62TH MIC VIRTUAL MEETING

LUNAR POLE LINK FOR ROVER SELF-OBSERVATION (LPLRSO)

2.4Ux5 Lunar CubeSat Constellation for Assisting Moon's Pole Rover Observation by self-navigation in harsh conditions





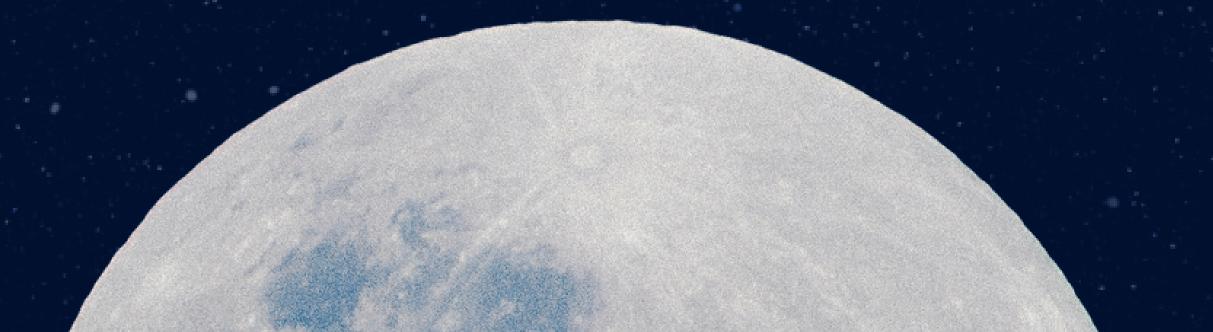




Team Members

WHY MOON POLAR REGION?

- Access to water ice & volatile-rich regolith in permanently shadowed regions—critical for ISRU, fuel, and long-term human presence.
- Extreme terrain & lighting (steep slopes, deep shadows, narrow thermal margins) demand fast, reliable navigation and sensing.
- Communication gaps & latency caused by crater self-occlusion and limited Earth visibility require persistent, low-latency local support.
- Conventional architectures fall short—polar missions need resilient, distributed systems (e.g., CubeSat constellations) to offload compute, ensure coverage, and reduce cost.



LUNAR'S ROVER EXPLORATION



In the need to investigate the potential of the polar region,

lunar rover's exploration is a robust option from its ability to navigate areas

But on such harsh conditions it is hard to navigate due to

- Hazardous PSR terrain demands fast, reliable off-board perception.
- Frequent comm blackouts from crater geometry need constant relay support.
- Earth command is too slow for sub-second mobility decisions like in conventional approach.
- Too power- and mass-limited to run heavy onboard computation.

The rover compute units need to use less power/mass for safety patrol/navigation on such conditions



When the rover get smaller, the need of the rover to be autonomous arise since they will be multiple units



The need of continuous communication to make the rover navigation self autonomous is needed

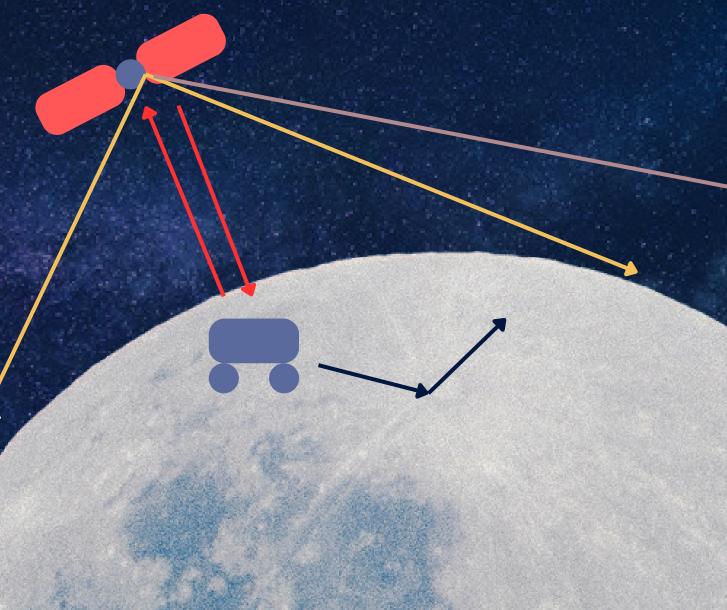


We propose the in-pole-orbit cubesats that help in offload and provide efficient communication to the rover



MISSION OBJECTIVES

- Peristent Pole Coverage
 - → To let the rover always have communication platform
- Provide orbital edge computing Al unit for rover
 - → To segment/ detect object in the navigation
- Safe, Timely Autonomous Mobility
 - → Acting like a hub to help rover navigate itself by help planning
- Resilient Inter Commnication
 - → To make the pentagon network 2.4Ux5 can be on its own



