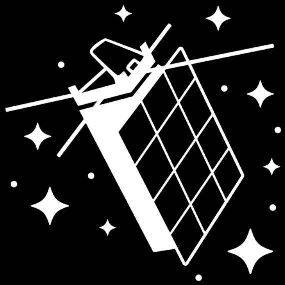
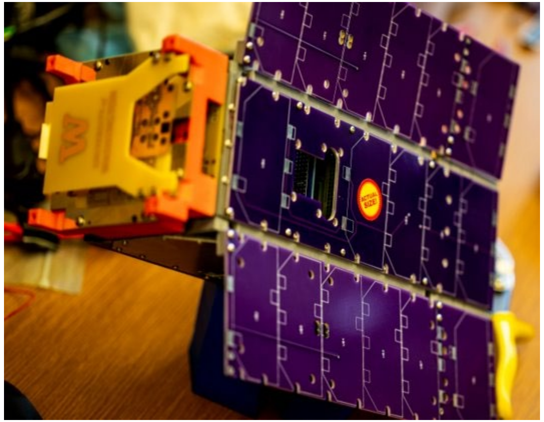


HuskySat-3

C3 Final Presentation

Team Overview



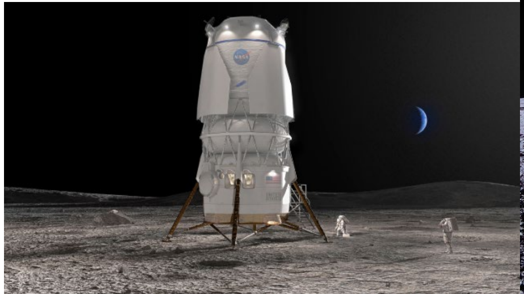
- HuskySat-3 is a Lunar CubeSat mission under development at the Husky Satellite Lab (HSL), a Research and Development laboratory set in the University of Washington. The HSL has long been dedicated to furthering the capabilities of Cube-Satellite (CubeSat) technologies and advancing efforts of scientific research and exploration.
- As it stands, HuskySat-3 is one of the most ambitious and top-of-the line CubeSat in development nationally.
- HuskySat-3 is the third mission in HSL’s interplanetary technology “package”, intended to serve as the ultimate demonstration that a CubeSat is capable of conducting interplanetary novel scientific research and exploration.

Advancing High Value Missions

Long term human settlements on the moon is right on the horizon! As the drive to settle on the moon increases, so does the urge of finding a habitable location.

Furthermore, as lunar infrastructure continues to thrive, cost and pace of development towards lunar research and science becomes increasingly important.

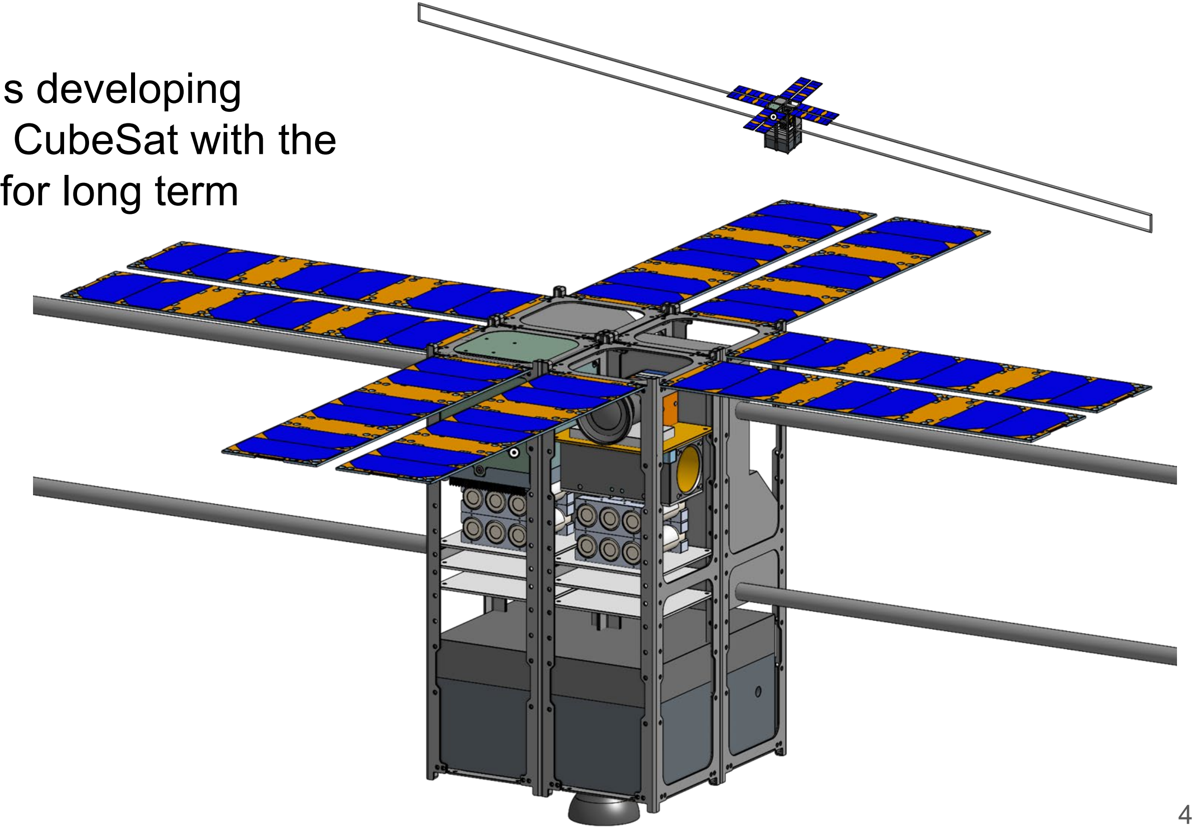
The demonstration of a scientific lunar CubeSat can hence be a significant milestone with immense long term effect, shifting the posture of lunar exploration towards CubeSats!




HuskySat-3

Mission Narrative

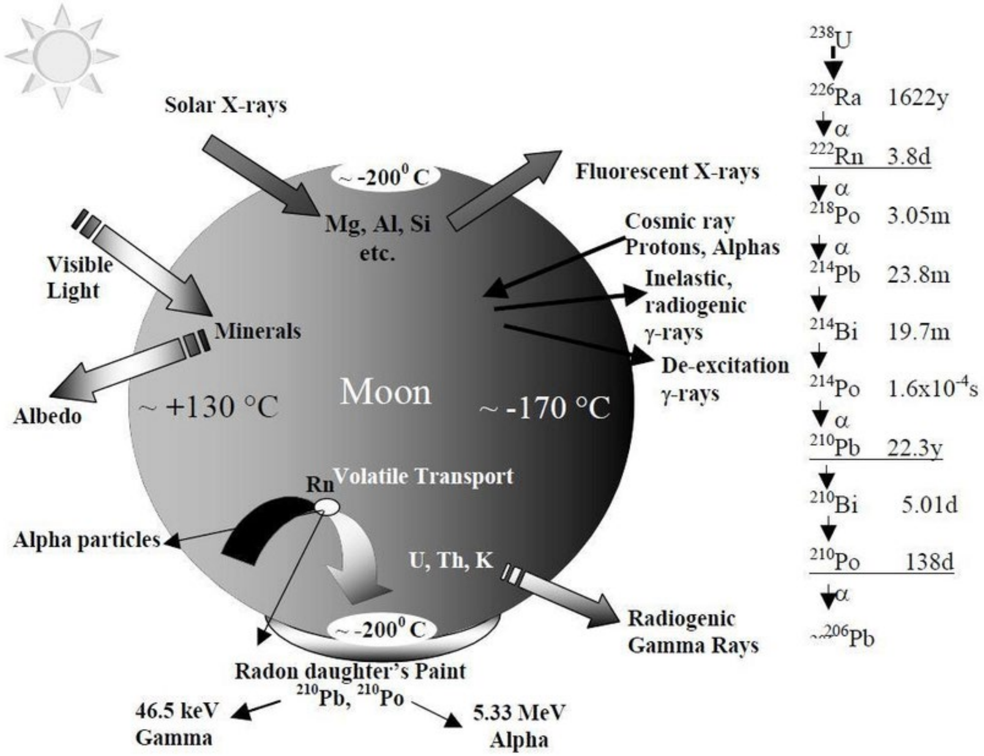
Therefore, the Husky Satellite Lab is developing *HuskySat-3* (HS-3), a lunar orbiting CubeSat with the goal of mapping promising regions for long term human settlements.



Lunar Human Habitation

Three main issues with long-term human settlements on lunar surface:

- Extreme thermal fluctuations as the moon rotates
- Vulnerability to direct solar radiation
- Vulnerability to natural phenomena such as meteorites or comets

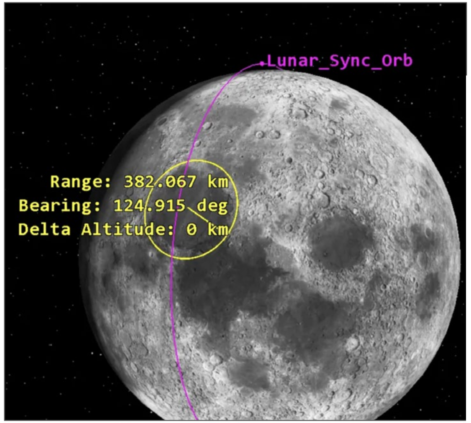


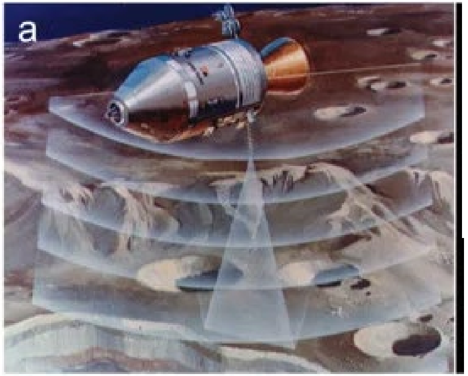
Lunar Human Habitation

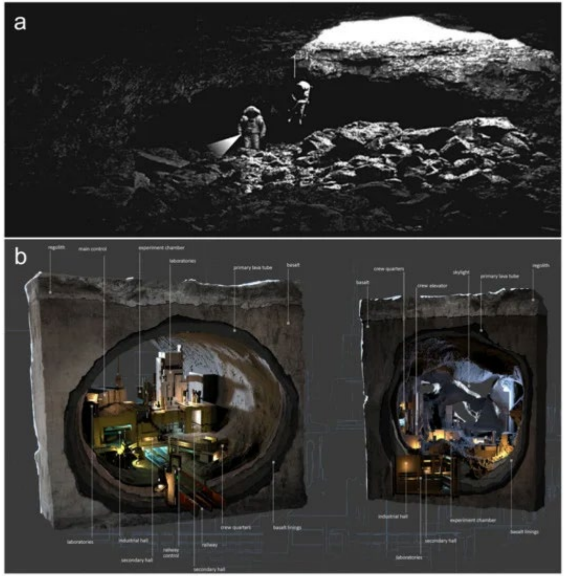
Solution:

- Move underground!
- Subsurface lava tube caves provide:
    - Natural radiation shielding
    - Stable thermal environment
    - Protection from meteorite/comet impact

HuskySat-3 is aiming to map these subsurface lava tube caves by using an orbital-based Ground Penetrating Radar (GPR)







Current State of Science

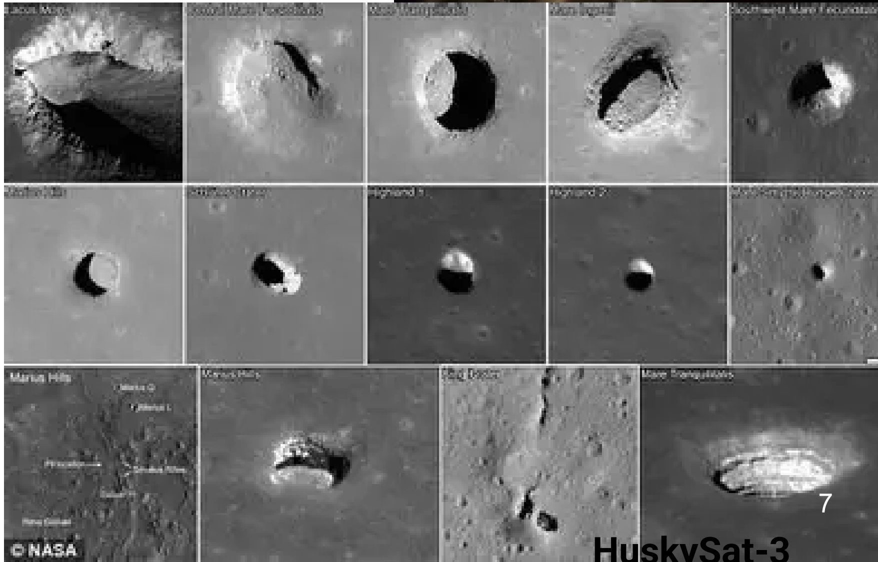
Currently, what's known about Lunar Lava Tube Caves:

- Surface level evidence (Skylights) from the Lunar Reconnaissance Orbiter
- Gravitational Modeling also indicate the existence of Lava Tubes Caves
- Every other bit of research is purely based on modeling

What's unknown:

- How many there are
- Internal characterizations (width, length, stability, etc)
- Coordinates

In other words, there is no "map" of these caves as of yet.



HuskySat-3's Mission Statement

HuskySat-3 shall obtain the ***span*****,** ***ceiling depth*****,** *and* ***floor depth*** *of subsurface lunar lava tube caves within the* ***Basaltic Maria*** *regions*

Program Management Milestones

	Winter												Spring											
Week	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Mission Ops Review (CONOPS & State Machine)						🟪																		
BUS Review						🟪																		
Mission Objective Review							🟪																	
System Concept & Requirements Review									🟪															
Mission Simulation Review (Radar, Thermals, Radiation, Orbital)											🟪													
Subsystem Development Begins!													🟪											
Preliminary Design Review																								🟪
Delta System Requirements Review																			🟪					
Delta Mission Ops Review																	🟪							
Mission Design Document								🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
C3 Milestone																								
Flash Talk	🟥																							
Final Presentation														🟥										
Paper Submission																		🟥						

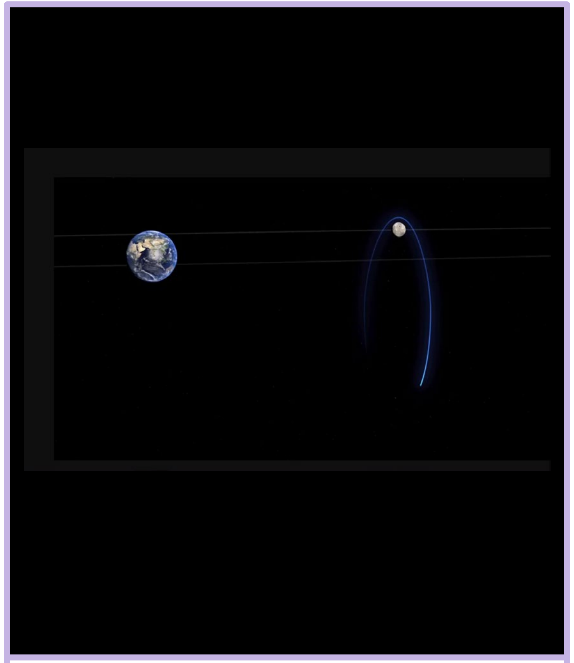
Key:

🟪 Internal Milestones

🟨 Continuous work

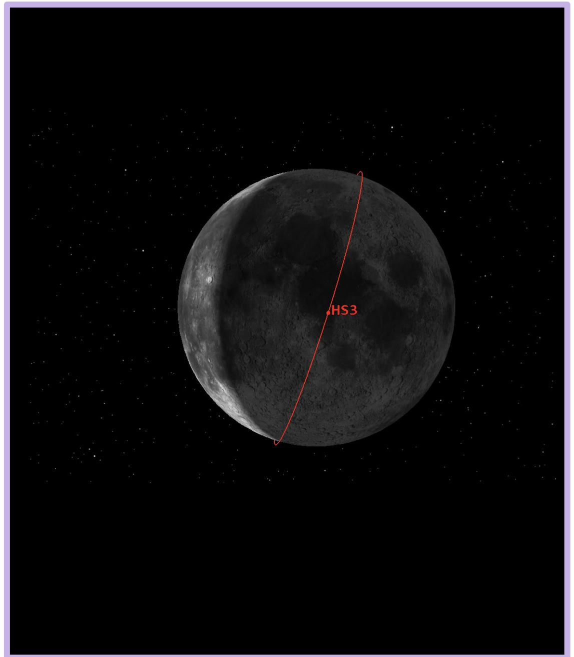
🟥 C3 Fixed Milestones

Animation - Orbital Path and Stages



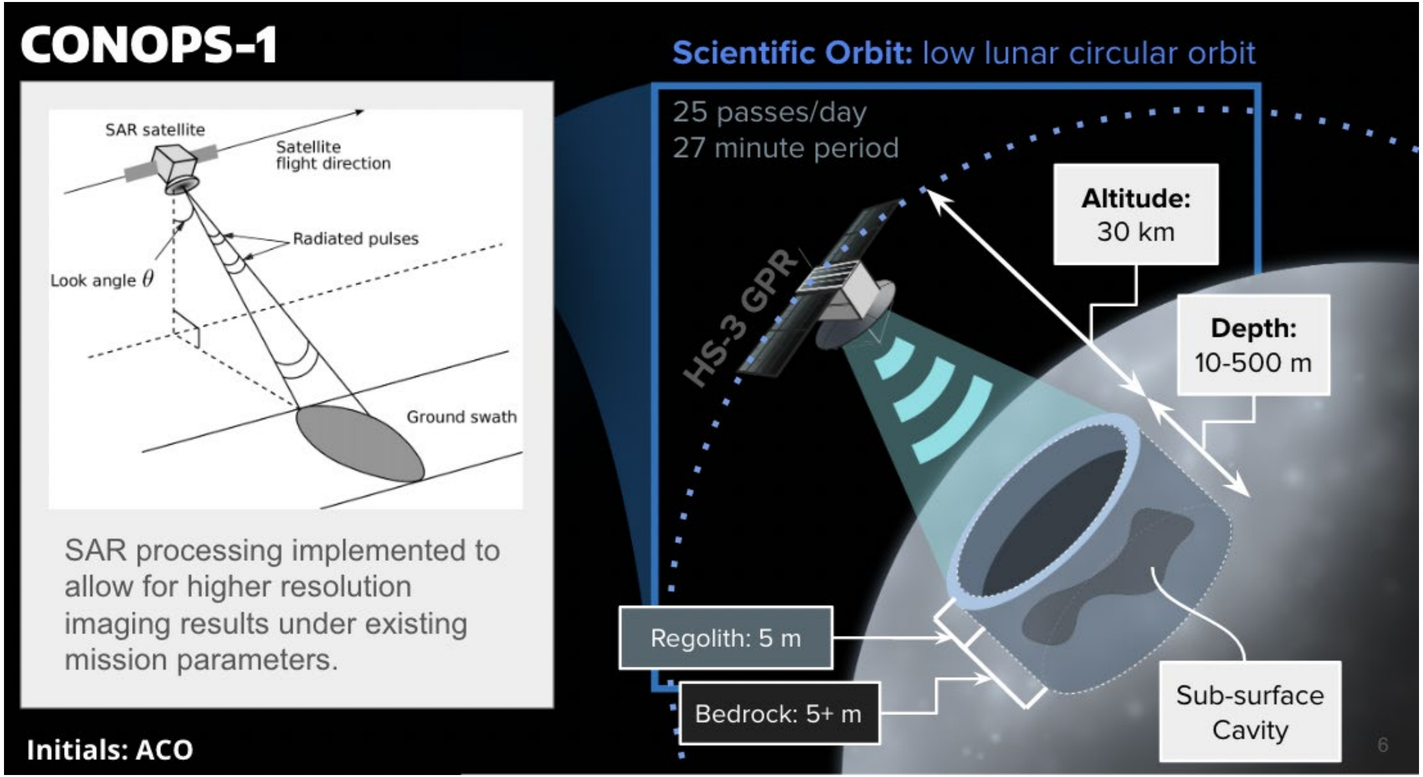
Deployed: Near Rectilinear Halo Orbit (NRHO - Gateway)

