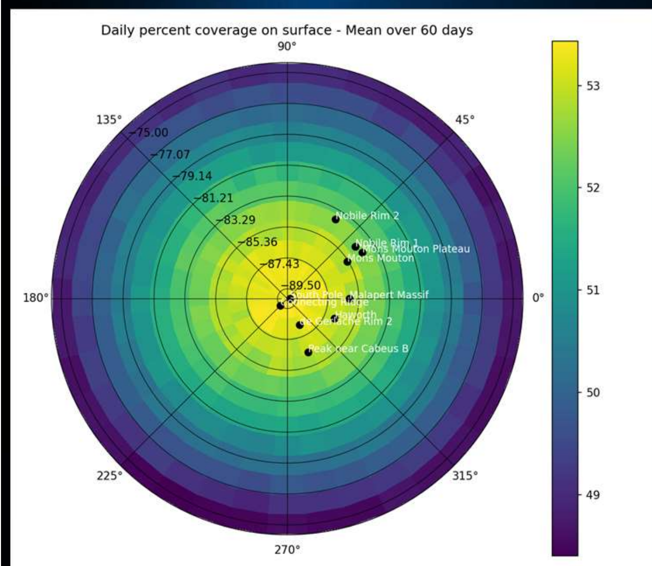
- Web Portal
  - Service Management – Service Availability, Scheduling Functions, Service Acquisition Data. Monitor and Control – Scheduled Asset Status, Service Reconfiguration, Service Status
  - Accessible via Web interface (human operable) or automated web services interface (API) for integration with user ground systems.

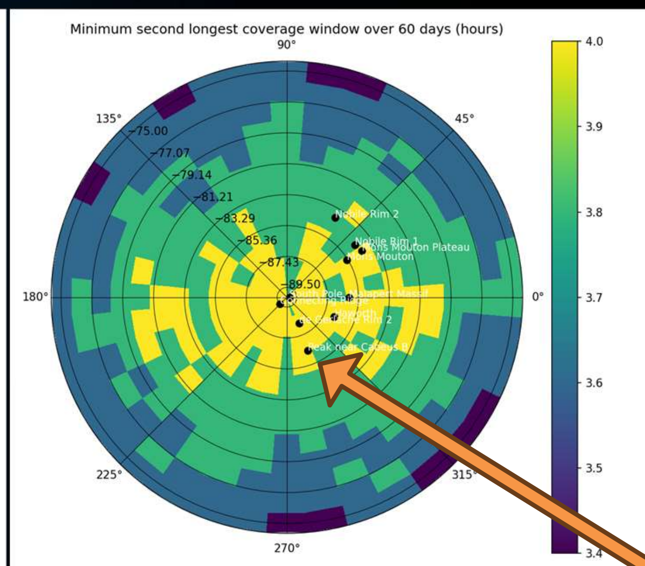
- Data Service Delivery Interface
  - Forward and Return Data Interface – streaming data via IP/IPSEC with SLE option. IPSEC and SLE tunnels bind to IM's Nova Core system in AWS GovCloud.
  - Radiometric and PNT product delivery – streaming data via IP/IPSEC or post-event tracking file delivery

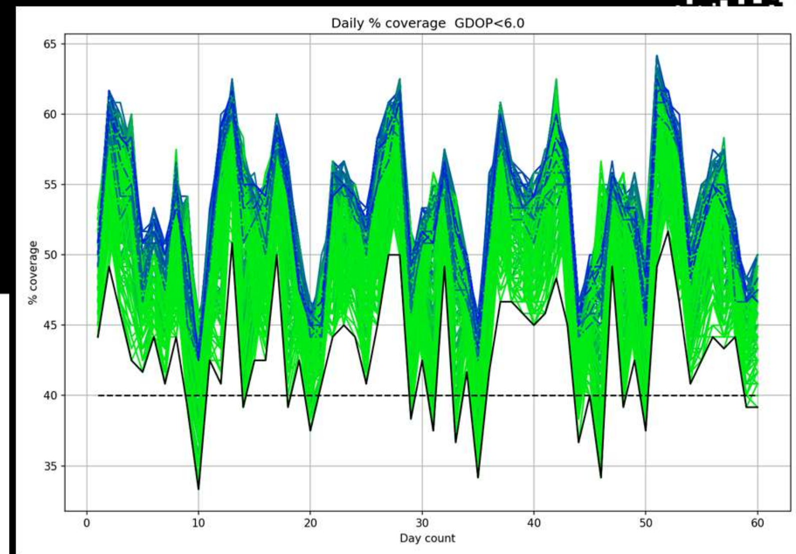
Specific implementation of service delivery interfaces are in work. IM working with the NASA to develop appropriate specifications, service designs, and ICDs.