CONCEPT OF OPERATIONS

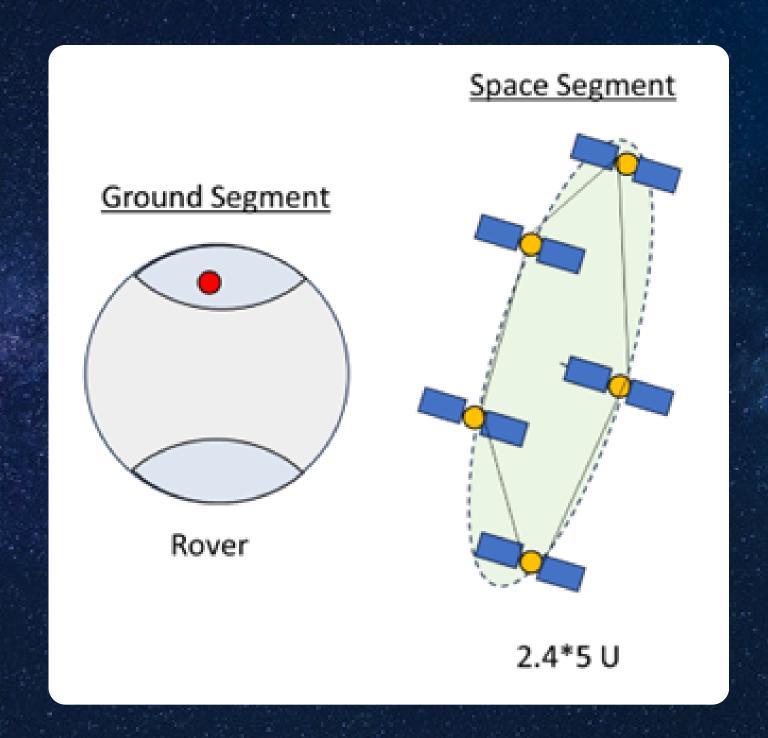
GROUND SEGMENT

A rover operating at more than 70 deg either in north and south pole.

Rover will be smaller, containing only necessary modules for survivalibility, optimized its system for hard terrain and need to only communicate to space segment.