Transition: NRHO Perigee to Low Lunar Orbit (LLO)



Final Orbit: LLO Science Orbit

Animation - Ground Penetrating Radar



CONOPS-1

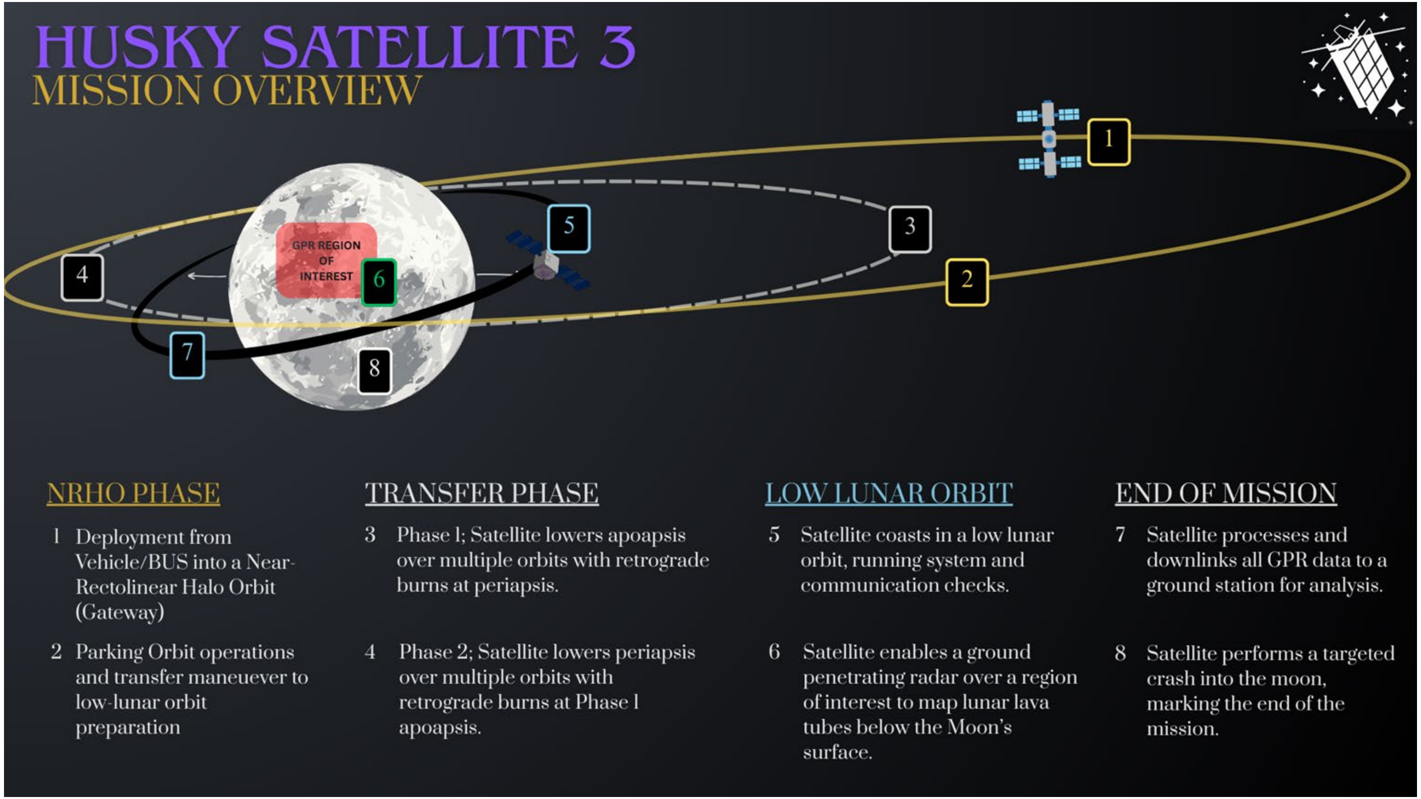
SAR processing implemented to allow for higher resolution imaging results under existing mission parameters.

Initials: ACO

Scientific Orbit: low lunar circular orbit

25 passes/day
27 minute period

Storyboard



HUSKY SATELLITE 3
MISSION OVERVIEW

NRHO PHASE

1 Deployment from Vehicle/BUS into a Near-Rectolinear Halo Orbit (Gateway)

2 Parking Orbit operations and transfer maneuever to low-lunar orbit preparation

TRANSFER PHASE

3 Phase 1; Satellite lowers apoapsis over multiple orbits with retrograde burns at periapsis.

4 Phase 2; Satellite lowers periapsis over multiple orbits with retrograde burns at Phase 1 apoapsis.

LOW LUNAR ORBIT

5 Satellite coasts in a low lunar orbit, running system and communication checks.

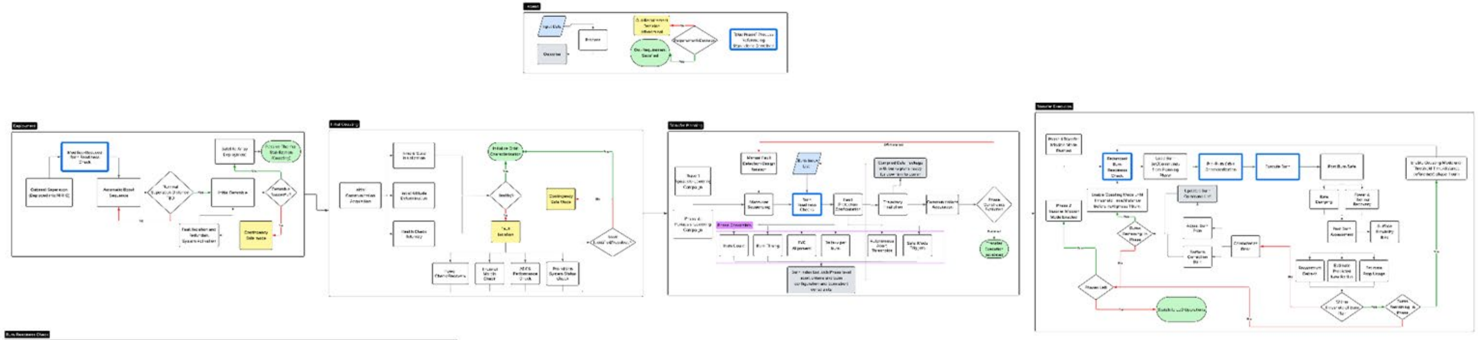
6 Satellite enables a ground penetrating radar over a region of interest to map lunar lava tubes below the Moon's surface.

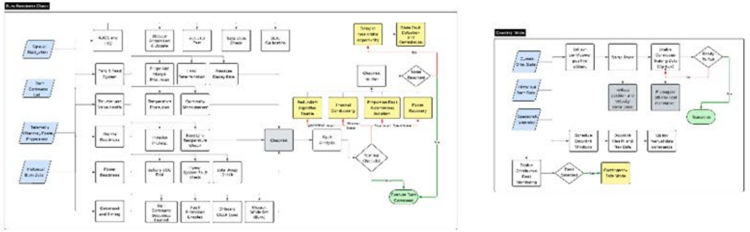
END OF MISSION

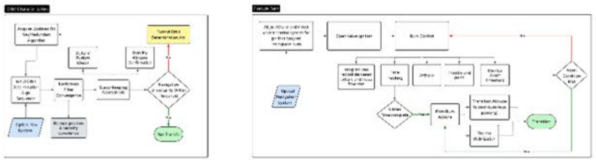
7 Satellite processes and downlinks all GPR data to a ground station for analysis.

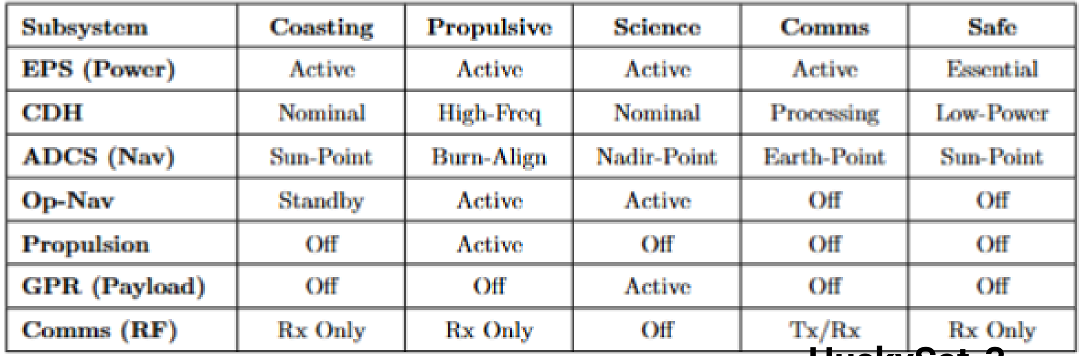
8 Satellite performs a targeted crash into the moon, marking the end of the mission.

Storyboard









Subsystem	Coasting	Propulsive	Science	Comms	Safe
EPS (Power)	Active	Active	Active	Active	Essential
CDH	Nominal	High-Freq	Nominal	Processing	Low-Power
ADCS (Nav)	Sun-Point	Burn-Align	Nadir-Point	Earth-Point	Sun-Point
Op-Nav	Standby	Active	Active	Off	Off
Propulsion	Off	Active	Off	Off	Off
GPR (Payload)	Off	Off	Active	Off	Off
Comms (RF)	Rx Only	Rx Only	Off	Tx/Rx	Rx Only

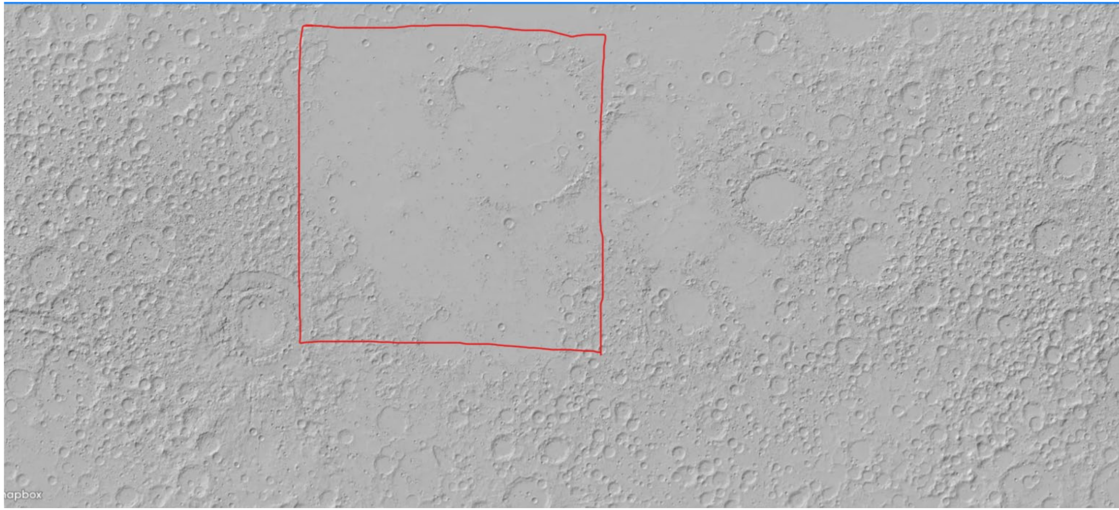
Risks

- Student driven: Multi-year design cycle requires very robust transfer of knowledge
- Low current TRL
- New/experimental operational model

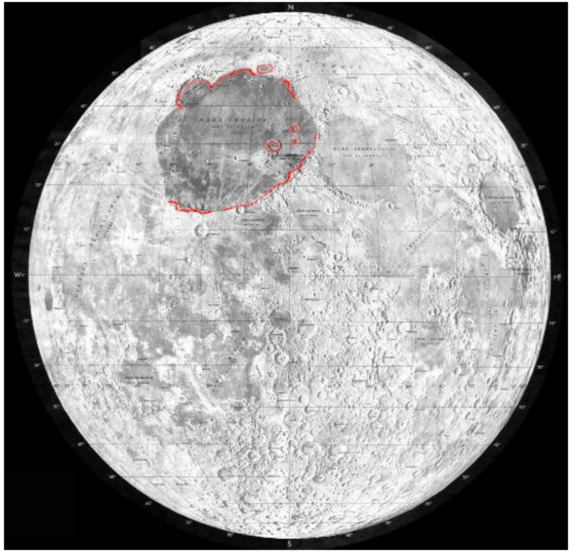
A genuine MOONSHOT of a mission!

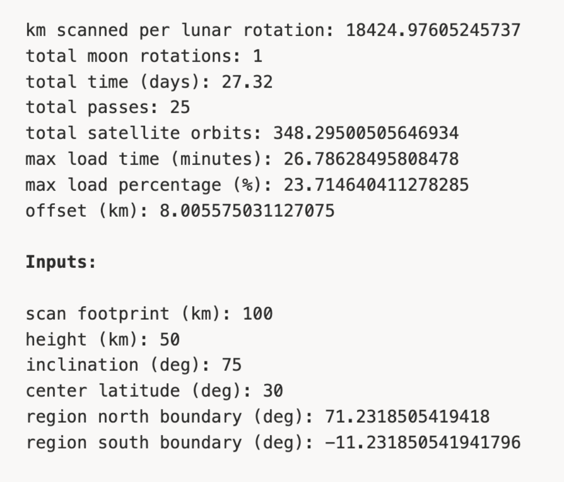
Data handling & comms - total data

- Assume bounding box around area of interest for max (worst case) condition
- Assume 8 repetitions of total passes (doable in one lunar rotation)
- Math flow:
    - Calculate data per each kilometer of tracing
    - Calculate data per each second of radar being operational
    - Find total amount of second the radar is operational
    - Find total amount of data collected



Data handling & comms - total data





```
km scanned per lunar rotation: 18424.97605245737
total moon rotations: 1
total time (days): 27.32
total passes: 25
total satellite orbits: 348.29500505646934
max load time (minutes): 26.78628495808478
max load percentage (%): 23.714640411278285
offset (km): 8.005575031127075

Inputs:

scan footprint (km): 100
height (km): 50
inclination (deg): 75
center latitude (deg): 30
region north boundary (deg): 71.2318505419418
region south boundary (deg): -11.231850541941796
```

bytes per trace = bits/8:

- low-band: $2{,}400 \div 8 = 300$ bytes/trace.
- high-band: $12{,}000 \div 8 = 1{,}500$ bytes/trace.

bytes per second (raw) = bytes/trace × PRF (1000):

- low-band: $300 \times 1000 = 300{,}000$ bytes/s.
- high-band: $1{,}500 \times 1000 = 1{,}500{,}000$ bytes/s.

Worst-case overall passes required over the region: 198

Time for each pass: ~ 26 minutes

Total time in seconds:

$$T = 26 \cdot 60 \cdot 198 = 308880\ sec$$

Total data:

$$Data_{total} = \left(0.2894415563\ \frac{MB}{s}\right) \cdot 308880\ s$$

$$Data_{total} = 89402.70791\ MB = 89.4\ GB$$

Pictures:
https://upload.wikimedia.org/wikipedia/commons/f/f3/Imbrium_location.jpg

Data handling & comms - Why KA Band

Frequency Ranges

- S-Band: 2→4 GHz
    - Long heritage of use
    - “Common” hardware
    - Crowded Bandwidth → Low data rate
- X-Band: 8→12 GHz
    - Used in previous lunar cubesat missions
    - “Common” hardware
    - Crowded Bandwidth → Low data rate
- Ka-Band: 26.5→40 GHz
    - Higher carrier frequency → larger bandwidth and higher data rates
    - Limited pre existing hardware

Ka-Band

- Not a completely novel technology
    - Gateway and JWST utilize Ka-Band for data downlink
    - Many LEO and GEO satellites have moved to Ka-Band
- Extensive ground infrastructure exists
    - The NSN and DNS support Ka-Band communication
    - High data throughput is possible on the NSN

Data handling & comms - Transmission Window

Orbital Velocity: $1.66\ \frac{km}{s}$

Orbital Radius: 1787.4 km

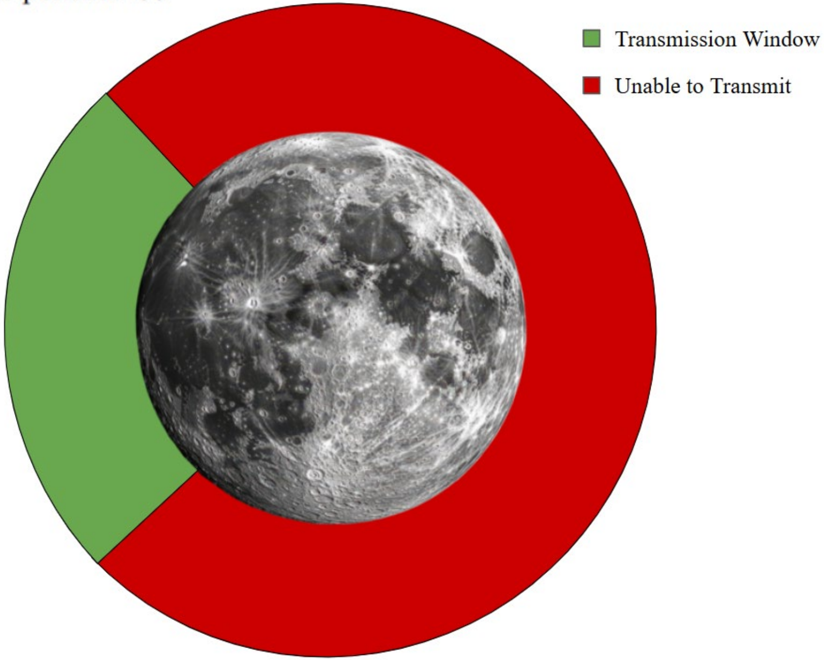
Assumed arc in which transmission is possible: 90°

$$L_{arc} = \text{radians} \cdot r$$

$$L_{arc} = 2807.64\,\text{km}$$

$$T_{transfer} = \frac{2807.64}{1.66} = 1691\,\text{s}$$

$$\boxed{\approx 28\,\text{min}}$$



Transmission Window

- Determined by how maneuverable our antenna is
- For a somewhat fixed antenna- transmission window is a few degrees → few minute transmit time

Innovative Concepts - Communications

Transmit Power:

$$P_t = 35\text{ W} = 35{,}000\text{ mW}$$

$$P_t(\text{dBm}) = 10\log_{10}(35000) = 45.44\text{ dBm}$$

Wavelength:

$$\lambda = \frac{c}{f} = \frac{3\times 10^8}{30\times 10^9} = 0.01\text{ m}$$

Antenna Gain Formula:

$$G = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

$$G_{\text{dBi}} = 10\log_{10}(G)$$

Transmit Antenna Gain $(D_t = 0.2\text{ m}, \eta = 0.6)$:

$$G_t = 0.6\left(\frac{\pi(0.2)}{0.01}\right)^2 = 0.6(62.83)^2 = 2368.7$$

$$G_t(\text{dBi}) = 10\log_{10}(2368.7) = 33.75\text{ dBi}$$

Ground Station Gain $(D_r = 13\text{ m}, \eta = 0.6)$:

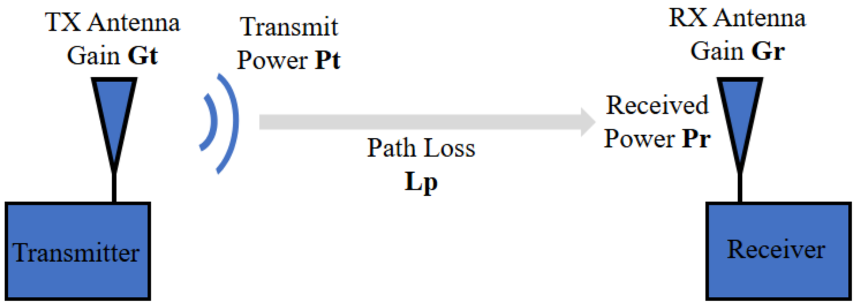
$$G_r = 0.6\left(\frac{\pi(13)}{0.01}\right)^2 = 0.6(4084.07)^2 = 1.001\times 10^7$$

$$G_r(\text{dBi}) = 10\log_{10}(1.001\times 10^7) = 70.01\text{ dBi}$$

Link Budget $(L = 241\text{ dB})$:

$$\begin{aligned} P_r &= P_t + G_t + G_r - L \\ &= 45.44 + 33.75 + 70.01 - 241 \\ &= -91.8\text{ dBm} \end{aligned}$$