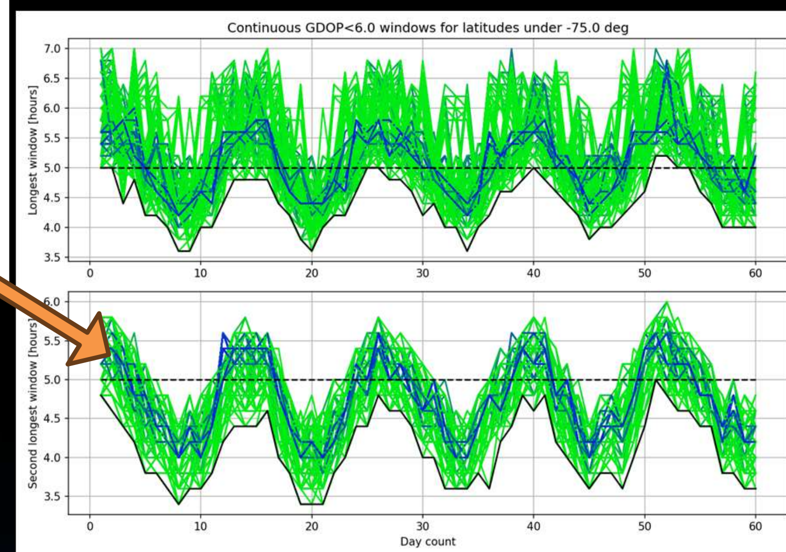


How to read performance plots









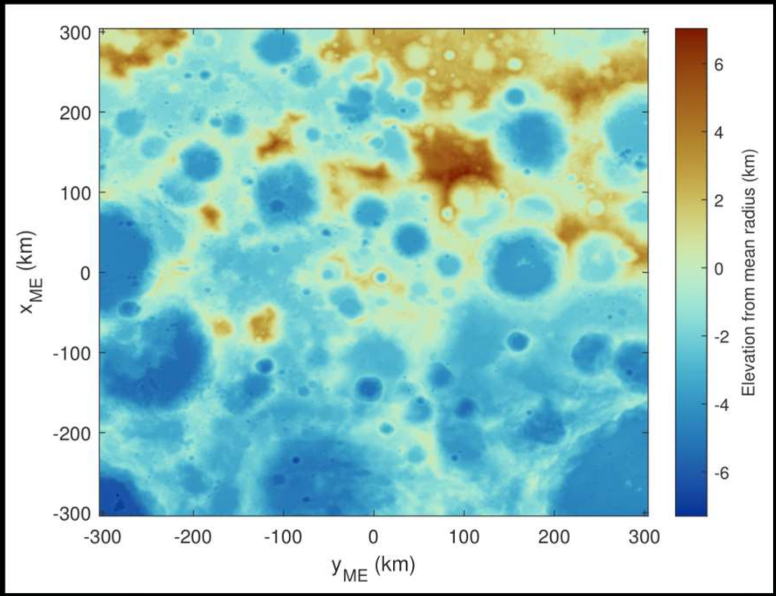
Dynamical Models – Surface

- Rovers and astronauts move between waypoints with simulated obstacle avoidance
  - Trajectories are piecewise splines for easy derivatives