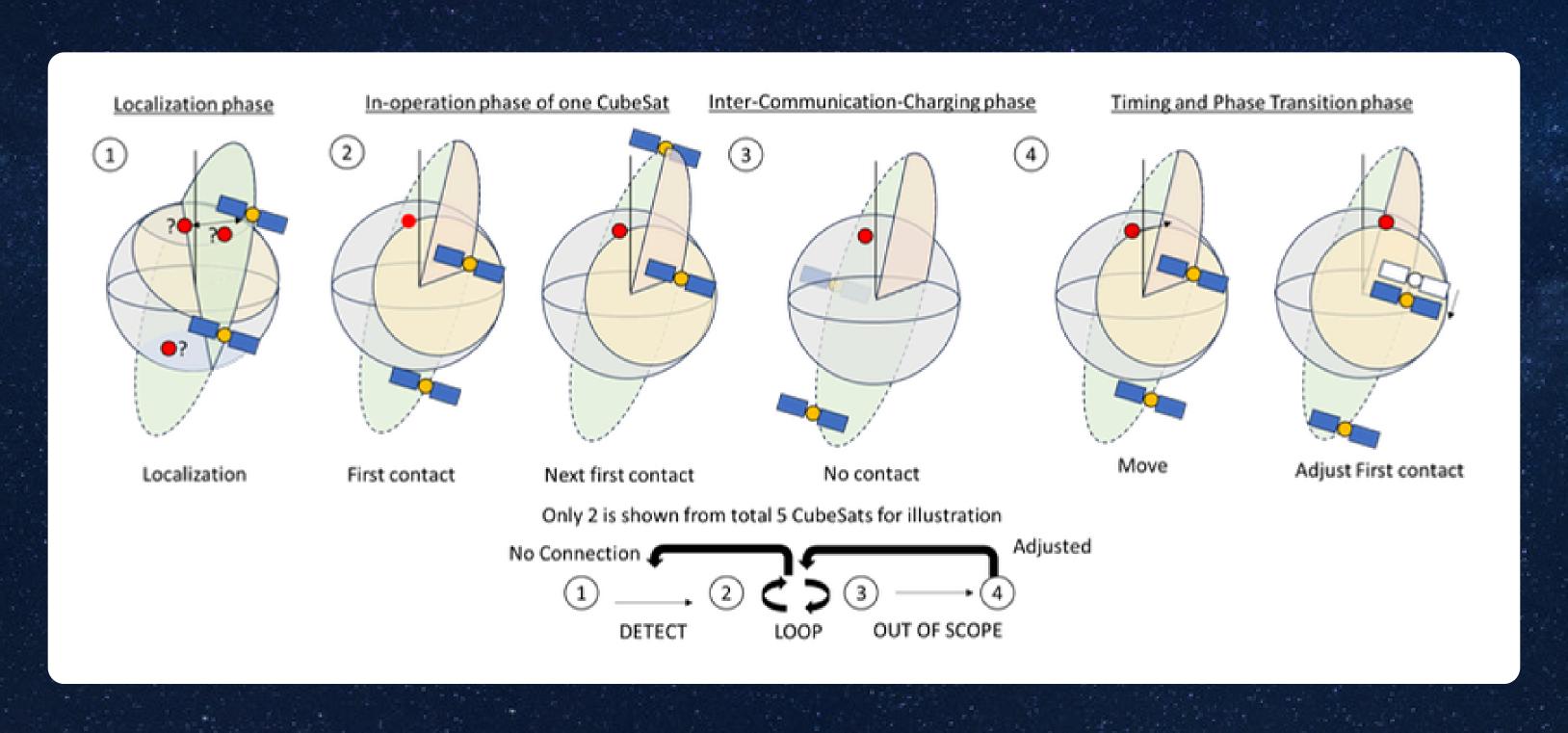
SPACE SEGMENT

The space segment will consists of 5, 2.4U satellites with a near-polar orbit 700km altitude, each CubeSat is equipped with an onboard computing unit, a communication subsystem for rover and intersatellite links, and autonomouspower management systems.



CONCEPT OF OPERATIONS

We have 4 main operational phases which are designed to maintain the connection with the rover.



CONCEPT OF OPERATIONS: SUMMARY

Phase 1 — Rover Localization

Rover and CubeSats perform mutual antenna/pointing calibration.

ADCS fine-pointing + rover antenna tracking establish accurate geometry.

Phase 2 — Data Operation

When in line-of-sight, the rover sends raw sensor data
CubeSat performs near-real-time DL inference: segmentation, terrain
classification, path planning then return info to robot.
Rover maintains pointing to keep the link stable during pass.

Phase 3 — Inter-Communication & Charging

After the pass, CubeSats recharge by solar exposure.

~36 min ISL period used to share rover status, sync navigation data, and balance compute tasks.

Distributed task allocation prevents overload and keeps the constellation synchronized.

<u>Phase 4 — Timing & Phase Transitions</u>

Adjust accordingly to the new rover position

Timing controlled via onboard clocks + cross-satellite handshakes for precise transitions.

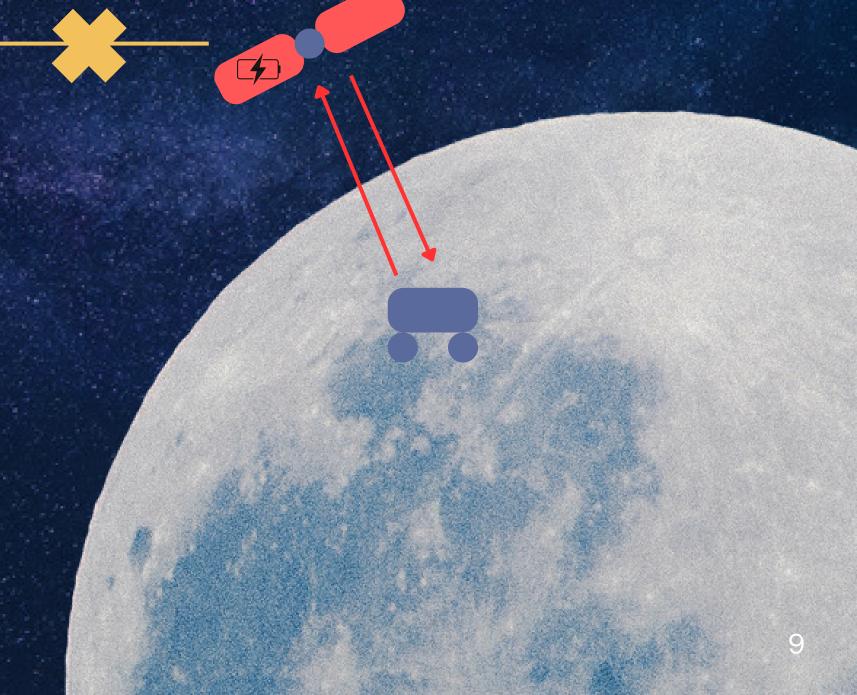
KEY PERFORMANCE PARAMETERS

- 1. Stable Comms: Keep rover—satellite links reliable from 700 km orbit with ≥60 kB/s throughput and ≤5 s latency using precise pointing and adaptive modulation.
- 2. Orbit-Assisted Navigation: Provide terrain maps, hazard labels, and path commands from orbit reducing rover compute and power use.
- 3. Adaptive Constellation: Reconfigure in real time via inter-satellite links to follow rover position, balance compute, and maintain service.

KEY PERFORMANCE PARAMETERS

4. Autonomous Observation Scheduling: Coordinate imaging and tasks under extreme polar lighting to achieve 290% observation uptime with minimal Earth intervention.