- Link margin is at least 5 dB
- NSN minimum signal strength for detection -100 dBm



Innovative Concepts - GPR

FINAL FREQUENCY REQUIREMENTS

GPR Operating Frequency	30 MHz	Final nominal frequency
Bandwidth	8.75 MHz	Final operating bandwidth
Pulse Duration (τ)	114.3 ns	τ = 1/B = 1/8.75 MHz
Wavelength (λ)	8.75 m	At 30 MHz nominal
Vertical Resolution	10.0 m	Target met
Unambiguous Pulse Time	5.71 µs	Min. PRI for 1 km depth
Max PRF (mission)	2.95 kHz	Shall not exceed

FINAL ANTENNA SPECIFICATIONS

HALF-WAVE DIPOLE ANTENNA

Each Arm: **2.5 m**

Total Length: **5.0 m**

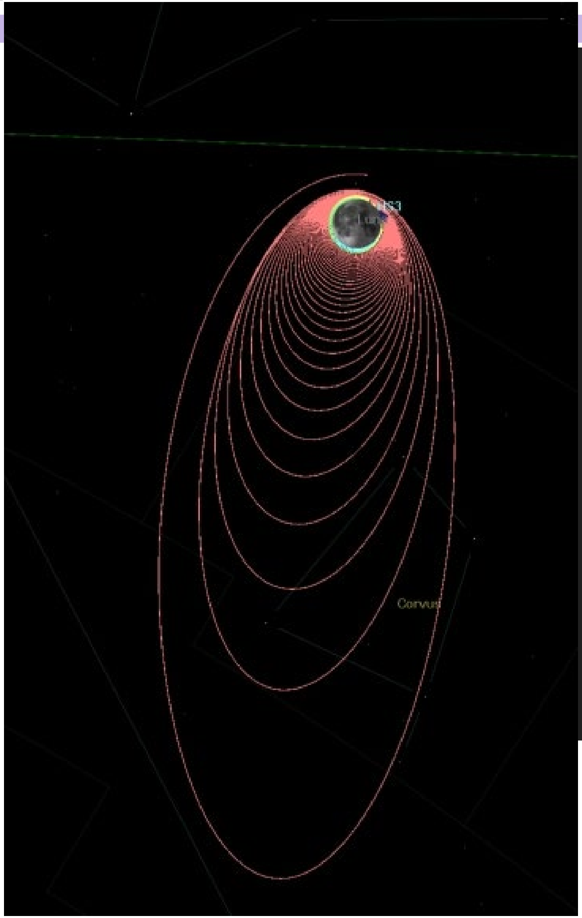
Half-wave dipole | L_total = 142.65/30MHz = 4.76 m theoretical → 5.0 m deployed

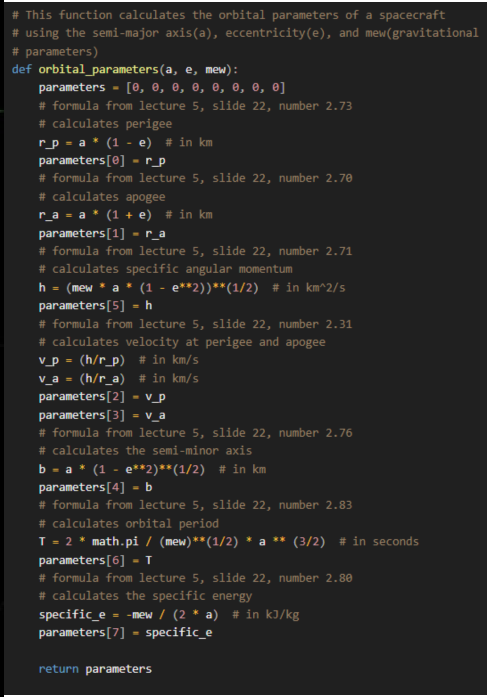
Antenna Type	Half-wavelength dipole	
Arm Length	2.5 m each	5.0 m total deployed
Frequency	30 MHz	Final nominal
Bandwidth	8.75 MHz	Final value
Energy / Pass	20.1 Wh	All onboard data ← 3 hr DSN
Pointing Accuracy	± 5°	100 km swath safety factor

Innovative Concepts - Propulsion

- Current trajectory assumes impulsive hohmann transfer burns
- Roughly 890 m/s of delta-v for a ~24 day transfer

- Will require heavy-duty combustion-based propulsion system onboard.
- In development on an Electrolysis bi-propellant engine currently (a water-based combustion system)!





```python
# This function calculates the orbital parameters of a spacecraft
# using the semi-major axis(a), eccentricity(e), and mew(gravitational
# parameters)
def orbital_parameters(a, e, mew):
    parameters = [0, 0, 0, 0, 0, 0, 0, 0]
    # formula from lecture 5, slide 22, number 2.73
    # calculates perigee
    r_p = a * (1 - e)  # in km
    parameters[0] = r_p
    # formula from lecture 5, slide 22, number 2.70
    # calculates apogee
    r_a = a * (1 + e)  # in km
    parameters[1] = r_a
    # formula from lecture 5, slide 22, number 2.71
    # calculates specific angular momentum
    h = (mew * a * (1 - e**2))**(1/2)  # in km^2/s
    parameters[5] = h
    # formula from lecture 5, slide 22, number 2.31
    # calculates velocity at perigee and apogee
    v_p = (h/r_p)  # in km/s
    v_a = (h/r_a)  # in km/s
    parameters[2] = v_p
    parameters[3] = v_a
    # formula from lecture 5, slide 22, number 2.76
    # calculates the semi-minor axis
    b = a * (1 - e**2)**(1/2)  # in km
    parameters[4] = b
    # formula from lecture 5, slide 22, number 2.83
    # calculates orbital period
    T = 2 * math.pi / (mew)**(1/2) * a ** (3/2)  # in seconds
    parameters[6] = T
    # formula from lecture 5, slide 22, number 2.80
    # calculates the specific energy
    specific_e = -mew / (2 * a)  # in kJ/kg
    parameters[7] = specific_e

    return parameters
```

Tech Gap Assessment

- There's a large gap in technology for support of non-Earth based CubeSat exploration:
    - Non-GPS based Navigation systems (actually the focus of HS-2!!!)
    - Radiation tolerant/hardened CubeSat scale hardware
    - Autonomous software pipelines for C&DH and mission operations
    - The GPR, Propulsion, and Comms are all novel needs that don't particularly exist at the required scale and TRL.

Biggest Challenges

- Ground Penetrating Radar system analysis:
    - Lots of unknowns and novelty around GPR performance and behavior
    - May require advanced synthetic processing
- CubeSat Propulsion:
    - A field no one has “figure out”
    - Many unexplored/tested issues in space
- Cost: HS-3 will likely be a multi-million dollar mission

Path to PDR

- Program-wide:
    - We’ll be recruiting more engineers to begin design of systems already analyzed
    - We’ll continue analysis cycles and iterating on requirement development (requirements will continue to change)
    - Mission Design Document
    - Risk management matrix
- Communications
    - Continue to put real world considerations into the calculations
    - Create a way to fold the antenna
    - Minimize the power needs of the comms system

Path to PDR

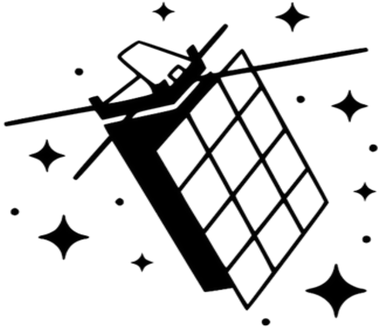
- Power:
    - Further refine power budget with more accurate numbers based on hardware and software
    - Thermals / propulsion estimates
- Science:
    - Recruit for Power and Thermal specific positions
    - Review GPR with different altitudes and conditions
    - Continue to solve SNR parameters
    - Continue Thermal and Radiation simulations
- Orbit:
    - Continue gathering reports from simulations and refine orbital elements to ensure mission works.
- Propulsion:
    - RCS propulsion analysis for pointing is yet to happen. That’ll be a primary focus from now.
    - Orbital maneuver allocations for thrust minimization

Conclusion

- Composed by UW’s best and brightest, HS-3 will go on a journey with extremely high pay-off potential to find habitable zones for long-term human habitation on the moon

- As one of the most ambitious missions out there, HS-3 is breaking ground on several top-of-the-line technologies with the ultimate goal of empowering CubeSat level interplanetary exploration and science.

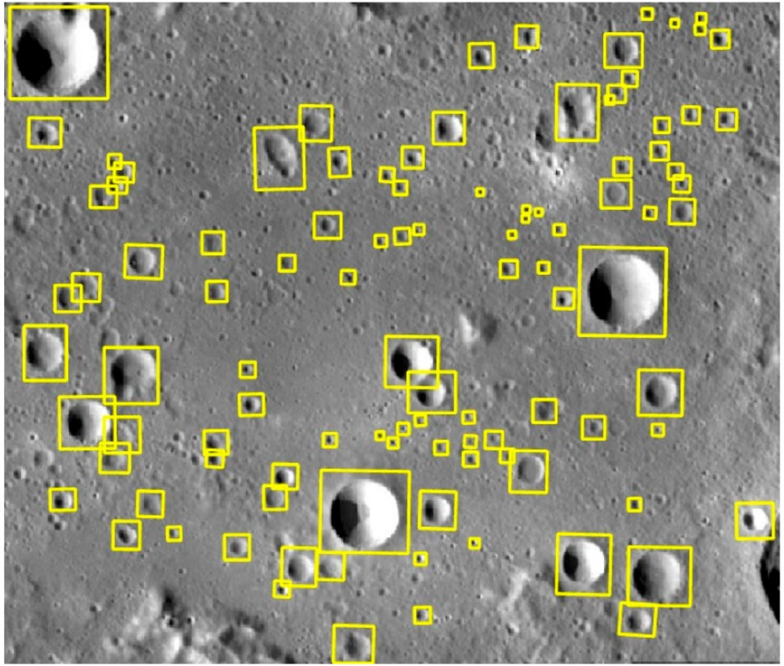
- Thank you so much for your attention!



BACKUPP!!!!

Data handling & comms - Pointing

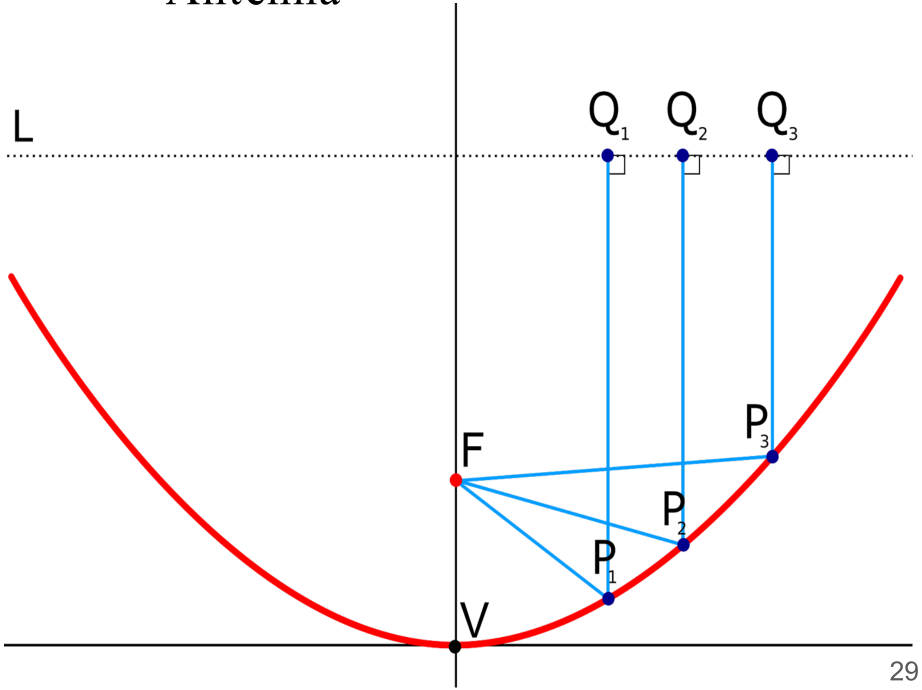
- A lunar positioning system is already required for lava tube mapping
- The satellite knows where it is above the moon
- The position of the earth relative to the moon is known
- Therefore the position of the satellite relative to the ground station is known
- Beacon pointing can aid in acquiring a stable satellite link



Determining Antenna Type

- Ka-Band patch antennas generally have large beam divergences
- Antenna needs to fit in 1U of space
- Parabolic antennas offer focused beams for better data transmission
  - More compact than horn antennas
  - Commonly used for high gain space communication applications

Parabolic Reflector Antenna



Antenna Pointing Accuracy

- Pointing accuracy increases for larger antenna diameters
- The pointing of the antenna will need to take refraction into account

$$\theta_{\mathrm{HPBW}} \approx \frac{70\lambda}{D}$$

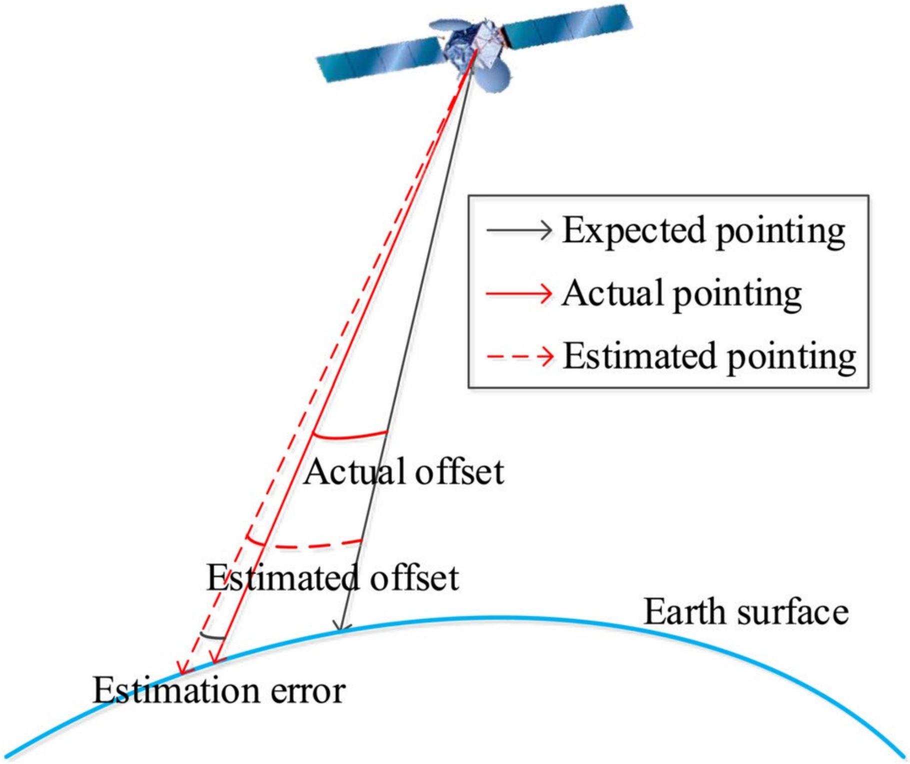
$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{30 \times 10^9} = 1 \times 10^{-2}\,\mathrm{m}$$

$$\theta_{\mathrm{HPBW}} \approx \frac{70(1 \times 10^{-2})}{0.2}$$

$$\theta_{\mathrm{HPBW}} \approx 3.5^\circ$$

$$\text{Pointing Accuracy} = \frac{1}{10} \cdot \theta_{\mathrm{HPBW}}$$

$$\boxed{\text{Pointing Accuracy} = 0.35^\circ}$$



Signal Losses

$$L_{\text{total}} = L_{\text{FS}} + L_{\text{atm}} + L_{\text{rain}} + L_{\text{pol}} + L_{\text{pointing}} + L_{\text{hardware}}$$

$$L_{\text{FS}} = \left(\frac{4\pi d}{\lambda}\right)^2$$

$$L_{\text{FS}} = \left(\frac{4\pi \cdot 3.84 \times 10^8\,\text{m}}{1.00 \times 10^{-2}\,\text{m}}\right)^2$$

$$L_{\text{FS}} \approx 2.33 \times 10^{23}$$

$$L_{\text{FS}} \approx -234\,\text{dB}$$

Values below are based on collected data[4]

$$L_{\text{atm}} \approx -2\,dB$$

$$L_{\text{rain}} \approx -3\,dB$$

$$L_{\text{pol}} \approx -1\,dB$$

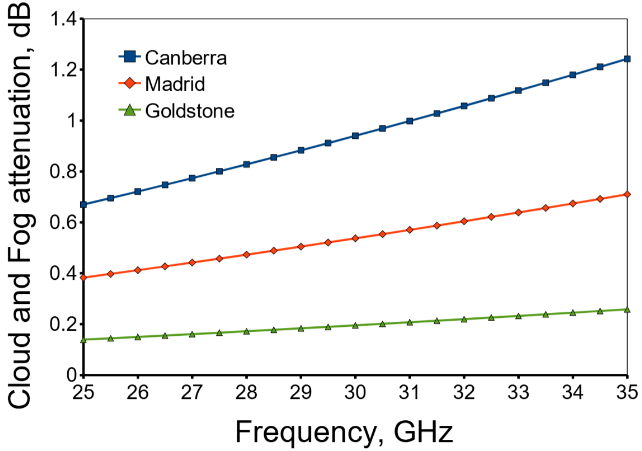
$$L_{\text{pointing}} \approx -1\,dB$$

$$L_{\text{total}} = -234 - 2 - 3 - 1 - 1$$

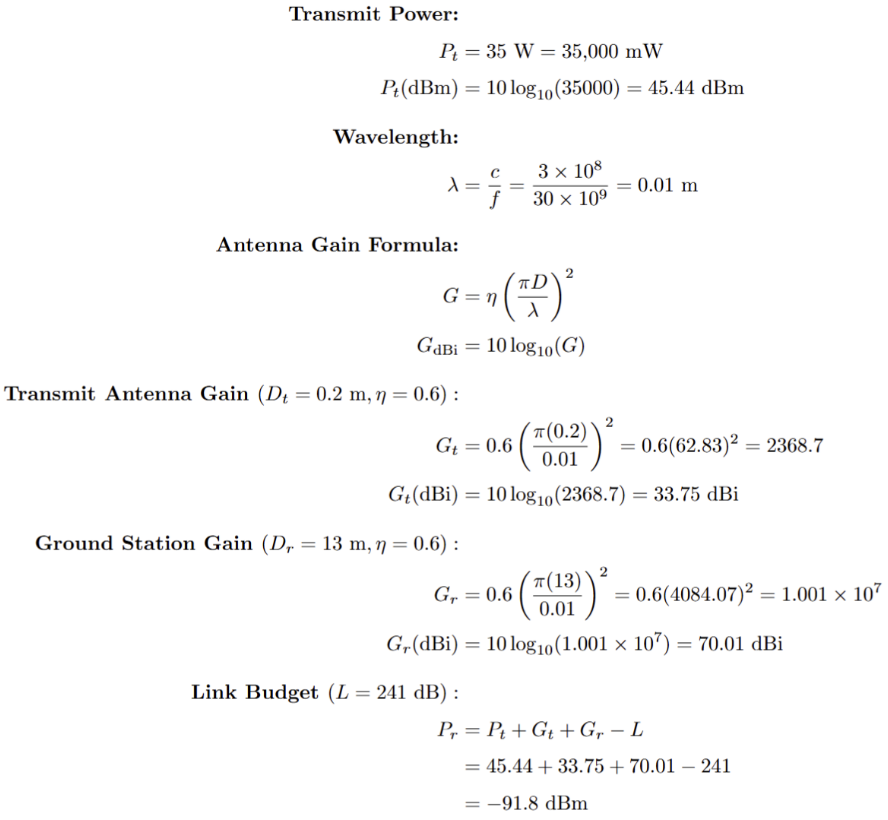
$$\boxed{L_{\text{total}} = -241\,\text{dB}}$$