$$\boldsymbol{r}(t) = \begin{bmatrix} \alpha_{3,i}t^3 + \alpha_{2,i}t^2 + \alpha_{1,i}t + \alpha_{0,i} \\ \beta_{3,i}t^3 + \beta_{2,i}t^2 + \beta_{1,i}t + \beta_{0,i} \\ \gamma_{3,i}t^3 + \gamma_{2,i}t^2 + \gamma_{1,i}t + \gamma_{0,i} \end{bmatrix}, t \in [t_i, t_{i+1}]$$

$$\dot{\boldsymbol{r}}(t) = \frac{d}{dt}\boldsymbol{r}(t) = \begin{bmatrix} 3\alpha_{3,i}t^2 + 2\alpha_{2,i}t + \alpha_{1,i} \\ 3\beta_{3,i}t^2 + 2\beta_{2,i}t + \beta_{1,i} \\ 3\gamma_{3,i}t^2 + 2\gamma_{2,i}t + \gamma_{1,i} \end{bmatrix}$$

$$\ddot{\boldsymbol{r}}(t) = \frac{d^2}{dt^2}\boldsymbol{r}(t)$$

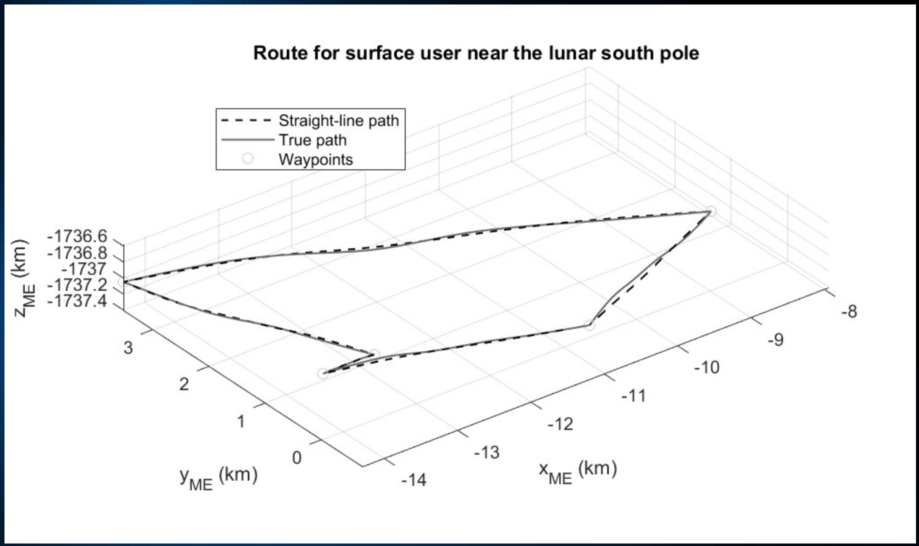


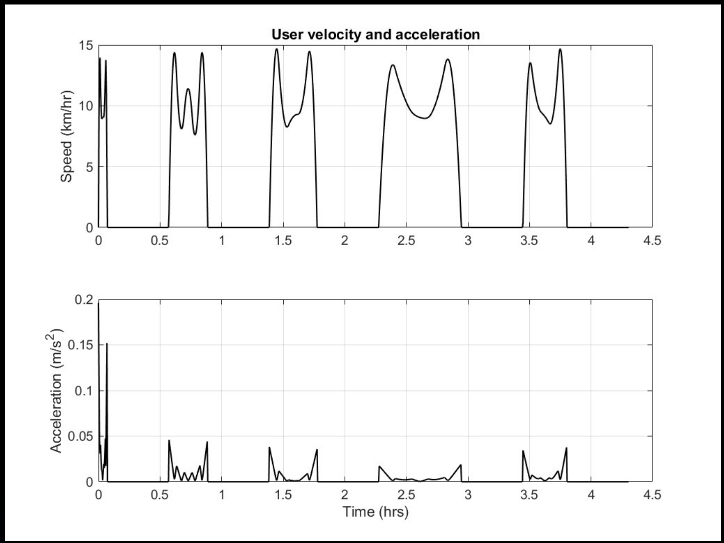
Dynamical Models – Surface

- Dynamics for filters are simply integration of acceleration

$$\boldsymbol{x}_{surf} = [\boldsymbol{r} \quad \dot{\boldsymbol{r}}]^T$$

$$\dot{\boldsymbol{x}}_{surf} = \begin{bmatrix} 0 & I_3 \\ 0 & 0 \end{bmatrix} \boldsymbol{x}_{surf} + \begin{bmatrix} 0 \\ I_3 \end{bmatrix} \ddot{\boldsymbol{r}} + \begin{bmatrix} 0 \\ \boldsymbol{\varepsilon}_{accel} \end{bmatrix}$$