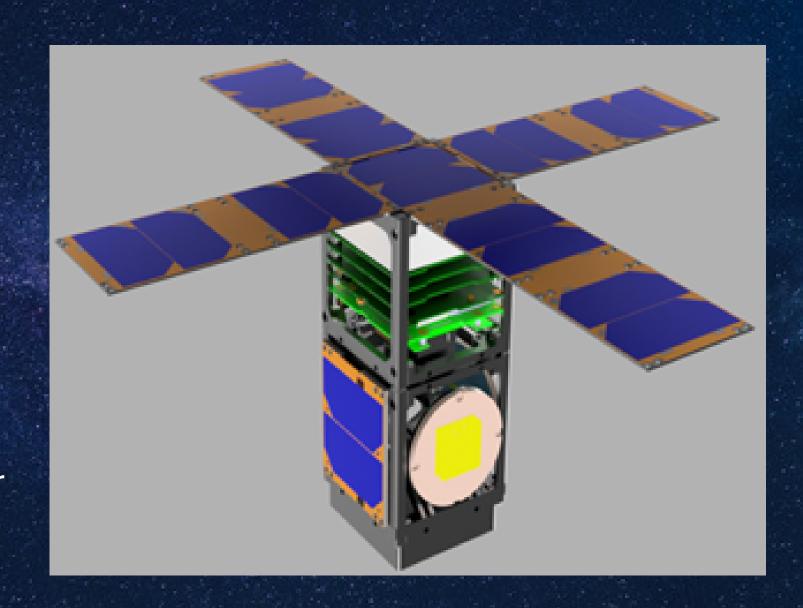
5. Power-Optimized Operations: Manage harvesting, storage, and loads to sustain >90% duty cycle while keeping battery depth-of-discharge <30% for long mission life.



SPACE SEGMENT DESCRIPTION

Compact 2.4U CubeSat with

- onboard deep-learning hardware for real-time rover support.
- communication module that can directly to coordinate tasks and maintain continuous coverage.
- designed specifically to host sustained onboard Al
- deployable solar arrays optimized for erratic polar illumination.
- include ADCS, EPS, Propulsion module also in stack manner



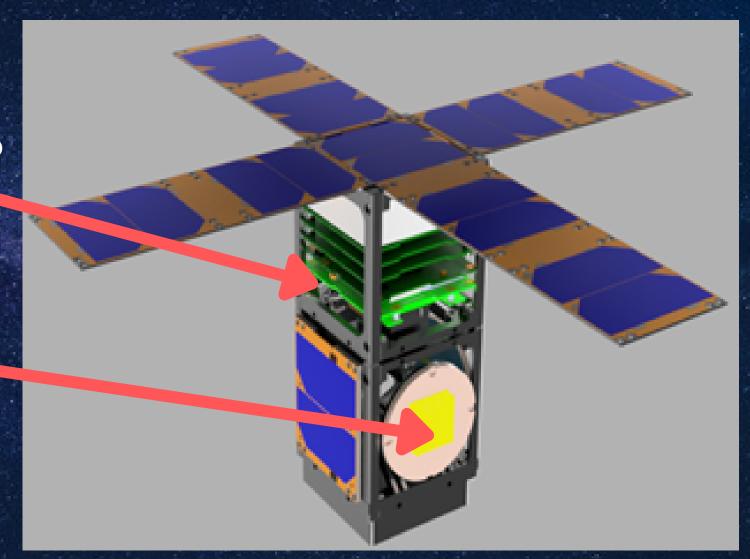
SPACE SEGMENT DESCRIPTION

Al for navigation module

- Orbit-class deep-learning module with multi-VPU processing.
- Runs real-time perception (terrain, hazards, path cues) to offload rover workloads.

Communication

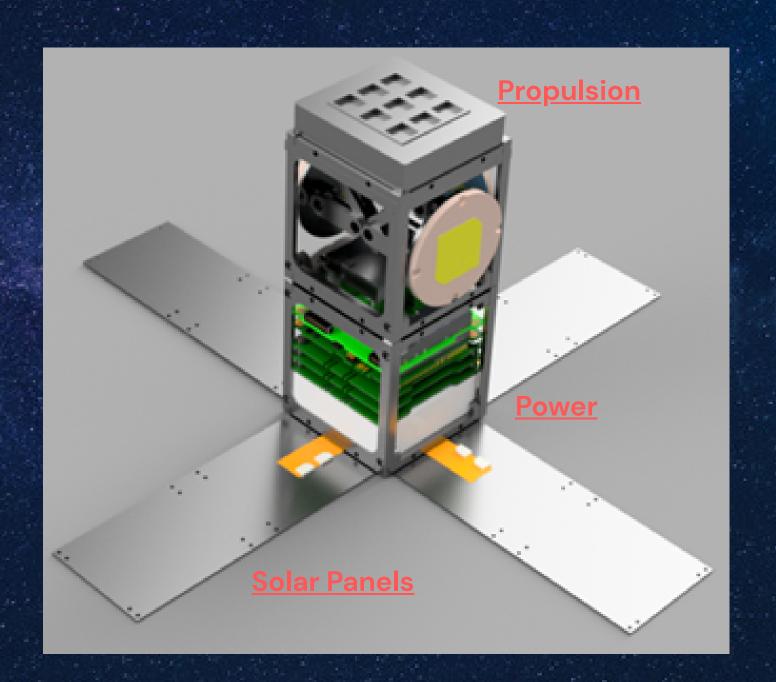
- S-band patch-array links enable reliable satellite-tosatellite coordination.
- Supports continuous coverage, fast handovers, and shared compute tasks.
- Another patch also use to downlink info to the rover.