- Rain attenuation poses a significant risk
- Free space loss accounts from majority of signal weakening
- Losses due to hardware are potentially large

On the left is an estimate of the total signal losses. On the right is a graph of water vapor attenuation for DSN sites



Link Budget



Transmit Power:

$$P_t = 35 \text{ W} = 35{,}000 \text{ mW}$$

$$P_t(\text{dBm}) = 10\log_{10}(35000) = 45.44 \text{ dBm}$$

Wavelength:

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{30\times10^9} = 0.01 \text{ m}$$

Antenna Gain Formula:

$$G = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

$$G_{\text{dBi}} = 10\log_{10}(G)$$

Transmit Antenna Gain $(D_t = 0.2 \text{ m}, \eta = 0.6)$:

$$G_t = 0.6\left(\frac{\pi(0.2)}{0.01}\right)^2 = 0.6(62.83)^2 = 2368.7$$

$$G_t(\text{dBi}) = 10\log_{10}(2368.7) = 33.75 \text{ dBi}$$

Ground Station Gain $(D_r = 13 \text{ m}, \eta = 0.6)$:

$$G_r = 0.6\left(\frac{\pi(13)}{0.01}\right)^2 = 0.6(4084.07)^2 = 1.001\times10^7$$

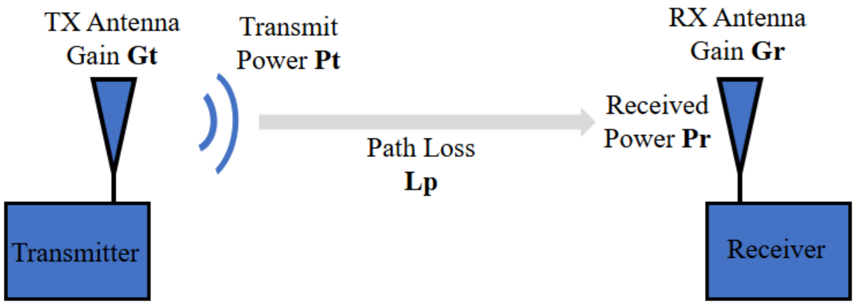
$$G_r(\text{dBi}) = 10\log_{10}(1.001\times10^7) = 70.01 \text{ dBi}$$

Link Budget $(L = 241 \text{ dB})$:

$$\begin{aligned} P_r &= P_t + G_t + G_r - L \\ &= 45.44 + 33.75 + 70.01 - 241 \\ &= -91.8 \text{ dBm} \end{aligned}$$

- Link margin is at least 5 dB
- NSN minimum signal strength for detection -100 dBm

32

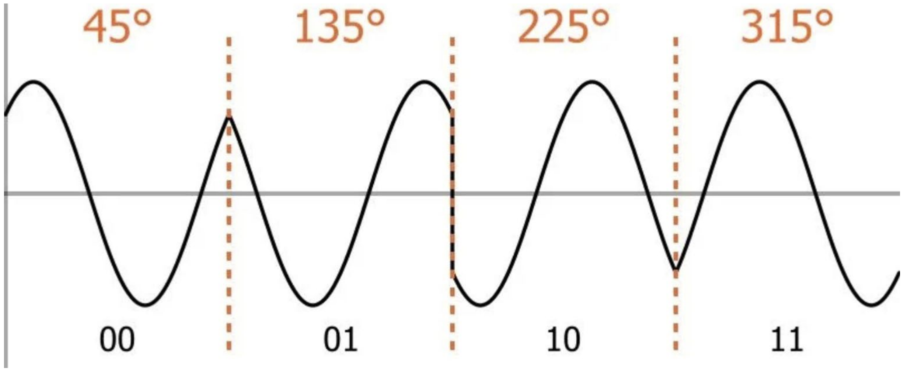


Frequency Modulation

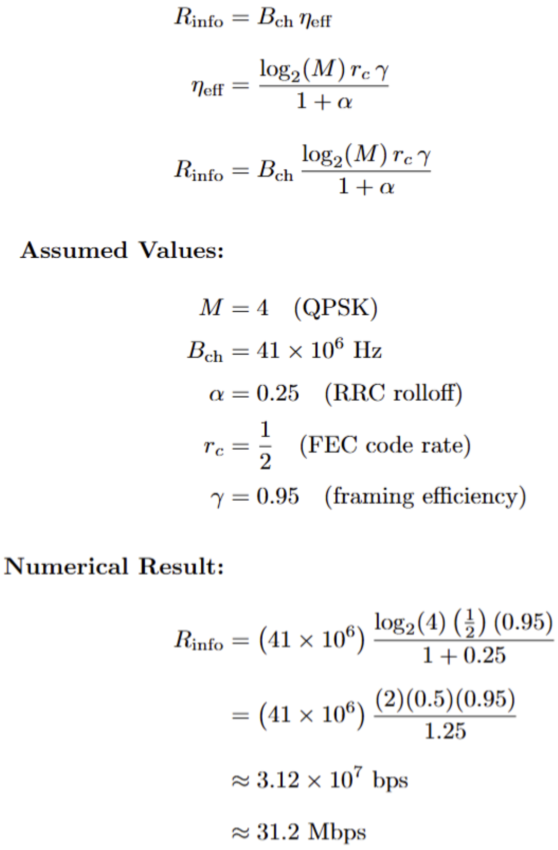
- GMSK is a possibility
  - Power efficient
  - Struggles in high S/N
- QPSK is an ideal
  - Decent data rate
  - Efficient use of bandwidth
  - Common in transceivers
  - Resilient in high S/N environments
- QAM-16 for high data rates
  - Offers high data rates (4 bits/sym)
  - Struggles in high S/N

QPSK Modulation

Slightly misleading, each symbol should stretch over several periods



Data Transmission Rates



$$R_{\text{info}} = B_{\text{ch}}\,\eta_{\text{eff}}$$

$$\eta_{\text{eff}} = \frac{\log_2(M)\,r_c\,\gamma}{1+\alpha}$$

$$R_{\text{info}} = B_{\text{ch}}\,\frac{\log_2(M)\,r_c\,\gamma}{1+\alpha}$$

Assumed Values:

$$M = 4 \quad \text{(QPSK)}$$
$$B_{\text{ch}} = 41 \times 10^6\ \text{Hz}$$
$$\alpha = 0.25 \quad \text{(RRC rolloff)}$$
$$r_c = \frac{1}{2} \quad \text{(FEC code rate)}$$
$$\gamma = 0.95 \quad \text{(framing efficiency)}$$

Numerical Result:

$$R_{\text{info}} = (41 \times 10^6)\,\frac{\log_2(4)\left(\frac{1}{2}\right)(0.95)}{1+0.25}$$
$$= (41 \times 10^6)\,\frac{(2)(0.5)(0.95)}{1.25}$$
$$\approx 3.12 \times 10^7\ \text{bps}$$
$$\approx 31.2\ \text{Mbps}$$

- Data rate is largely determined by
  - Allowed bandwidth
  - Modulation scheme
- Terms
  - Rolloff → how much extra bandwidth signal occupies
  - FEC → transmitting a copy of the data
  - Framing efficiency → percent of transmitted bits that are payload
- 3.9 MBps
- 6 hour 25 min transmit time

System Noise

Noise Spectral Density $(T = 400\ \text{K})$:

$$\begin{aligned} N_0 &= kT \\ N_0 &= (1.38 \times 10^{-23})(400) \\ &= 5.52 \times 10^{-21}\ \text{W/Hz} \end{aligned}$$

Energy Per Bit:

$$\begin{aligned} R_b &= 32.1 \times 10^6\ \text{bps} \\ E_b &= \frac{P_r}{R_b} \\ &= \frac{6.61 \times 10^{-13}}{32.1 \times 10^6} \\ &\approx 2.06 \times 10^{-20}\ \text{J} \end{aligned}$$

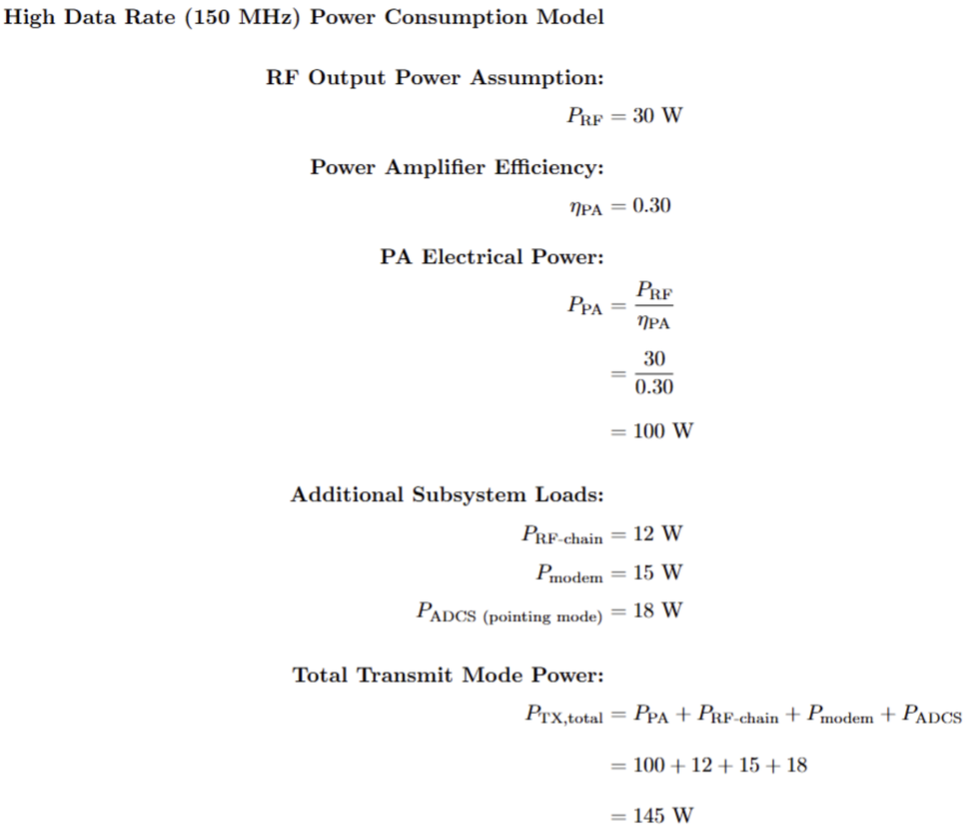
Energy per Bit to Noise Density Ratio:

$$\begin{aligned} \frac{E_b}{N_0} &= \frac{2.06 \times 10^{-20}}{5.52 \times 10^{-21}} \\ &\approx 3.73 \end{aligned}$$

$$\begin{aligned} \left(\frac{E_b}{N_0}\right)_{\text{dB}} &= 10 \log_{10}(3.73) \\ &\approx 5.72\ \text{dB} \end{aligned}$$

- Eb/N0 → Energy per bit to noise power spectral density ratio
- Measure of how much energy a bit has compared to noise of channel
- Thermal noise at 400K assumed for calculations
- Eb/N0 must be at least 4 dB for coded QPSK

Power Usage of Comms System



High Data Rate (150 MHz) Power Consumption Model

RF Output Power Assumption:

$$P_{\text{RF}} = 30\ \text{W}$$

Power Amplifier Efficiency:

$$\eta_{\text{PA}} = 0.30$$

PA Electrical Power:

$$\begin{aligned} P_{\text{PA}} &= \frac{P_{\text{RF}}}{\eta_{\text{PA}}} \\ &= \frac{30}{0.30} \\ &= 100\ \text{W} \end{aligned}$$

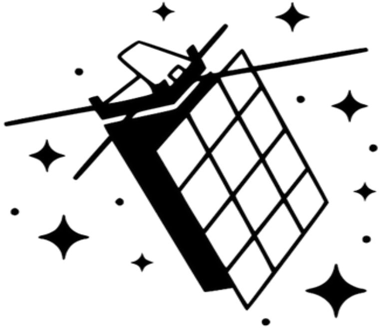
Additional Subsystem Loads:

$$\begin{aligned} P_{\text{RF-chain}} &= 12\ \text{W} \\ P_{\text{modem}} &= 15\ \text{W} \\ P_{\text{ADCS (pointing mode)}} &= 18\ \text{W} \end{aligned}$$

Total Transmit Mode Power:

$$\begin{aligned} P_{\text{TX,total}} &= P_{\text{PA}} + P_{\text{RF-chain}} + P_{\text{modem}} + P_{\text{ADCS}} \\ &= 100 + 12 + 15 + 18 \\ &= 145\ \text{W} \end{aligned}$$

- High power amplifier accounts for majority of energy usage
- Higher frequencies → amplifier less efficient
- The communication system on JWST is 170 W
    - HS-3’s comm system has similar energy usage
- Cubesat Ka-Band transceivers are available



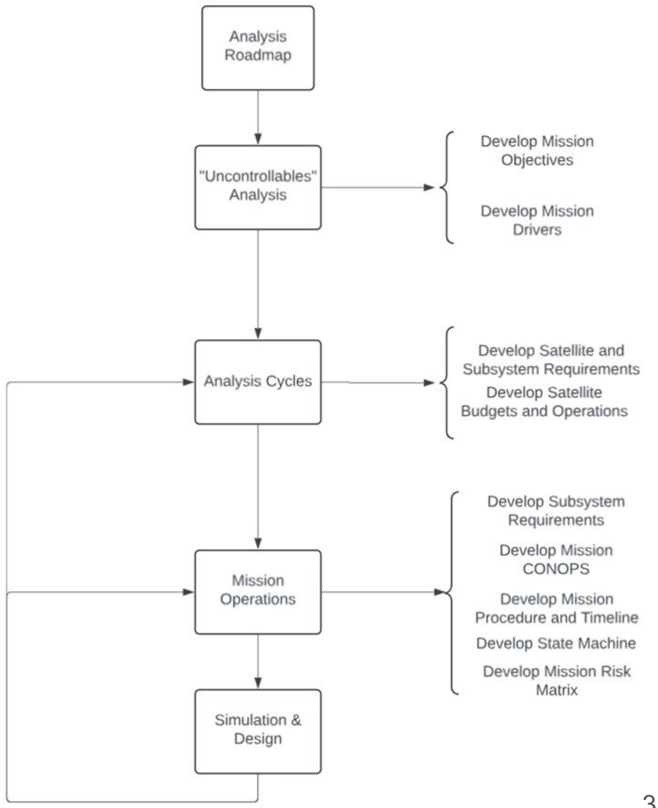
Analysis Roadmap

Analysis Roadmap

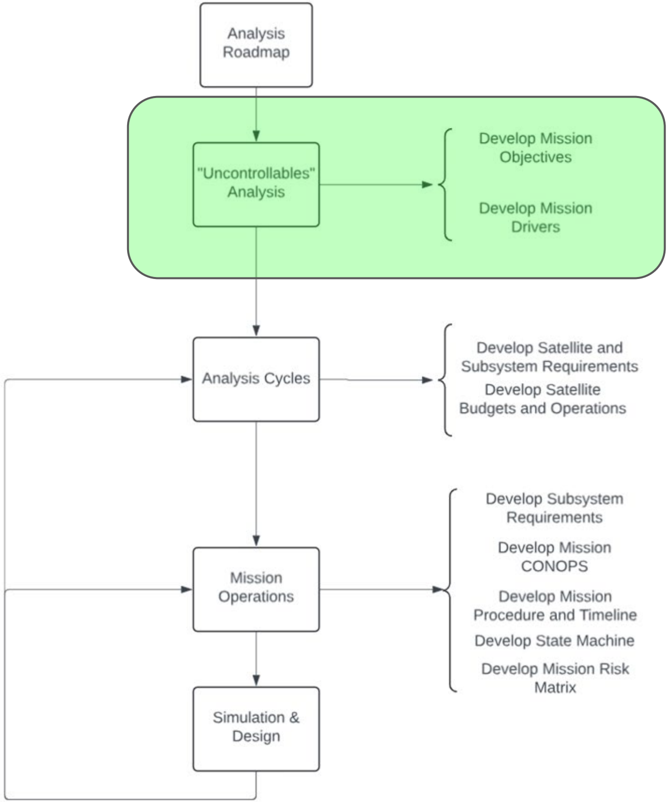
- Operationally, HS-3 is experimenting with new methods of mission development to find more efficient and mathematically-sound avenues

- Large emphasis on mathematical rationale, fast faced analysis (standardization), and a no-go-back attitude towards requirement development.

- Other important benefits:
    - Preventing paralysis by analysis
    - Clean, top-down flow of requirements



Uncontrollables Analysis



Analysis Roadmap

"Uncontrollables" Analysis

Develop Mission Objectives

Develop Mission Drivers

Analysis Cycles

Develop Satellite and Subsystem Requirements

Develop Satellite Budgets and Operations

Mission Operations

Develop Subsystem Requirements

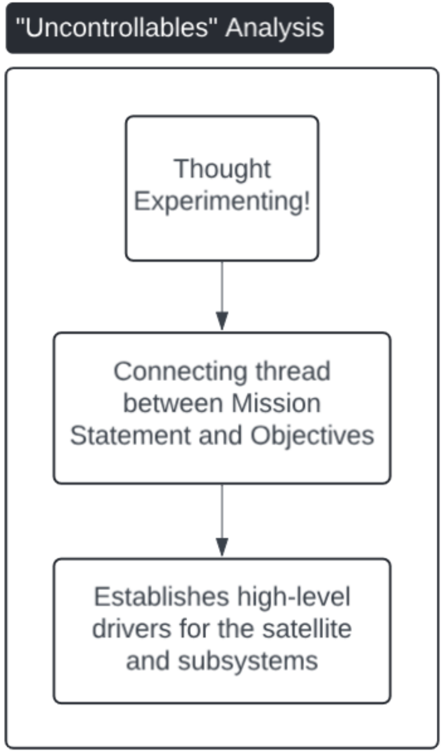
Develop Mission CONOPS

Develop Mission Procedure and Timeline

Develop State Machine

Develop Mission Risk Matrix

Simulation & Design



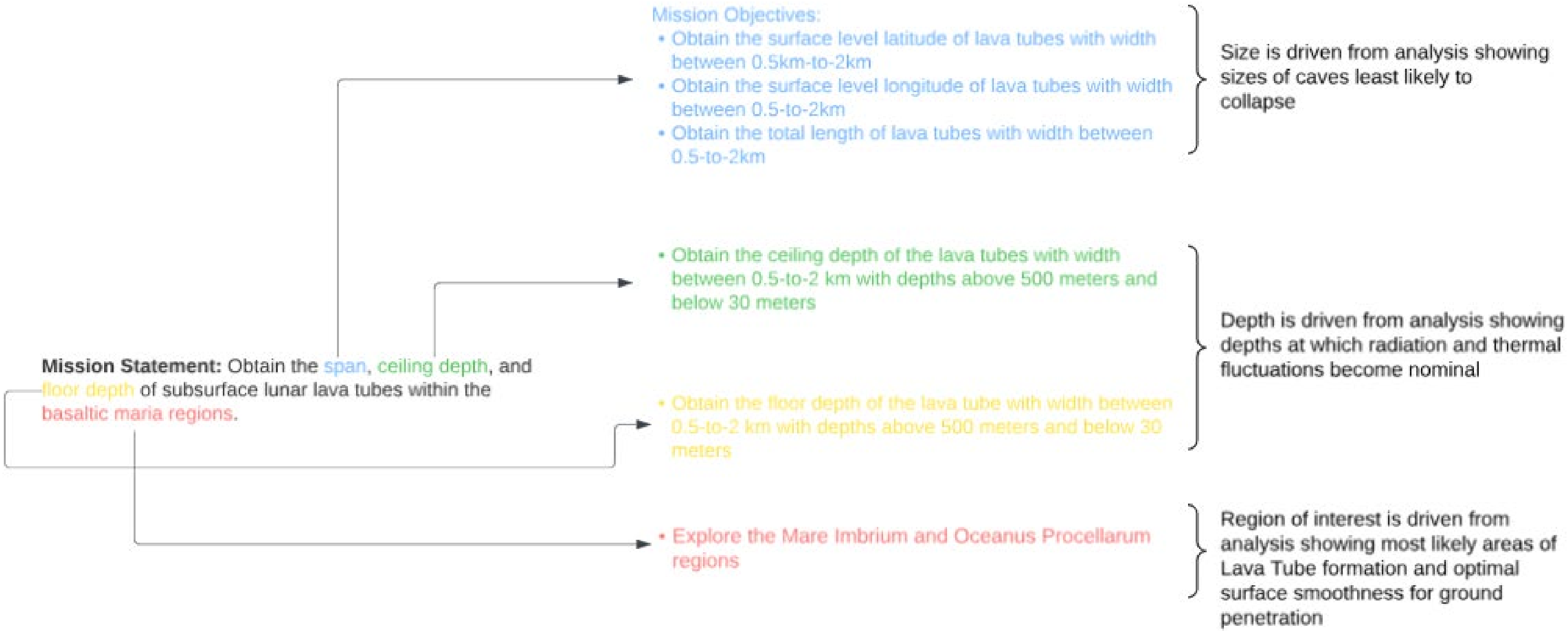
"Uncontrollables" Analysis

Thought Experimenting!