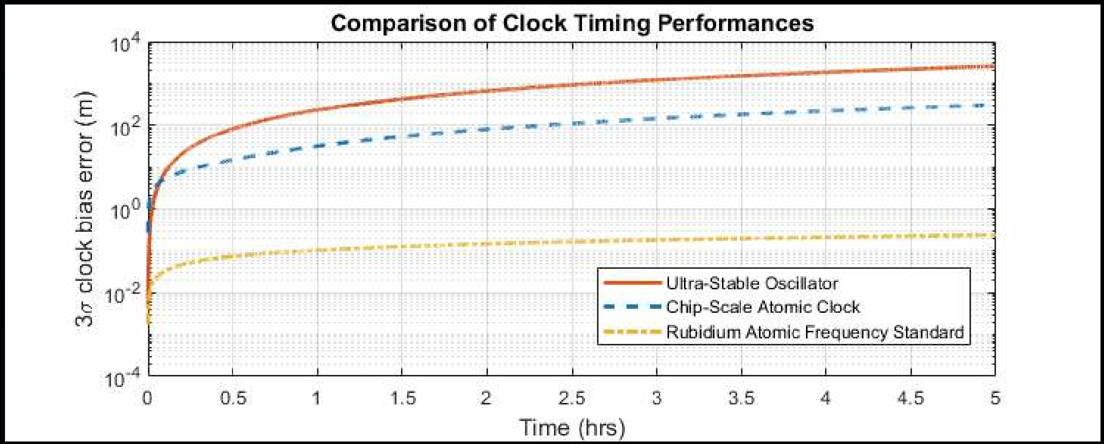


Dynamical Models – Clock

- Zucca and Tavella [6] describe oscillators using a random walk- and run-type process
  - b is phase offset
  - $\dot{b}$ is frequency offset
  - a is frequency drift / aging rate

$$\dot{\boldsymbol{x}}_{clk} = \begin{bmatrix} \dot{b} \\ a \\ \dot{a} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} b \\ \dot{b} \\ a \end{bmatrix} + \boldsymbol{\varepsilon}_{clk}$$

$$E\left[\boldsymbol{\varepsilon}_{clk}\boldsymbol{\varepsilon}_{clk}^T\right] = Q_{clk} = \begin{bmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{bmatrix}$$



Measurement Model

$$\rho_i(t) = \|\boldsymbol{r}_i(t-\tau) - \boldsymbol{r}_u(t)\| + c * \delta t_u(t) + \varepsilon_\rho(t)$$

$$\dot{\rho}_i(t) = \frac{[\boldsymbol{v}_i(t-\tau) - \boldsymbol{v}_u(t)] \cdot [\boldsymbol{r}_i(t-\tau) - \boldsymbol{r}_u(t)]}{\|\boldsymbol{r}_i(t-\tau) - \boldsymbol{r}_u(t)\|} + c * \delta \dot{t}_u(t) + \varepsilon_{\dot{\rho}}(t)$$

- Onboard, $\dot{\rho}_i$ is computed as time-differenced carrier phase measurements (T=1s) and approximated as an instantaneous range-rate
  - Future work to implement as a change in range over the interval to see if performance improves
- Measurement uncertainty is SRD SISE budget (13.43 m and 1.2 mm/s 3σ) plus UEE budget (receiver noise, no multipath)
  - Receiver contributed ~15 cm and ~0.25 mm/s 3σ on average
- Measurements updated at 1 Hz