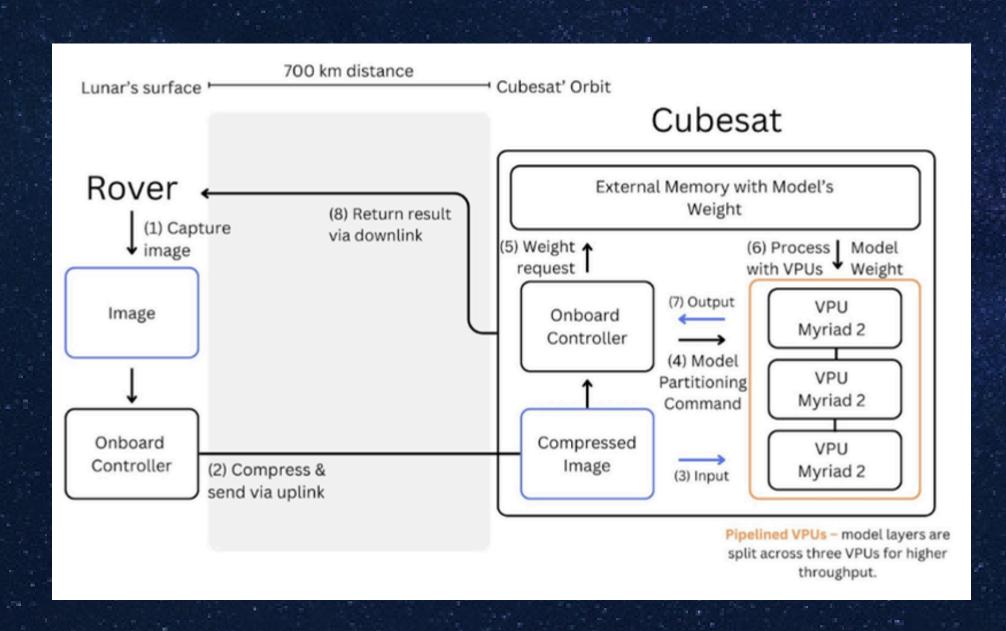
SPACE SEGMENT DESCRIPTION

Another system included in system

- Deployable solar panels generate up to 30 W peak power, with about 16 W average under typical illumination.
- Power regulation and storage via lithium-ion batteries and an EPS comparable to GomSpace P60.
- Scalable Ion Electrospray Propulsion System (S-iEPS) for orbital maneuvering and constellation maintenance.
- **S-iEPS** provides ~74 µN thrust, specific impulse >1,150 s, with power draw <1.5 W.



SOFTWARE - ONBOARD DEEP LEARNING INFERENCE IN CUBESATS



the full round-trip—from image capture to processed result delivery—takes approximately **4532 milliseconds**, enabling timely navigation and decision–making in harsh lunar polar environments.

LINK BUDGET

FSPL = 20log(f(GHz)) + 20log(d(km)) + 92.45

1 DOWNLINK/ UPLINK

- RP (dB) = -110.20 to -117.94 dB
- This link margin supports data rates of approximately 500–1000 kBd, 62.5–125 kB/s (with BPSK modulation (1bit 1symbol))
- Under misalignment (gain → ~4 dB): 100-500 kbps (12.5-62.5 kB/s) until pointing is corrected.
- FSPL 156.2–163.94 dB. (from slant range)

2 INTER-COMMUNICATION

- RP(dB) = -122.44 dB
- signal level is sufficient to achieve 100 kBd (12.5 kB/s (BPSK)) throughput with expected minor degradation from noise that may reach even 10–100 kBd
- even 1-10kB/s is sufficient for exchanging critical telemetry
- FSPL 168.44 dB.

Coverage spans –44.5° to +44.5°, with slant range 700–1708 km.

Antenna gain varies 4–6.5 dB

Transceiver output 20–33 dBm (33 dBm / 10.8 W during high-rate TX).

POWER MANAGEMENT LOOP

IO Power In IO phase (M Power U	sage (Wh) IO (nominal) Power Usage	e (Wh) IO (max Per Duration
-6,5	-3.9	-7.15 36 min (nominal)
-3.55	-2.13	-3.905 66 min (max)
-10.8	-6.48	-11.88
16	9.6	17.6
-0.3	-0.18	-0.33
-1.5 (Per Month)	0	Ö
	-3.09	-5.665
	-6.5 -3.55 -10.8 16 -0.3	-3.55 -2.13 -10.8 -6.48 16 9.6 -0.3 -0.18 -1.5 (Per Month) 0

Subsystem	IO Power In IO phase Powe	r Usage (Wh) ICC (nomina Power Us	sage (Wh) IO (min)Per Duration
OBC+Myriad VPU x3	-2	-4.8	-3.8 144 min (nomina
ADCS + reaction control	-3.55	-8.52	-6.745 114 min (min)
Communication (ISL) (36min)	-10.8	-6.48	-6.48
Solar Cell	16	38.4	30.4
Other(switch)+EPS	-0.3	-0.72	-0.57
Thruster	-1.5 (Per Month)	0	0
Energy Per Loop (ICC)		17.88	12.805