Connecting thread between Mission Statement and Objectives

Establishes high-level drivers for the satellite and subsystems

Mission Statement → Objectives



Mission Statement: Obtain the span, ceiling depth, and floor depth of subsurface lunar lava tubes within the basaltic maria regions.

Mission Objectives:

- Obtain the surface level latitude of lava tubes with width between 0.5km-to-2km
- Obtain the surface level longitude of lava tubes with width between 0.5-to-2km
- Obtain the total length of lava tubes with width between 0.5-to-2km

Size is driven from analysis showing sizes of caves least likely to collapse

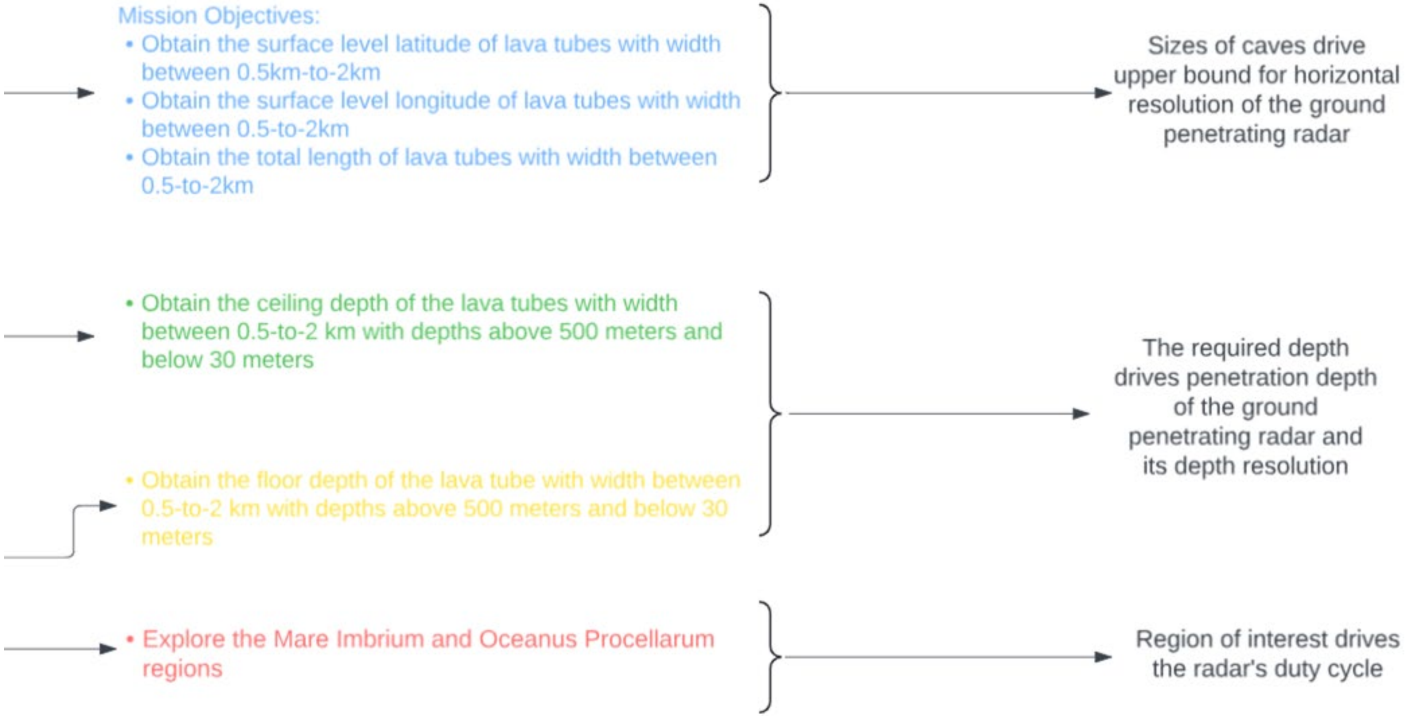
- Obtain the ceiling depth of the lava tubes with width between 0.5-to-2 km with depths above 500 meters and below 30 meters
- Obtain the floor depth of the lava tube with width between 0.5-to-2 km with depths above 500 meters and below 30 meters

Depth is driven from analysis showing depths at which radiation and thermal fluctuations become nominal

- Explore the Mare Imbrium and Oceanus Procellarum regions

Region of interest is driven from analysis showing most likely areas of Lava Tube formation and optimal surface smoothness for ground penetration

Mission Objectives → High-level drivers



Mission Objectives:

- Obtain the surface level latitude of lava tubes with width between 0.5km-to-2km
- Obtain the surface level longitude of lava tubes with width between 0.5-to-2km
- Obtain the total length of lava tubes with width between 0.5-to-2km

Sizes of caves drive upper bound for horizontal resolution of the ground penetrating radar

- Obtain the ceiling depth of the lava tubes with width between 0.5-to-2 km with depths above 500 meters and below 30 meters

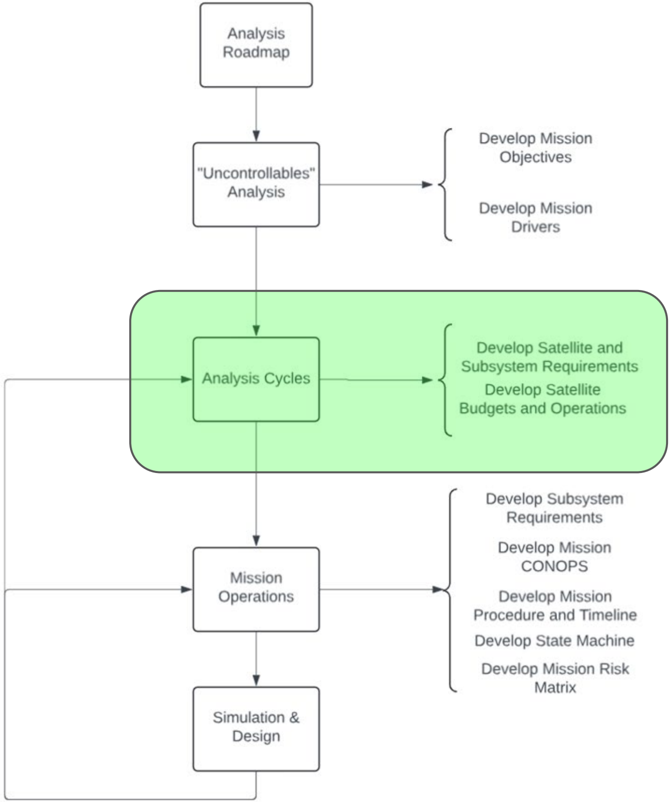
- Obtain the floor depth of the lava tube with width between 0.5-to-2 km with depths above 500 meters and below 30 meters

The required depth drives penetration depth of the ground penetrating radar and its depth resolution

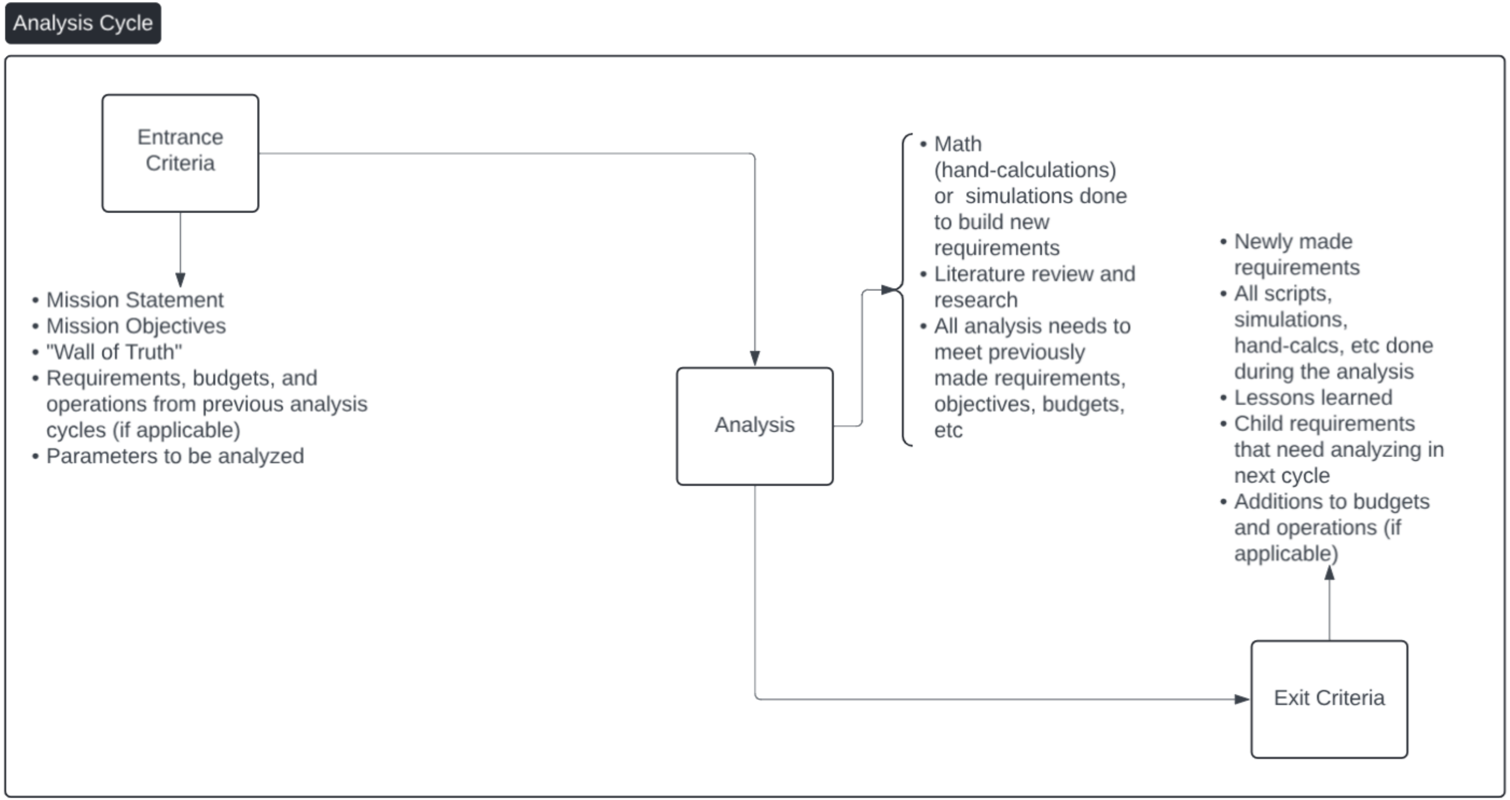
- Explore the Mare Imbrium and Oceanus Procellarum regions

Region of interest drives the radar's duty cycle

Analysis Cycles



Analysis Cycles



Analysis Cycle

Entrance Criteria

- Mission Statement
- Mission Objectives
- "Wall of Truth"
- Requirements, budgets, and operations from previous analysis cycles (if applicable)
- Parameters to be analyzed

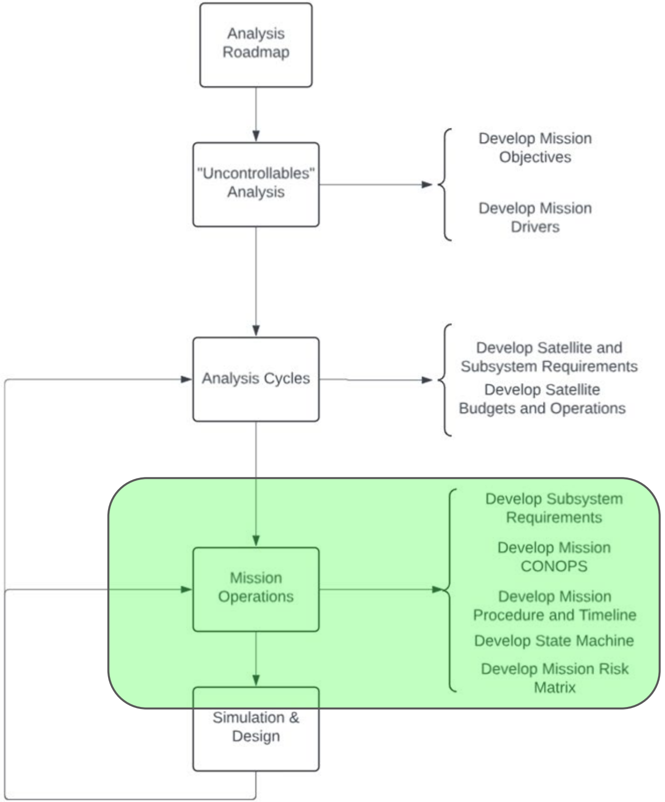
Analysis

- Math (hand-calculations) or simulations done to build new requirements
- Literature review and research
- All analysis needs to meet previously made requirements, objectives, budgets, etc

Exit Criteria

- Newly made requirements
- All scripts, simulations, hand-calcs, etc done during the analysis
- Lessons learned
- Child requirements that need analyzing in next cycle
- Additions to budgets and operations (if applicable)

Mission Operations



Analysis Roadmap

"Uncontrollables" Analysis

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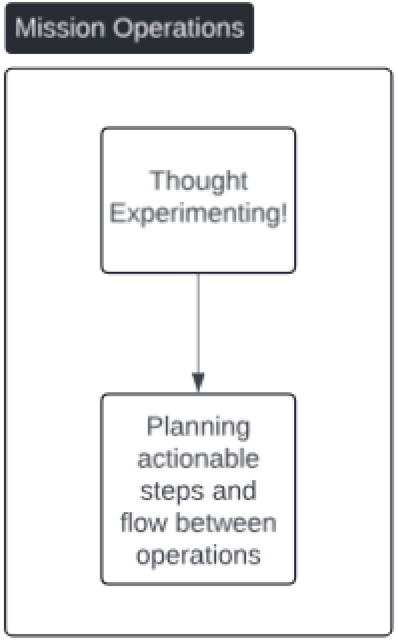
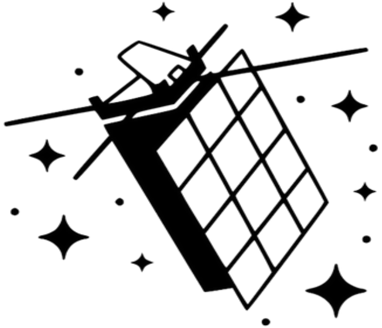


Mission Operations

Thought Experimenting!

Planning actionable steps and flow between operations



Mission Objective Analysis (Uncontrollables)

HuskySat-3’s Mission Statement

HuskySat-3 shall obtain the ***span*****,** ***ceiling depth*****,** *and* ***floor depth*** *of subsurface lunar lava tube caves within the* ***Basaltic Maria*** *regions*

Cycle 1 Mission Objectives

Current MS: Obtain the span, ceiling depth, and floor depth of subsurface lunar lava tubes within the basaltic maria regions.

Thoughts/considerations: Should we have a bottom limit for the depth? Is it okay to create primary stages based on ground commands???

MO.1: Obtain the surface level latitude of lava tubes with width between TBD-to-TBD meters with an accuracy of TBD

MO.2: Obtain the surface level longitude of lava tubes with width between TBD-to-TBD meters with an accuracy of TBD

MO.3: Obtain the total length of lava tubes with width between TBD-to-TBD meters with an accuracy of TBD

Thoughts/considerations: Should there be a packet loss of some kind? Error percentage over the span?? Should we have some sort of bottom limit as to how many it needs to find? Is just laying down accuracy enough to pull down requirements from these objectives?

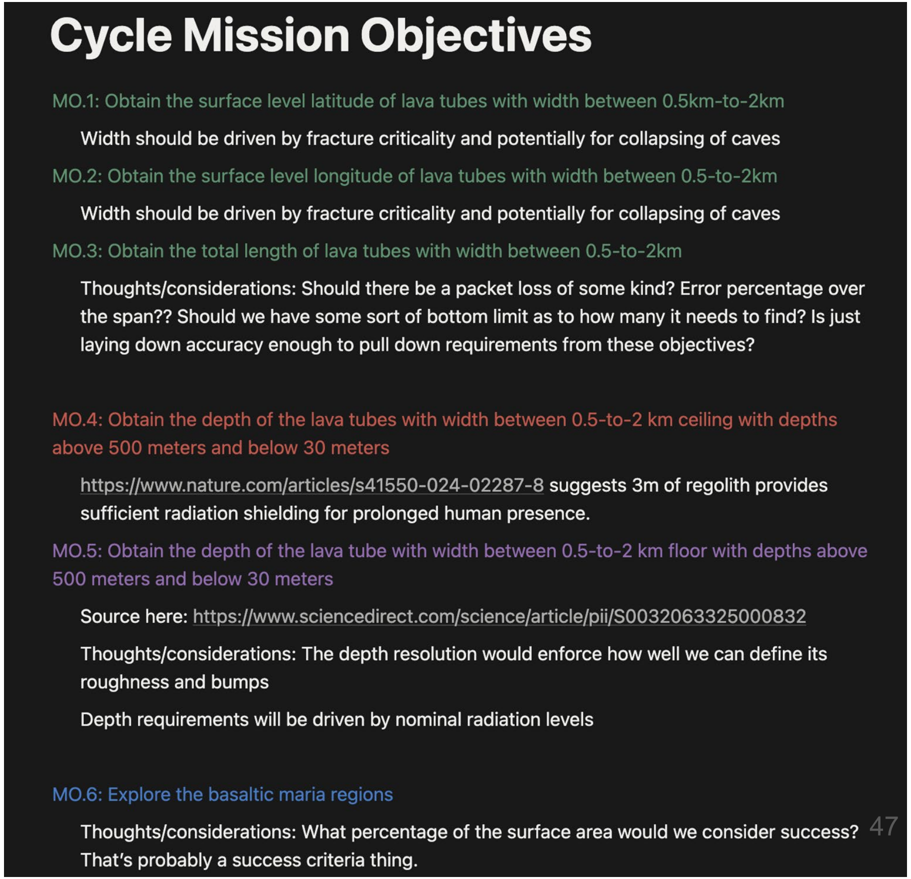
MO.4: Obtain the depth of the lava tubes with width between TBD-to-TBD meters ceiling with an accuracy of TBD at depths above 500(TBR) meters

MO.5: Obtain the depth of the lava tube with width between TBD-to-TBD meters floor with an accuracy of TBD at depths above 500(TBR) meters

Thoughts/considerations: The depth resolution would enforce how well we can define its roughness and bumps

MO.6: Explore the basaltic maria regions with an accuracy of TBD with a margin of TBD percent in total surface area

Thoughts/considerations: What percentage of the surface area would we consider success? That's probably a success criteria thing.



Cycle Mission Objectives

MO.1: Obtain the surface level latitude of lava tubes with width between 0.5km-to-2km

Width should be driven by fracture criticality and potentially for collapsing of caves

MO.2: Obtain the surface level longitude of lava tubes with width between 0.5-to-2km

Width should be driven by fracture criticality and potentially for collapsing of caves

MO.3: Obtain the total length of lava tubes with width between 0.5-to-2km

Thoughts/considerations: Should there be a packet loss of some kind? Error percentage over the span?? Should we have some sort of bottom limit as to how many it needs to find? Is just laying down accuracy enough to pull down requirements from these objectives?

MO.4: Obtain the depth of the lava tubes with width between 0.5-to-2 km ceiling with depths above 500 meters and below 30 meters

https://www.nature.com/articles/s41550-024-02287-8 suggests 3m of regolith provides sufficient radiation shielding for prolonged human presence.