Nominal Case (Wh)	14.79
Maximum use case (Wh)	7.14

IO (In Operation Phase)

- 36 minutes nominal operation (180/5)
 (So 144 minutes Charging Phase)
- 66 minutes maximum duration (calculated)

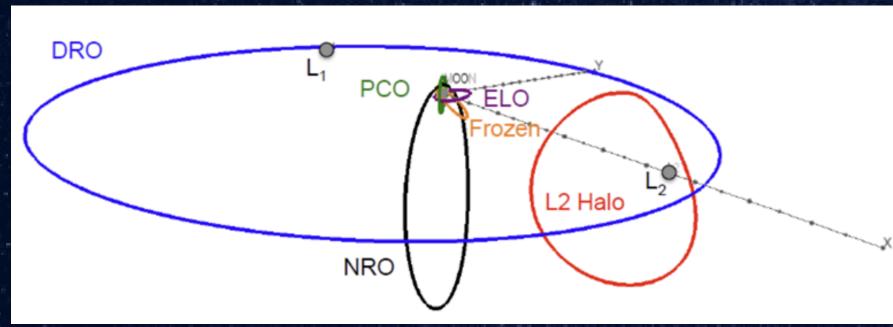
The rest time is for ICC (Inter-communication and charging phase)

There will be 36 minutes communication in the charging phase and all of the calculation show the healthy power loop.

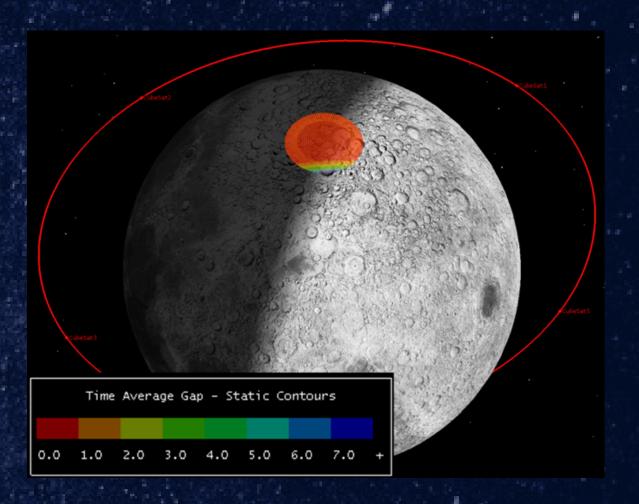
With maximum eclipse time it reduce at most -11.9Wh so in nominal case it will still perform.

MISSION ORBIT OVERVIEW

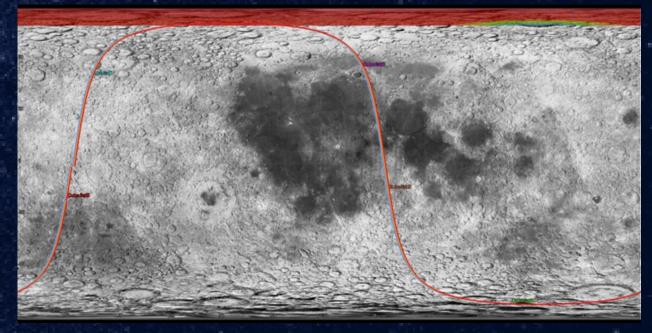
- Orbit Type: Near-circular, 700 km altitude, 84° inclination
- Design Goal: Approximate frozen orbit → maximize long-term stability
- Why 700 km?
 - O Higher than typical LLO (100–300 km) → reduces mascon-induced eccentricity growth & periapsis drift
- Stability: Maintains orbital parameters with minimal correction
- Lifetime: Supports ~15 years of operations
- Multi-body effects mitigated: Earth, Sun, solar radiation pressure
- Autonomous network: Direct CubeSat-to-CubeSat & CubeSat-to-rover data relay → no mothership needed



Source: https://selenianboondocks.com/2016/04/lunar-orbital-facility-location-options/
Types of Lunar Orbits



Daily Time Coverage Gaps (s) for Polar Region Rover Operations

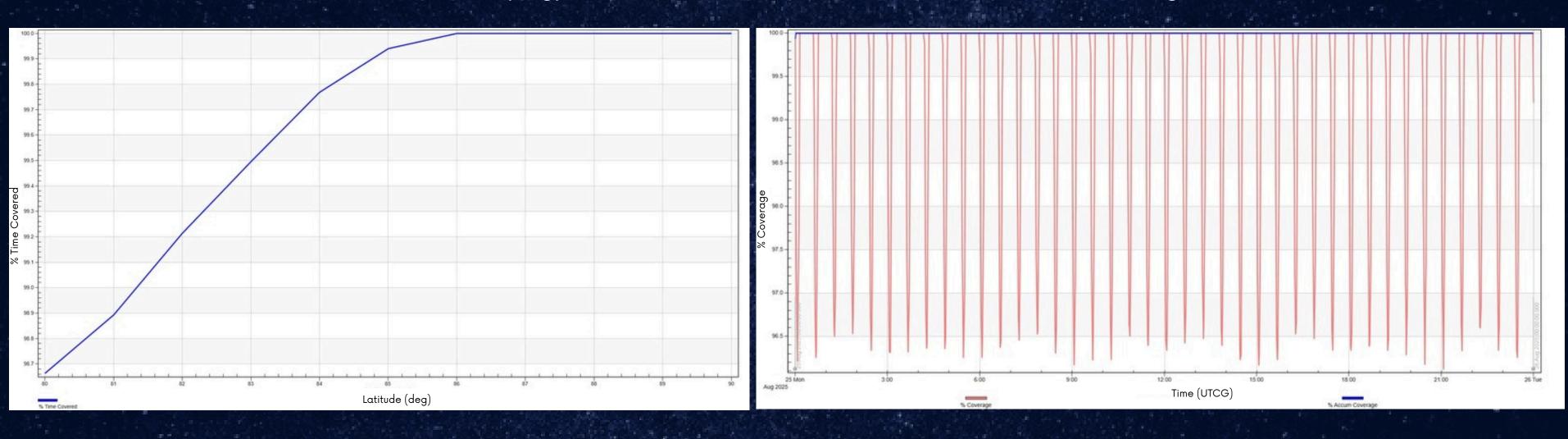


2D Map of Lunar Polar Coverage Highlighting Accessible Latitude Range

TEMPORAL AND SPATIAL COVERAGE CHARACTERISTICS IN POLAR REGION OPERATIONS

% Time Covered vs Latitude (deg)

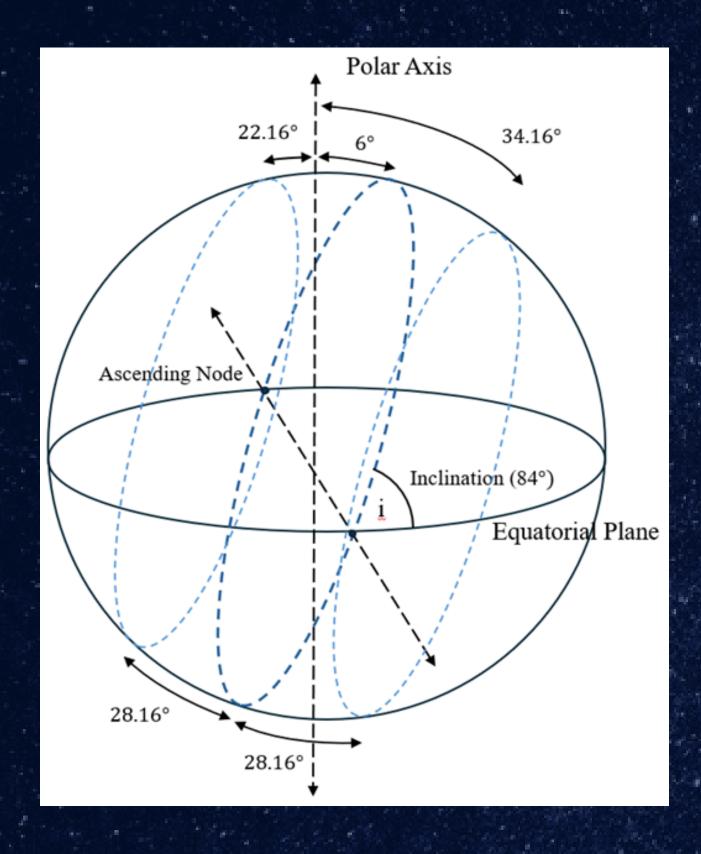




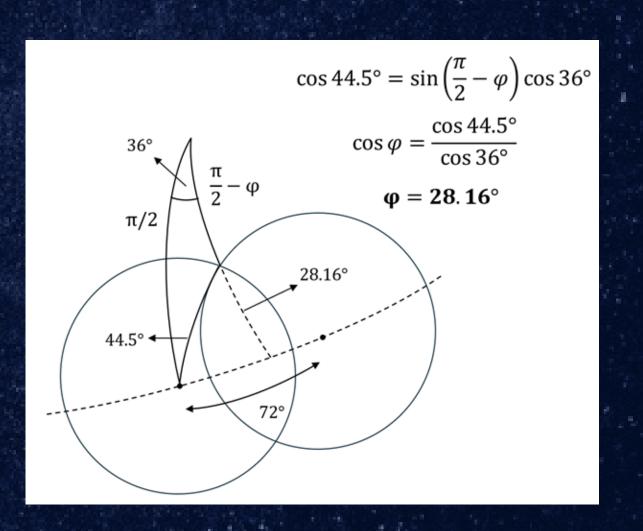
Relationship Between Percentage of Time Covered (Y-axis) and Latitude +80° to +90° (X-axis)

Relationship Between Percentage Coverage (Y-axis) and Time Over a Day (25 Aug 2025 – 26 Aug 2025)

POLAR COVERAGE



- Target latitude: Always cover ≥ ±70°
- Inclination effect: 84° orbit → orbital equator deviates ±6° from pole
- Coverage range per satellite: +34.16° to -34.16°
- Ensures pole coverage: Smooth transition between satellites → continuous coverage