MO.5: Obtain the depth of the lava tube with width between 0.5-to-2 km floor with depths above 500 meters and below 30 meters

Source here: https://www.sciencedirect.com/science/article/pii/S0032063325000832

Thoughts/considerations: The depth resolution would enforce how well we can define its roughness and bumps

Depth requirements will be driven by nominal radiation levels

MO.6: Explore the basaltic maria regions

Thoughts/considerations: What percentage of the surface area would we consider success? That's probably a success criteria thing.

Cycle 1 Mission Objectives

MO.1: Obtain the surface level latitude of lava tubes with width between 0.5km-to-2km

MO.2: Obtain the surface level longitude of lava tubes with width between 0.5-to-2km

MO.3: Obtain the total length of lava tubes with width between 0.5-to-2km

MO.4: Obtain the depth of the lava tubes with width between 0.5-to-2 km ceiling with depth between 50-to-250m

MO.5: Obtain the depth of the lava tube with width between 0.5-to-2 km floor with depth between 50-to-250m

MO.6: Collect data from lava tubes in the Mare Imbrium and Oceanus Procellarum regions

Lunar Lava Tube Specifications - Overview

MISSION OBJECTIVES

MO.1	**Surface Latitude**	Lava tubes with width 0.5 – 2 km
MO.2	**Surface Longitude**	Lava tubes with width 0.5 – 2 km
MO.3	**Total Length**	Lava tubes with width 0.5 – 2 km
MO.4	**Ceiling Depth**	Width 0.5–2 km, depth 50 – 250 m
MO.5	**Floor Depth**	Width 0.5–2 km, depth 50 – 250 m

TUBE SIZE SPECIFICATIONS

TARGET RANGE: 0.5 – 2 km width | MEDIUM to LARGE classification

SMALL

Width: 50–300 m

Roof: 2–20 m

GPR: <30 m / 500 MHz

HIGH

0.2–1.0 MPa

tensile req.

MEDIUM ★

Width: 300–1,000 m

Roof: 50–150 m

GPR: 60–500 MHz

MOD-HIGH

0.5–1.5 MPa

tensile req.

LARGE

Width: 1,000–5,000 m

Roof: 200–1,000 m

GPR: >150 m / low-freq

MODERATE

1.0–2.5 MPa

tensile req.

Lunar Lava Tube - Key Eqns & Collapse Factors

KEY EQUATIONS

Cross Section (Height)

$$H = k \times W$$

H = height   W = width   k = aspect ratio (≈0.33 for 3:1)

Max Stable Width

$$W\_max = C(\sigma / \rho g)$$

σ = tensile strength (1–3 MPa) ρ = 3,000 kg/m³   g = 1.62 m/s²   C = 0.5–1.0

Roof Thickness

$$T = (0.3 - 0.5) \times W$$

T = roof thickness   W = tube width

Depth to Tube Center

$$D = T = H / 2$$

D = depth to center   T = roof thickness   H = tube height

GPR Detectability

$$\lambda = v / f$$

Tube detectable if dimensions ≥ GPR wavelength λ v = wave velocity in basalt   f = frequency

COLLAPSE TRIGGERS & STABILITY FACTORS

HIGH	**Shallow Moonquakes** M 5.5 events at 50–100 km depth; largest seismic threat. 28 events in 8 years.
MOD	**Meteoroid Impacts** Primary surface trigger. Roof-penetrating craters 50–500 m diameter. Threshold: T/D ≈ 0.7.
MOD-LOW	**Thermal Cycling** 12,000+ thermal moonquakes found (Civilini 2023). Cumulative crack growth over 3B+ years.
LOW	**Deep Moonquakes** 700–1,100 km depth, M < 2. Tidal origin. Too deep for direct collapse but fatigue contributor.

KEY STRUCTURAL NOTES

- **Mare Tranquillitatis pit (2024):** First confirmed accessible lunar cave — 40–100m wide, 130–170m deep
- **Width-to-height ratio:** Typically 3:1 | Width:roof ≥ 0.3–0.5×W | 5 km = max stable configuration

Thermal Specifications

SURFACE THERMAL ENVIRONMENT

☀ DAY

+150°C

Direct solar irradiance

NIGHT

-150°C

No solar input

300°C swing every 29.5 Earth days (lunar day cycle)

SURFACE TEMPERATURE (LST) AFFECTED BY:

- → Solar irradiance (primary driver)
- → Earthshine contribution
- → Heat flow for flat mare regions

HABITATION CONCLUSION

Any tube depth > 15 cm is effectively insulated from surface extremes. **Optimal:** 15–20 cm below surface — variation drops to 1–3°C, stabilizing near 0°C mean.

TEMPERATURE vs. DEPTH

0 cm — SURFACE	`-150 to +150°C`	Extreme swing — uninhabitable
~3 cm depth	`±37°C (25% of swing)`	1× skin depth — still significant
~6 cm depth	`±14°C (9% of swing)`	2× skin depth — improving
~9 cm depth	`±5°C (3% of swing)`	3× skin depth — approaching stable
~13 cm depth ★	`±1.5°C (1% of swing)`	Negligible variation — habitable zone begins
~20 cm depth	`±0.3°C (0.1% swing)`	Thermally stable — optimal for habitation

★ Skin depth $\delta \approx 2.9$ cm | Variation = $\Delta T\_surface \times \exp(-x/\delta)$ | Surface ΔT = 300°C total swing

Thermal Specifications - Models and Eqns

THERMAL DIFFUSION MODEL

1D Thermal Diffusion (Carslaw & Jaeger)

$$\partial T/\partial t = \partial/\partial x[K(\partial T/\partial x)/\rho c] + Qt/\rho c$$

K = thermal conductivity ρ = bulk density c = heat capacity Qt = radiative term

Thermal Conductivity (depth-dependent)

$$K(T) = Kc(1 + \chi \cdot T^3)$$

Top 2cm: Kc = 9.2×10^{-4} W/mK, $\chi = 1.48$ Deep: Kc = 9.3×10^{-3} W/mK, $\chi = 0.073$

Temperature vs Depth

$$T(x) = T\_surface \times \exp(-x/\delta)$$

x = depth δ = thermal skin depth T_surface = surface temperature amplitude

Thermal Skin Depth

$$\delta = \sqrt{(2\kappa/\omega)}$$

κ = thermal diffusivity = K/(ρc) ω = angular frequency of temp cycle

WORKED CALCULATION — OPTIMAL DEPTH

01 **Thermal Diffusivity κ**

$$\kappa = K/(\rho c) = (9.2\times10^{-4})/(1500\times600)$$

$$\rightarrow \kappa = 1.02\times10^{-9}\ \mathrm{m^2/s}$$

02 **Lunar Day Angular Frequency ω**

$$\omega = 2\pi / 2.55\times10^{6}\ \mathrm{s}$$

$$\rightarrow \omega = 2.46\times10^{-6}\ \mathrm{rad/s}$$

03 **Thermal Skin Depth δ**

$$\delta = \sqrt{(2 \times 1.02\times10^{-9} / 2.46\times10^{-6})}$$

$$\rightarrow \delta \approx 2.9\ \mathrm{cm}$$

04 **Depth for 1% Variation (±1.5°C)**

$$\exp(-x/\delta) = 0.01 \rightarrow x = \delta \times \ln(100)$$

$$\rightarrow x = 2.9 \times 4.6 \approx 13.3\ \mathrm{cm}$$

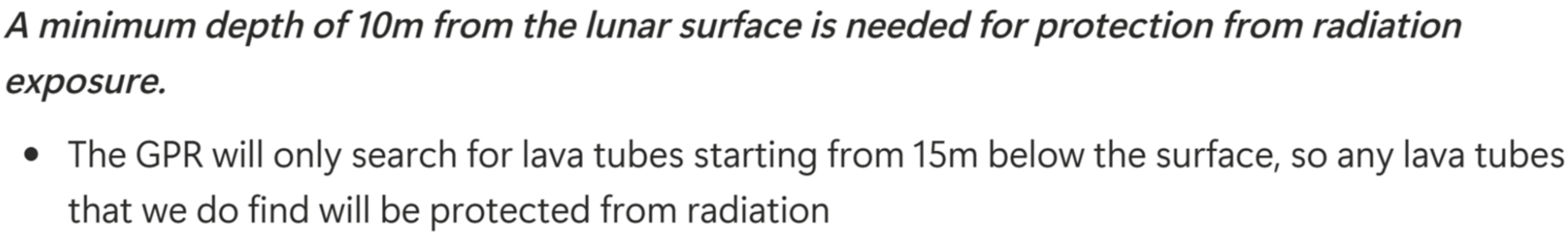
05 **Depth for 0.1% Variation (±0.3°C)**

$$\exp(-x/\delta) = 0.001 \rightarrow x = \delta \times \ln(1000)$$

$$\rightarrow x = 2.9 \times 6.9 \approx 20\ \mathrm{cm}$$

Model: 1D thermal diffusion (Carslaw & Jaeger) | Regolith: K=9.2×10^{-4} W/mK, ρ=1500 kg/m³, c=600 J/kgK | Result: 15–20 cm optimal habitation depth

Radiation Specifications



A minimum depth of 10m from the lunar surface is needed for protection from radiation exposure.

- The GPR will only search for lava tubes starting from 15m below the surface, so any lava tubes that we do find will be protected from radiation

"By sheltering under only 500 g/cm2 of lunar regolith (a little more than 3 meters), the effective dose is reduced to roughly 20 times the public dose. Once the regolith thickness reaches 1200 g/cm2 (7.5 meters) or more, **the effective dose drops below that experienced by humans on Earth, and is truly negligible for overburden of 1500 g/cm2 or greater (10 meters).**"

Mare Imbrium and Oceanus Procellarum Rationale

Collect data from lava tubes in Mare Imbrium and Oceanus Procellarum

MARE IMBRIUM

Formation: Impact basin flooded by lava ~3.9 Ga

Key Features:

- Basaltic mare plains, primary lava tube-forming geology
- Adjacent Carpathian Mountains provide tube network potential near crater edges
- Chang'e-3 confirmed 1–6m ejecta layers, evidence of layered volcanic stratigraphy
- Near-side orbital access = superior radar coverage (LRO, Kaguya)
- Hadley Rille, a sinuous rille or winding canyon, believed to be a collapsed lava tube or a lava channel that went into tubes

OCEANUS PROCELLARUM

Scale: Largest mare (~4M km²) — single largest basaltic region on Moon

Key Features:

- Hosts Marius Hills — highest concentration of confirmed skylights and lava tubes
- Basaltic plains formed from ancient effusive eruptions, ideal tube-forming conditions
- Tubes up to 500m wide detected; lower lunar gravity enables larger stable structures
- Skylights confirmed via Kaguya & LRO imaging = direct subsurface access points
- Rima Prinz, a sinuous rille, believed to be a collapsed lava tube or a lava channel that went into tubes

Geological Rationale: Both regions are basaltic maria — the only lunar terrain where lava tubes form and are the smoothest on the moon making it ideal for GPR. Together they represent the highest confirmed tube density accessible from near-side orbit, directly satisfying width (0.5–2km) and depth (50–250m).

Cycle 1 Mission Objectives

MO.1: Obtain the surface level latitude of lava tubes with width between 0.5km-to-2km

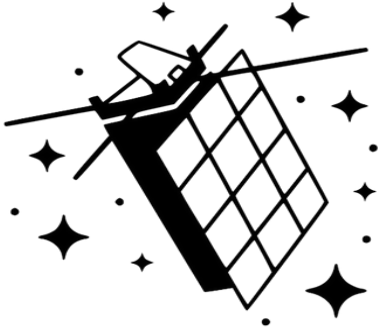
MO.2: Obtain the surface level longitude of lava tubes with width between 0.5-to-2km

MO.3: Obtain the total length of lava tubes with width between 0.5-to-2km

MO.4: Obtain the depth of the lava tubes with width between 0.5-to-2 km ceiling with depth between 50-to-250m

MO.5: Obtain the depth of the lava tube with width between 0.5-to-2 km floor with depth between 50-to-250m

MO.6: Collect data from lava tubes in the Mare Imbrium and Oceanus Procellarum regions

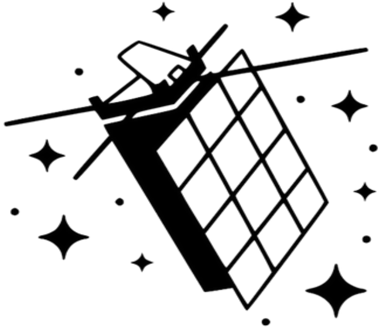


Requirement Analysis

Coming up!

[All red sections will be omitted from this presentation]
What composes the rest of the mission development:

- Satellite analysis
  - Uncontrollable drivers
  - Orbital trajectory
- Subsystem analysis
  - Ground penetrating radar
  - Propulsion
  - Communications
  - Optical navigation
  - Structures
  - Electrical systems
- Budget analysis:
  - Power
  - Data
- Concept of Operations
  - Order of Operations
  - Autonomy
  - Flight Software
  - Risk management



Satellite Requirements

Drivers

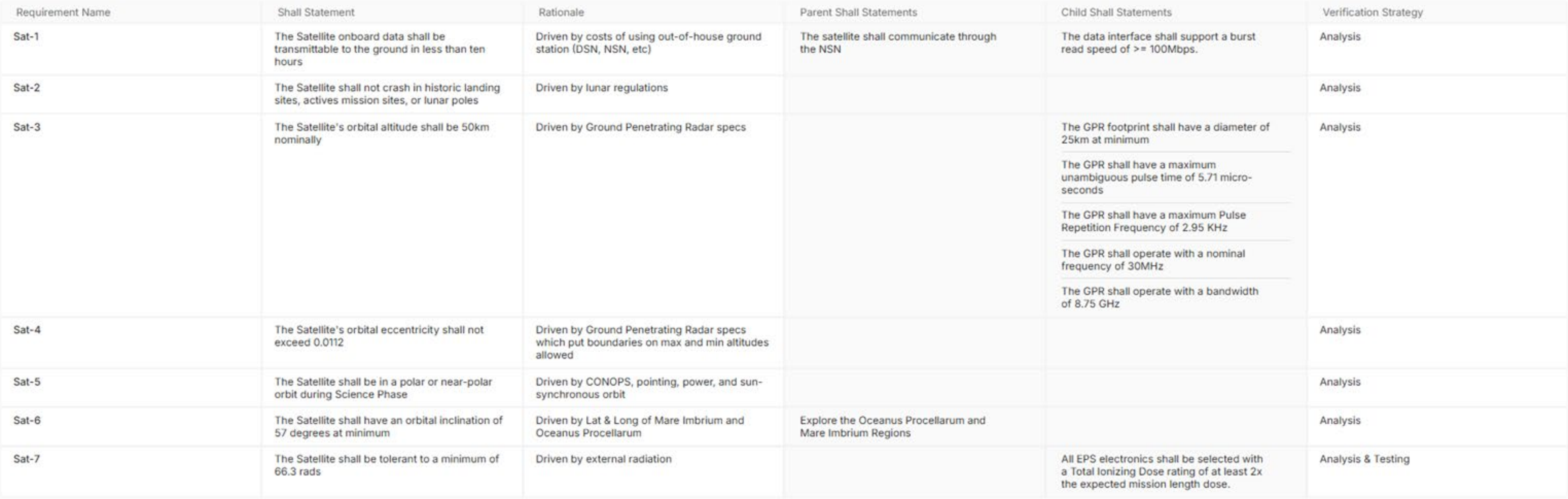
Uncontrollable drivers behind Sat requirements:

- Latitude & Longitude of Mare Imbrium and Oceanus Procellarum
- Sun-synchronous inclination requirements
- Radiation
- Legal Regulations

Controllable drivers behind Sat requirements:

- Ground penetrating radar specs
- Power
- Pointing
- CONOPS

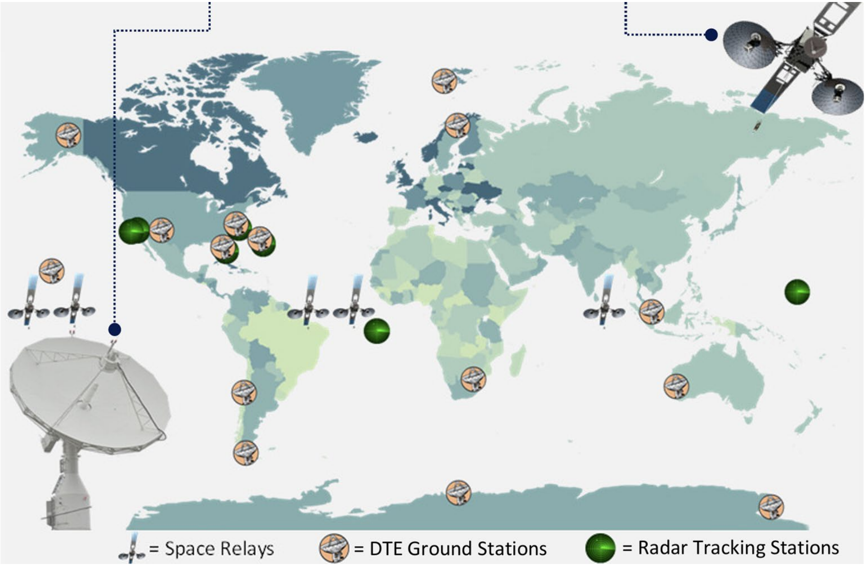
Satellite Requirements Overview



Requirement Name	Shall Statement	Rationale	Parent Shall Statements	Child Shall Statements	Verification Strategy
Sat-1	The Satellite onboard data shall be transmittable to the ground in less than ten hours	Driven by costs of using out-of-house ground station (DSN, NSN, etc)	The satellite shall communicate through the NSN	The data interface shall support a burst read speed of >= 100Mbps.	Analysis
Sat-2	The Satellite shall not crash in historic landing sites, actives mission sites, or lunar poles	Driven by lunar regulations			Analysis
Sat-3	The Satellite's orbital altitude shall be 50km nominally	Driven by Ground Penetrating Radar specs		The GPR footprint shall have a diameter of 25km at minimum The GPR shall have a maximum unambiguous pulse time of 5.71 micro-seconds The GPR shall have a maximum Pulse Repetition Frequency of 2.95 KHz The GPR shall operate with a nominal frequency of 30MHz The GPR shall operate with a bandwidth of 8.75 GHz	Analysis
Sat-4	The Satellite's orbital eccentricity shall not exceed 0.0112	Driven by Ground Penetrating Radar specs which put boundaries on max and min altitudes allowed			Analysis
Sat-5	The Satellite shall be in a polar or near-polar orbit during Science Phase	Driven by CONOPS, pointing, power, and sun-synchronous orbit			Analysis
Sat-6	The Satellite shall have an orbital inclination of 57 degrees at minimum	Driven by Lat & Long of Mare Imbrium and Oceanus Procellarum	Explore the Oceanus Procellarum and Mare Imbrium Regions		Analysis
Sat-7	The Satellite shall be tolerant to a minimum of 66.3 rads	Driven by external radiation		All EPS electronics shall be selected with a Total Ionizing Dose rating of at least 2x the expected mission length dose.	Analysis & Testing

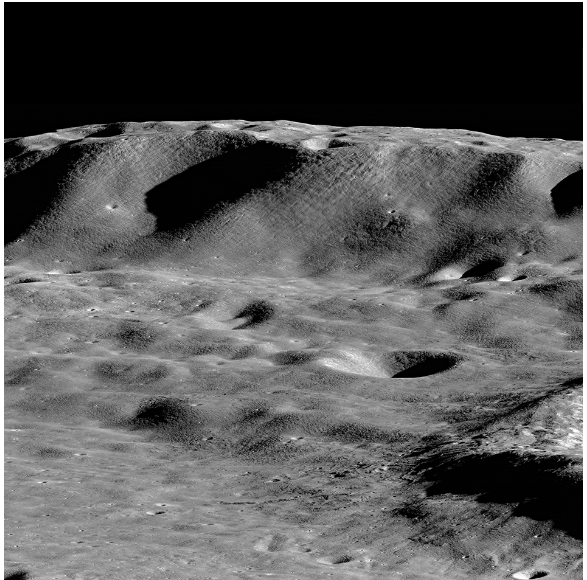
The Near Space Network (NSN)

- The near Earth counterpart to DSN
- Supports higher frequencies and data rates
- For satellites within 2 million km of earth
- Wide coverage, so comms link can be established when HS-3 is facing earth
- Less strained than DSN



Satellite Altitude & Eccentricity

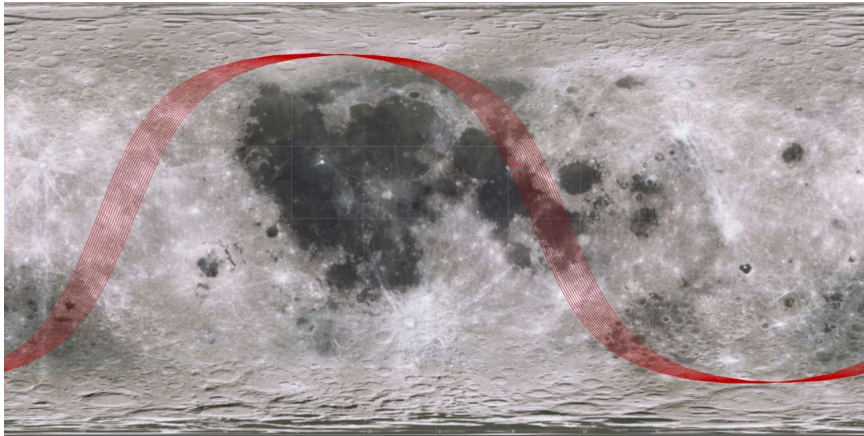
- Low-bound determined by marginal safety from mountain impact with the moon
- High bound determined by Signal-to-Noise ratio
- “Sweet spot” determined by ground penetrating radar specifications



Satellite inclination

Two uncontrollable drivers:

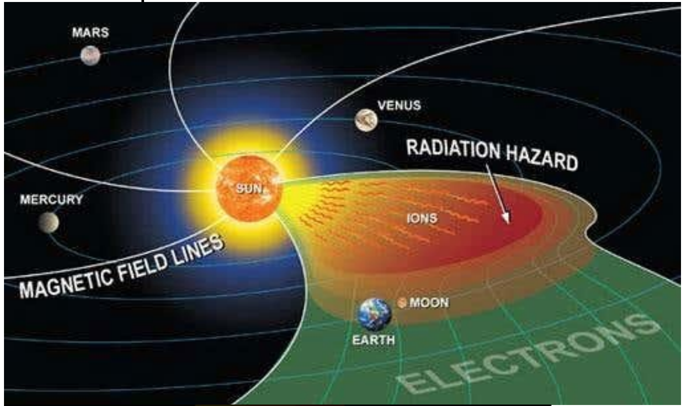
- Required sun-synchronous inclination based on J2 effects: ~ 86 degrees
- Required minimum inclination based on minimum longitude of region of interest: ~57 degrees
- Sat inclination will be ~86 degrees
    - Best for mapping, minimizes pointing requirements

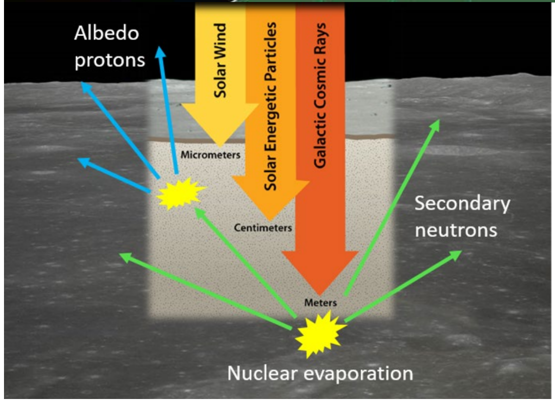


Radiation

The numbers below represent the incident radiation, not internal.
LLO Phase:

Orbital period = 118 min = 1.88 Hrs





Radiation Sources:

- Galactic Cosmic Rays : ~5.3μGy / orbit
- Solar Particle Events : ~6.6μGy / orbit
  - During major events, can increase by 10-100x
  - (In the last 50 years, we have had only 1 or 2 large SPEs per 11-yr solar cycle).
- Secondary Radiation from Lunar Surface adds 30-50% to the primary dose

Adding these numbers:

- Nominal: 15μGy / orbit
- Worst-case (Solar Max + Major SPE): 290μGy / orbit

During the transfer phase, the secondary radiation decreases, so these numbers hold as a worst-case for all phases of the mission.

Pictures: https://www.aeronomie.be/sites/default/files/2021-04/1-10-Fig1-NuclearEvaporation-focus.png
https://encrypted-tbn0.gstatic.com/images?q=tbn:ANd9GcTL_B6yoZoy4kJTTC_y5LDc2-ubHSdgpFxkGw&s

Sources: https://www.sciencedirect.com/science/article/abs/pii/S0032063312002085
http://www.marsjournal.org/contents/2006/0004/files/rapp_mars_2006_0004.pdf

Total Ionising Dose

Using ~12.7 orbits/day and a conservative mission length of 6 months:

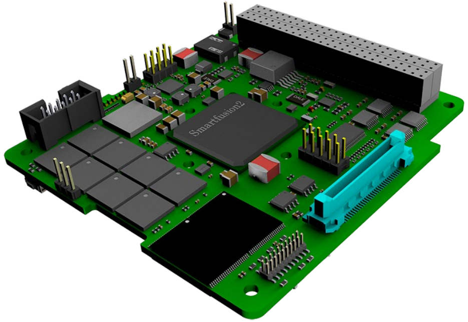
Nominal (15μGy/orbit):

- **Per Day : 190.5μGy**
- **Total Mission Length : 34.3mGy = 3.43rad**

Worst Case (290μGy/orbit):

- **Per Day : 3.68mGy**
- **Total Mission Length : 663mGy = 66.3rad**

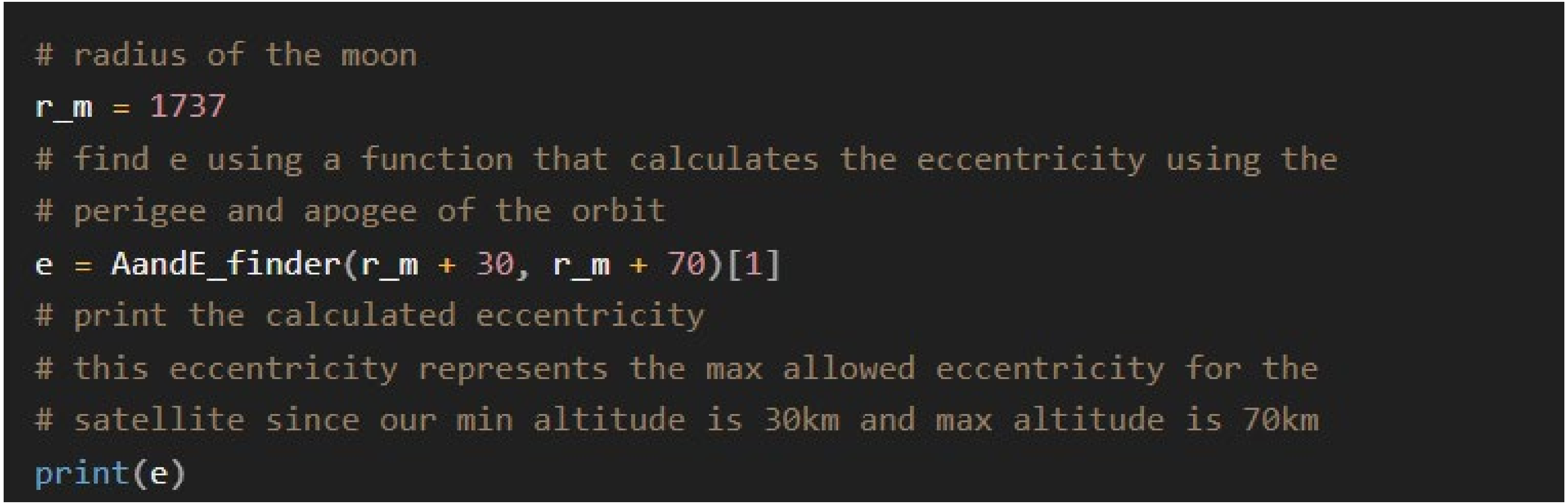
Within safety ratings of COTS CubeSat components, which are usually rated in kilo-rad ranges.
The experienced radiation will be mitigated by appropriately sized aluminum shielding.



Sources:
https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5135&context=smallsat
https://satsearch.co/products/endurosat-onboard-computer
https://www.a-azadi.com/wp-content/uploads/2024/07/OBC-Cube-104_900x563.png

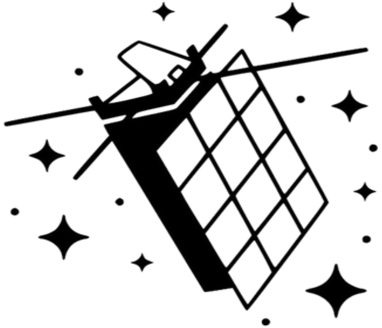
Satellite Requirements

- The satellite shall not crash into historic landing sites, active mission sites, or polar sites
- The satellites scientific altitude should be 50∓ km nominally
- The orbit eccentricity shall not not exceed 0.0112 [TBR]
- The satellite shall have an orbital inclination of no less than 57 degrees
  - Minimum scanning latitude is 57 degrees
- The satellite shall be in polar orbit
  - Best inclination for mapping and communication
  - Stable orbit to balance Lunar mascons



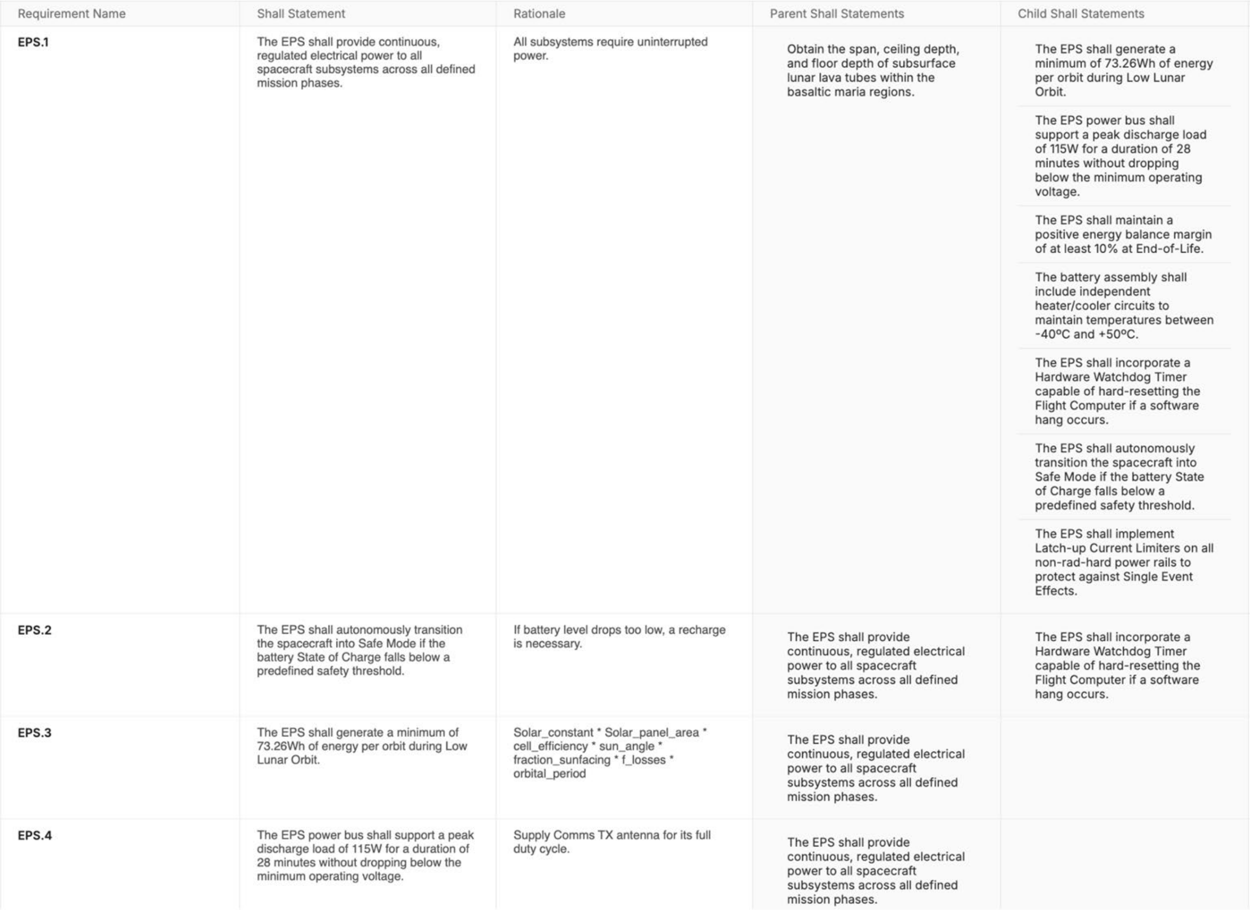
```
# radius of the moon
r_m = 1737
# find e using a function that calculates the eccentricity using the
# perigee and apogee of the orbit
e = AandE_finder(r_m + 30, r_m + 70)[1]
# print the calculated eccentricity
# this eccentricity represents the max allowed eccentricity for the
# satellite since our min altitude is 30km and max altitude is 70km
print(e)
```

Portion of orbital code to find maximum eccentricity



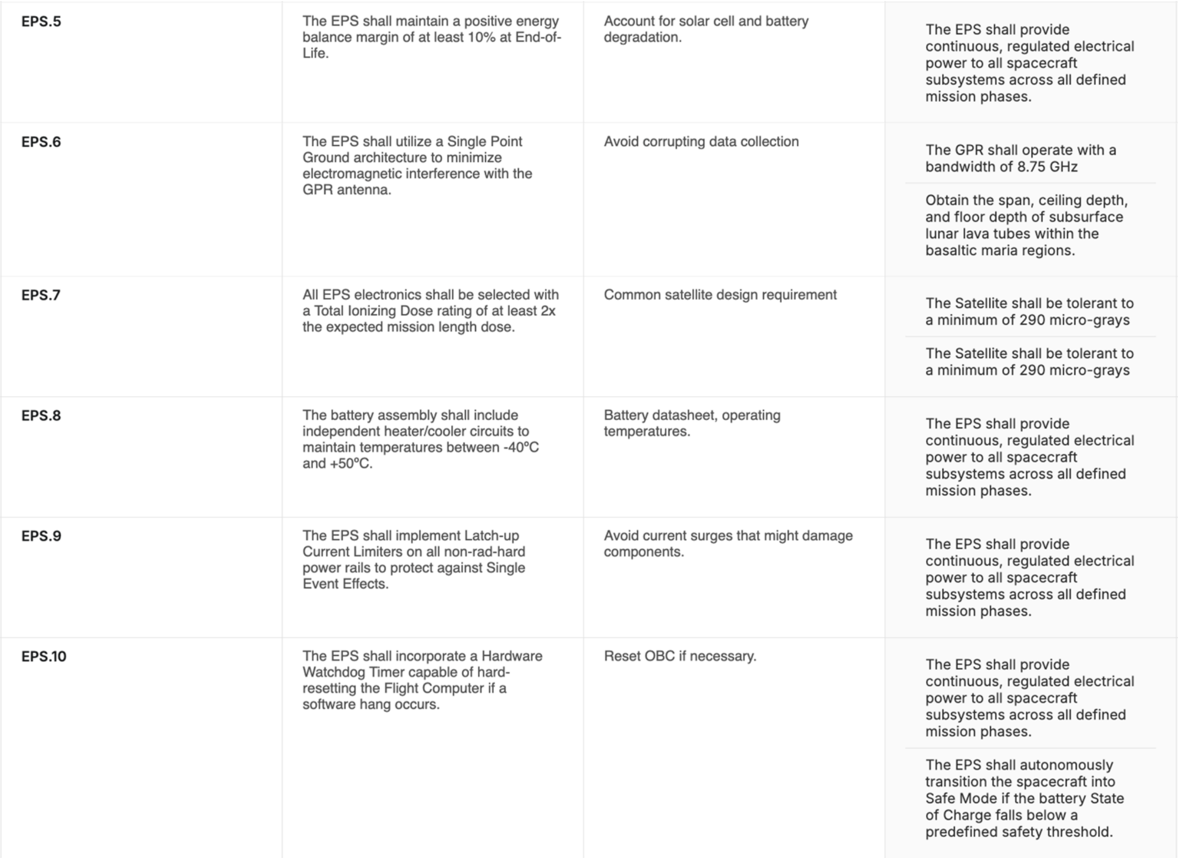
Subsystem Requirements

Electrical Power System Requirements



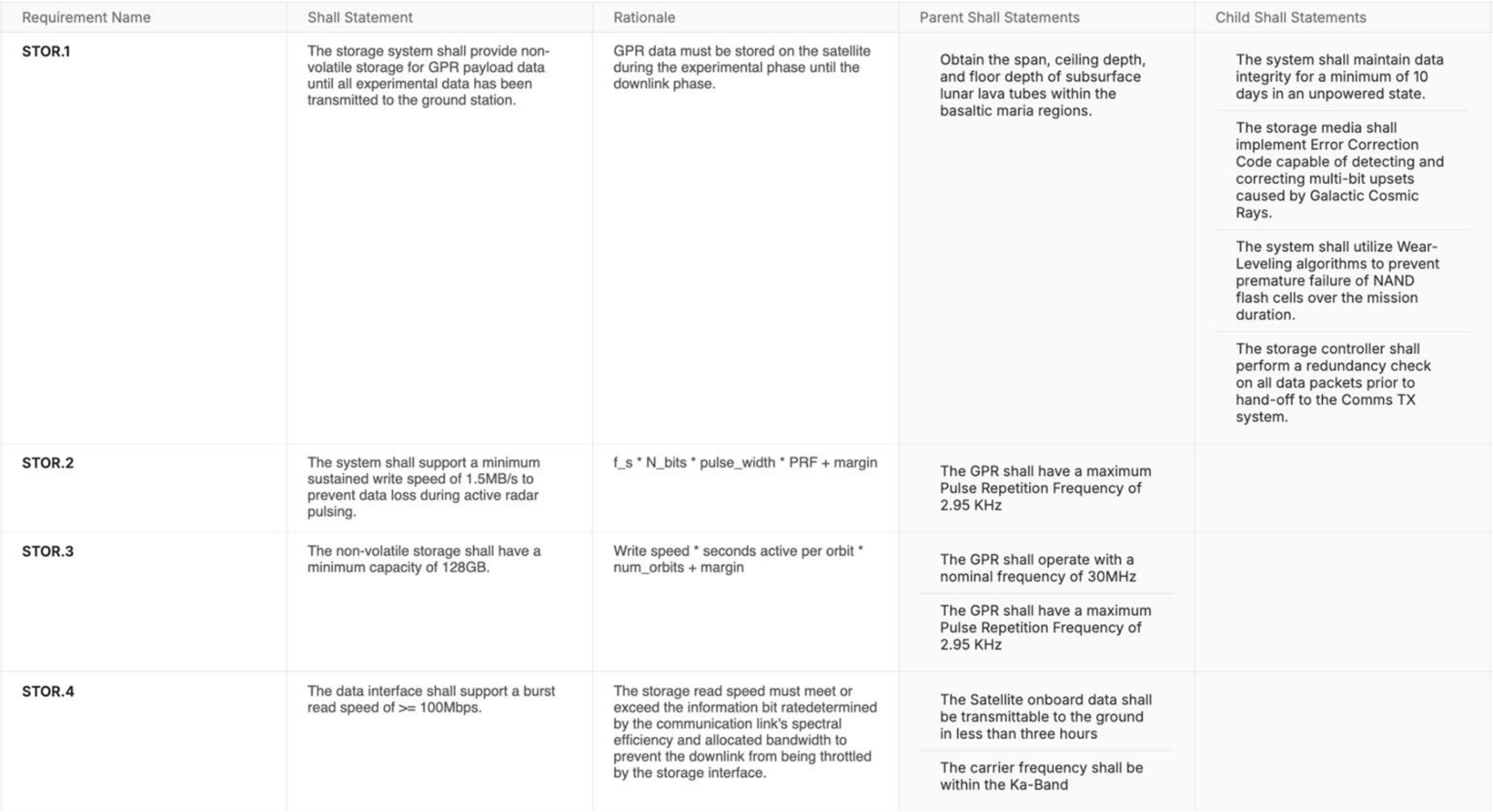
Requirement Name	Shall Statement	Rationale	Parent Shall Statements	Child Shall Statements
EPS.1	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases.	All subsystems require uninterrupted power.	Obtain the span, ceiling depth, and floor depth of subsurface lunar lava tubes within the basaltic maria regions.	The EPS shall generate a minimum of 73.26Wh of energy per orbit during Low Lunar Orbit. The EPS power bus shall support a peak discharge load of 115W for a duration of 28 minutes without dropping below the minimum operating voltage. The EPS shall maintain a positive energy balance margin of at least 10% at End-of-Life. The battery assembly shall include independent heater/cooler circuits to maintain temperatures between -40ºC and +50ºC. The EPS shall incorporate a Hardware Watchdog Timer capable of hard-resetting the Flight Computer if a software hang occurs. The EPS shall autonomously transition the spacecraft into Safe Mode if the battery State of Charge falls below a predefined safety threshold. The EPS shall implement Latch-up Current Limiters on all non-rad-hard power rails to protect against Single Event Effects.
EPS.2	The EPS shall autonomously transition the spacecraft into Safe Mode if the battery State of Charge falls below a predefined safety threshold.	If battery level drops too low, a recharge is necessary.	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases.	The EPS shall incorporate a Hardware Watchdog Timer capable of hard-resetting the Flight Computer if a software hang occurs.
EPS.3	The EPS shall generate a minimum of 73.26Wh of energy per orbit during Low Lunar Orbit.	Solar_constant * Solar_panel_area * cell_efficiency * sun_angle * fraction_sunfacing * f_losses * orbital_period	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases.	
EPS.4	The EPS power bus shall support a peak discharge load of 115W for a duration of 28 minutes without dropping below the minimum operating voltage.	Supply Comms TX antenna for its full duty cycle.	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases.	