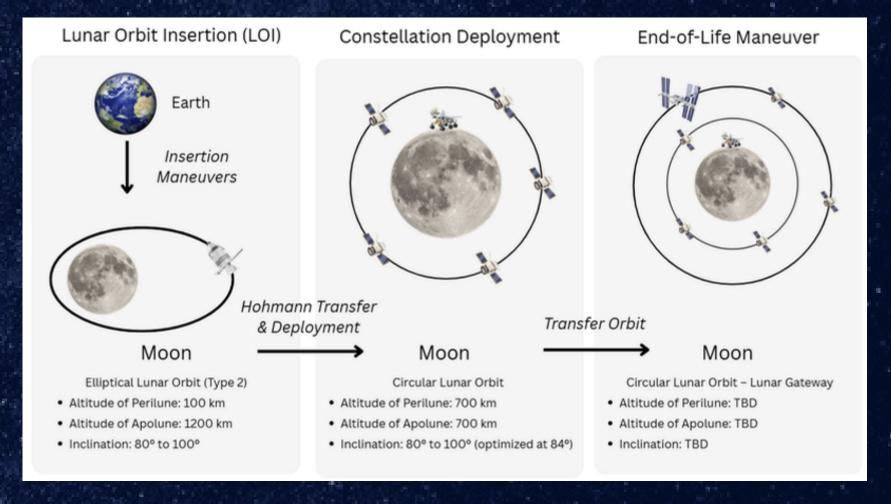


INSERTION & CIRCULARIZATION

- Type-2 transfer \rightarrow Elliptical orbit: 100 km × 1200 km ($\alpha = 2387$ km)
- Circularization maneuver: Single burn at true anomaly 108.34°, flight path angle 13.27°
- Delta-v required: ~0.326 km/s (efficient)
- Deployment sequence: CubeSats released sequentially → even angular spacing → uniform polar coverage
- End-of-life disposal: Final burn to higher, stable orbit → collision avoidance & cislunar sustainability

ORBITAL STABILITY & CONSTELLATION DESIGN

- Eccentricity drift
- Inclination drift
- Argument of periapsis drift
- Station-keeping Δv



End-to-End Mission Flow for the Lunar CubeSat Constellation

IMPLEMENTATION PLAN & BUDGET

Development Timeline

- 2025–2026: Mission definition & preliminary design (SRR, PDR)
- 2026–2027: Detailed design & prototypes (breadboarding, lab demos, CDR)
- 2027–2028: Integration, environmental testing, mission simulation
- 2029: Launch pathfinder (early) + full constellation deployment (late)

Budget Highlights (per CubeSat)

- Total: €300,000
- Hardware: €140,000
- Launch: €90,000 (rideshare)
- Operations: €70,000 (2 years)
- Outsourced assembly, integration and verification (AIV) → ~€435,000 per CubeSat
- Cost-efficient, scalable approach for 5-satellite constellation

PROJECT RISKS

Risk	Level	Mitigation
High onboard compute under thermal stress	Low	Optimize model inference; adaptive scheduling
Rover–CubeSat comm loss (terrain/antenna)	Low	Active rover antenna-tracking protocol
Insufficient funding	Medium	Collaborate with space agencies & governments
Limited manpower	Medium	Expand team; seek mentorship from space agencies
Power shortage (low illumination)	Medium	Add buffer battery; energy-aware AI algorithms

REMARKS

- There is some change of number from the abstract version since we have made the whole calculation again from the start since some number didn't make sense from internal miscommunication when we are writing the full paper.
- Since <u>we firstly design our system on 100 km altitude</u> and so back then all calculation is based on this altitude before we realized that the orbital period is 180 minutes not 120 minutes at new 700 km that ensures all to all satellites connection
- Then we realized that the signal value of symbol/s didn't directly translate to 1 byte/s but 1 bit/s so the link budget number is all revised and checked thorughly.

As now we had recalculated everything for orbital/ power management/ software comptation time and now the full paper should only contain all correct with only one typo that the illuminaiton time on solar cell is not 90 minutes but 114–144 minutes (from new 180 minutes).

<u>Apart of that, all of the cores idea of this proposal is the same and remain unchanged.</u>

We are really sorry for the mistakes we have made and <u>we are ready to fix both abstract and full paper before any</u>

<u>publication after our self-revision and fix everything from other commets from reviewer if needed.</u>

CONCLUSION: LPLRSO

Designed to work in extreme polar conditions:

→ 700 km near-frozen orbit Resilient and self-coordinating Cubesats.

Fully autonomous navigation support:

The <5-second perception loop—uplink → orbital inference → downlink—lets the rover make safe decisions without waiting for Earth commands.

Orbital edge-Al reduces rover burden:

→ Segmentation, hazard detection, and path planning run on the CubeSat's multi-VPU (~1 TOPS INT8)

payload, cutting rover mass, compute needs, and power draw.

Earth-light operations:

→ The constellation acts as an orbiting "compute fabric," enabling rovers to operate safely and continuously in regions where Earth contact is delayed or unavailable.