Electrical Power System Requirements



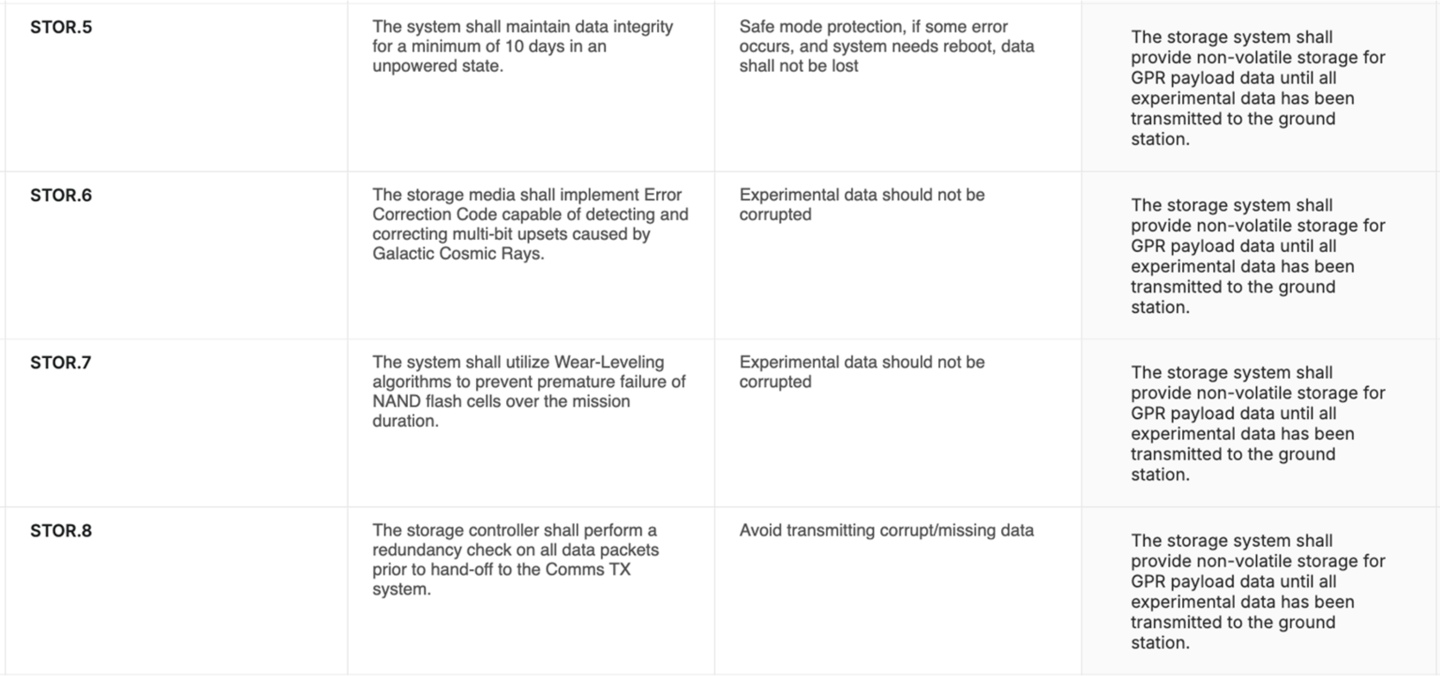
EPS.5	The EPS shall maintain a positive energy balance margin of at least 10% at End-of-Life.	Account for solar cell and battery degradation.	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases.
EPS.6	The EPS shall utilize a Single Point Ground architecture to minimize electromagnetic interference with the GPR antenna.	Avoid corrupting data collection	The GPR shall operate with a bandwidth of 8.75 GHz Obtain the span, ceiling depth, and floor depth of subsurface lunar lava tubes within the basaltic maria regions.
EPS.7	All EPS electronics shall be selected with a Total Ionizing Dose rating of at least 2x the expected mission length dose.	Common satellite design requirement	The Satellite shall be tolerant to a minimum of 290 micro-grays The Satellite shall be tolerant to a minimum of 290 micro-grays
EPS.8	The battery assembly shall include independent heater/cooler circuits to maintain temperatures between -40ºC and +50ºC.	Battery datasheet, operating temperatures.	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases.
EPS.9	The EPS shall implement Latch-up Current Limiters on all non-rad-hard power rails to protect against Single Event Effects.	Avoid current surges that might damage components.	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases.
EPS.10	The EPS shall incorporate a Hardware Watchdog Timer capable of hard-resetting the Flight Computer if a software hang occurs.	Reset OBC if necessary.	The EPS shall provide continuous, regulated electrical power to all spacecraft subsystems across all defined mission phases. The EPS shall autonomously transition the spacecraft into Safe Mode if the battery State of Charge falls below a predefined safety threshold.

Storage System Requirements

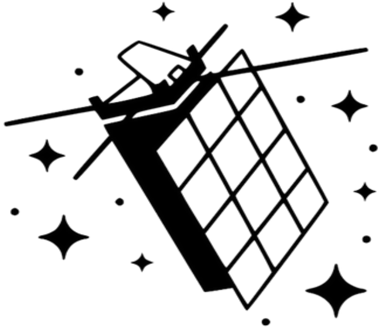


Requirement Name	Shall Statement	Rationale	Parent Shall Statements	Child Shall Statements
STOR.1	The storage system shall provide non-volatile storage for GPR payload data until all experimental data has been transmitted to the ground station.	GPR data must be stored on the satellite during the experimental phase until the downlink phase.	Obtain the span, ceiling depth, and floor depth of subsurface lunar lava tubes within the basaltic maria regions.	The system shall maintain data integrity for a minimum of 10 days in an unpowered state. The storage media shall implement Error Correction Code capable of detecting and correcting multi-bit upsets caused by Galactic Cosmic Rays. The system shall utilize Wear-Leveling algorithms to prevent premature failure of NAND flash cells over the mission duration. The storage controller shall perform a redundancy check on all data packets prior to hand-off to the Comms TX system.
STOR.2	The system shall support a minimum sustained write speed of 1.5MB/s to prevent data loss during active radar pulsing.	f_s * N_bits * pulse_width * PRF + margin	The GPR shall have a maximum Pulse Repetition Frequency of 2.95 KHz	
STOR.3	The non-volatile storage shall have a minimum capacity of 128GB.	Write speed * seconds active per orbit * num_orbits + margin	The GPR shall operate with a nominal frequency of 30MHz The GPR shall have a maximum Pulse Repetition Frequency of 2.95 KHz	
STOR.4	The data interface shall support a burst read speed of >= 100Mbps.	The storage read speed must meet or exceed the information bit ratedetermined by the communication link's spectral efficiency and allocated bandwidth to prevent the downlink from being throttled by the storage interface.	The Satellite onboard data shall be transmittable to the ground in less than three hours The carrier frequency shall be within the Ka-Band	

Storage System Requirements

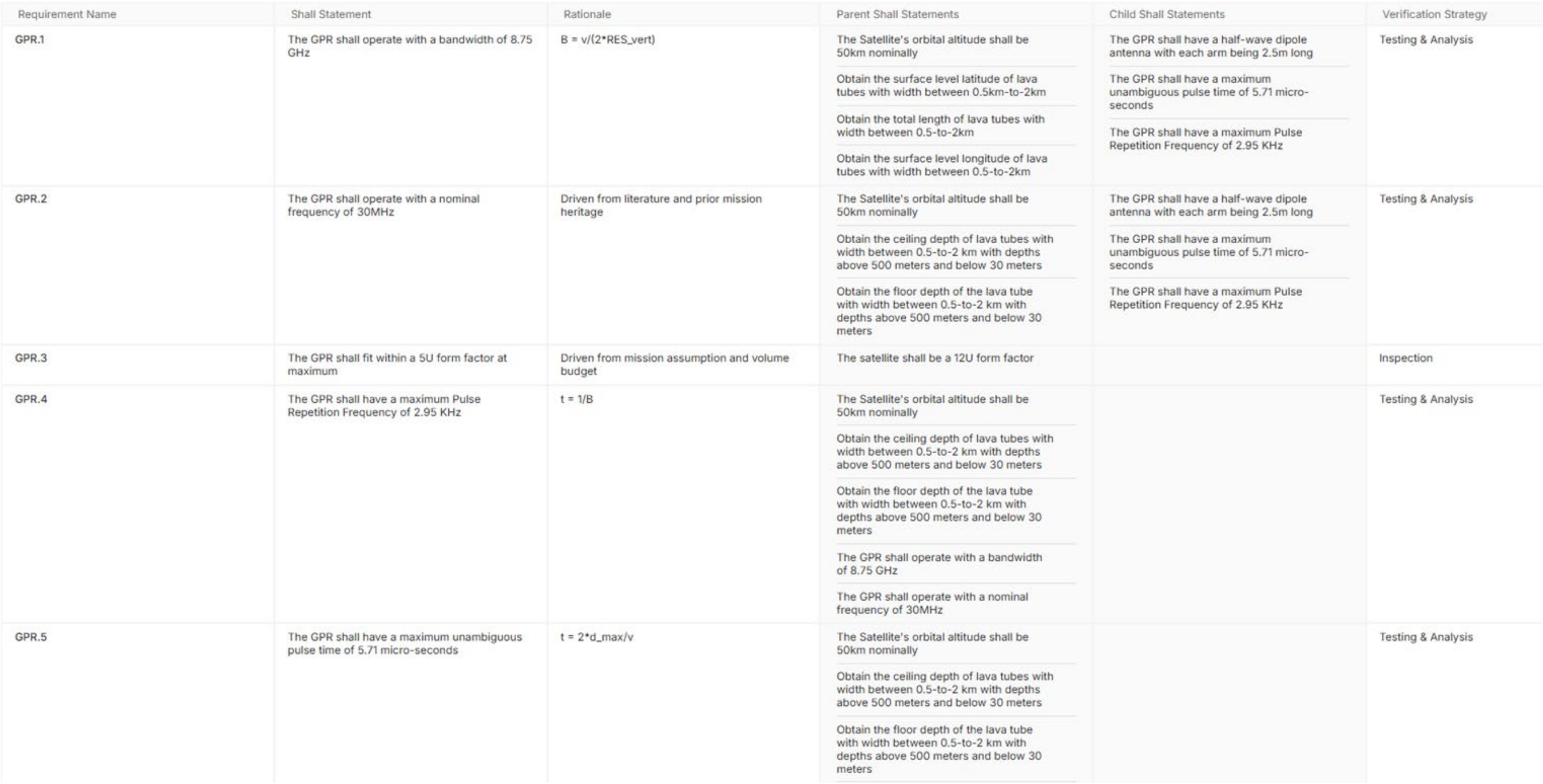


STOR.5	The system shall maintain data integrity for a minimum of 10 days in an unpowered state.	Safe mode protection, if some error occurs, and system needs reboot, data shall not be lost	The storage system shall provide non-volatile storage for GPR payload data until all experimental data has been transmitted to the ground station.
STOR.6	The storage media shall implement Error Correction Code capable of detecting and correcting multi-bit upsets caused by Galactic Cosmic Rays.	Experimental data should not be corrupted	The storage system shall provide non-volatile storage for GPR payload data until all experimental data has been transmitted to the ground station.
STOR.7	The system shall utilize Wear-Leveling algorithms to prevent premature failure of NAND flash cells over the mission duration.	Experimental data should not be corrupted	The storage system shall provide non-volatile storage for GPR payload data until all experimental data has been transmitted to the ground station.
STOR.8	The storage controller shall perform a redundancy check on all data packets prior to hand-off to the Comms TX system.	Avoid transmitting corrupt/missing data	The storage system shall provide non-volatile storage for GPR payload data until all experimental data has been transmitted to the ground station.



GPR

Requirements Overview - GPR



Requirement Name	Shall Statement	Rationale	Parent Shall Statements	Child Shall Statements	Verification Strategy
GPR.1	The GPR shall operate with a bandwidth of 8.75 GHz	B = v/(2*RES_vert)	The Satellite's orbital altitude shall be 50km nominally Obtain the surface level latitude of lava tubes with width between 0.5km-to-2km Obtain the total length of lava tubes with width between 0.5-to-2km Obtain the surface level longitude of lava tubes with width between 0.5-to-2km	The GPR shall have a half-wave dipole antenna with each arm being 2.5m long The GPR shall have a maximum unambiguous pulse time of 5.71 micro-seconds The GPR shall have a maximum Pulse Repetition Frequency of 2.95 KHz	Testing & Analysis
GPR.2	The GPR shall operate with a nominal frequency of 30MHz	Driven from literature and prior mission heritage	The Satellite's orbital altitude shall be 50km nominally Obtain the ceiling depth of lava tubes with width between 0.5-to-2 km with depths above 500 meters and below 30 meters Obtain the floor depth of the lava tube with width between 0.5-to-2 km with depths above 500 meters and below 30 meters	The GPR shall have a half-wave dipole antenna with each arm being 2.5m long The GPR shall have a maximum unambiguous pulse time of 5.71 micro-seconds The GPR shall have a maximum Pulse Repetition Frequency of 2.95 KHz	Testing & Analysis
GPR.3	The GPR shall fit within a 5U form factor at maximum	Driven from mission assumption and volume budget	The satellite shall be a 12U form factor		Inspection
GPR.4	The GPR shall have a maximum Pulse Repetition Frequency of 2.95 KHz	t = 1/B	The Satellite's orbital altitude shall be 50km nominally Obtain the ceiling depth of lava tubes with width between 0.5-to-2 km with depths above 500 meters and below 30 meters Obtain the floor depth of the lava tube with width between 0.5-to-2 km with depths above 500 meters and below 30 meters The GPR shall operate with a bandwidth of 8.75 GHz The GPR shall operate with a nominal frequency of 30MHz		Testing & Analysis
GPR.5	The GPR shall have a maximum unambiguous pulse time of 5.71 micro-seconds	t = 2*d_max/v	The Satellite's orbital altitude shall be 50km nominally Obtain the ceiling depth of lava tubes with width between 0.5-to-2 km with depths above 500 meters and below 30 meters Obtain the floor depth of the lava tube with width between 0.5-to-2 km with depths above 500 meters and below 30 meters		Testing & Analysis

Requirements Overview - GPR

			The GPR shall operate with a bandwidth of 8.75 GHz The GPR shall operate with a nominal frequency of 30MHz		
GPR.6	The GPR shall have a half-wave dipole antenna with each arm being 2.5m long	L = (c/f)/4	The GPR shall operate with a bandwidth of 8.75 GHz The GPR shall operate with a nominal frequency of 30MHz		Inspection
GPR.7	The GPR footprint shall have a diameter of 25km at minimum	Driven from the Moon's rate of rotation and surface area coverage.	The Satellite's orbital altitude shall be 50km nominally Obtain the total length of lava tubes with width between 0.5-to-2km Explore the basaltic maria regions	The GPR antenna pointing shall have an accuracy within 5°	Inspection

Radar Specifications - Cycle 1

RADAR SPECIFICATIONS

Frequency, Size & Bandwidth

Analysis Parameters:

- → Nominal Frequency / Wavelength (depth & resolution)
- → Physical Size
- → Bandwidth
- → Transmitter / Antenna Length

RADAR SPECIFICATIONS — CYCLE 1

Nominal Frequency / Wavelength

GPR FREQUENCY REQUIREMENTS

Nominal Operating Frequency

20 MHz

Center Frequency (baseline)

10 MHz

Operating Range

5 – 20 MHz

Multi-frequency capability

Velocity through Regolith

1.75×10^8 m/s

Avg assumed; $v = c/\sqrt{\varepsilon r}$

Wavelength in Basalt @ 10 MHz

11.3 m

$\lambda = v/f$, $\varepsilon r = 7$

Penetration Depth

150 – 300 m

In mare basalts

RESOLUTION & DEPTH PERFORMANCE

★ **RECOMMENDED:** 10 MHz — optimal for medium-to-large lava tube detection (10–100 m diameter)

Freq	Penetration	V.Res (reg/bslt)	H.Res
5 MHz	200–400 m	8.7 m / 5.7 m	10–15 m @ 100m
10 MHz ★	150–300 m	4.3 m / 2.8 m	7–10 m @ 100m
15 MHz	100–200 m	2.9 m / 1.9 m	~5–8 m @ 100m
20 MHz	75–150 m	2.2 m / 1.4 m	~4–6 m @ 100m

KEY EQUATIONS

$\lambda_{mat} = c/(f\times\sqrt{\varepsilon r})$ | $v = c/\sqrt{\varepsilon r}$ | Vert. Res. $= \lambda/4$

$\varepsilon r_{regolith} \approx 3.0$ | $\varepsilon r_{basalt} \approx 7.0$ | $v_{reg} = 1.73\times10^8$ m/s | $v_{bslt} = 1.13\times10^8$ m/s

Sources: Chang'E-3/4 LPR missions | Carrer & Bruzzone (2018) | Esmaeili et al. (2020) | Dong et al. (2020)

RADAR SPECIFICATIONS — CYCLE 1

Physical Size — 12U CubeSat Constraints

ANTENNA DIMENSIONS (HALF-WAVELENGTH DIPOLE)

`L_total = 142.65 / f_MHz  (m)      L_leg = 71.325 / f_MHz  (m)`

Accounts for end effects — standard dipole shortening factor

Freq	Total L	Each Leg	Deployment
5 MHz	28.5 m	14.25 m	Wire dipole w/ deployer
10 MHz ★	14.3 m	7.15 m	Tape spring or wire dipole
15 MHz	9.5 m	4.75 m	Tape spring — feasible
20 MHz	7.1 m	3.55 m	Tape spring or rigid boom

MASS & VOLUME BUDGET (12U CUBESAT)

GPR Electronics

Volume: 2 – 3U

Mass: 1.5 – 2.5 kg

Antenna Deploy Mechs

Volume: 0.4–0.5U ea

Mass: 0.4–0.9 kg ea

Antenna System (TX+RX)

Volume: ~1U total

Mass: 1.0 – 2.0 kg

Feed Structure

Volume: ~0.1U

Mass: 0.1–0.2 kg ea

TOTAL GPR PAYLOAD

Volume: **3 – 5U** of 12U available

Heritage: Hera-Juventas 6U CubeSat @ 60 MHz validates MHz-range GPR on CubeSat platform

Sources: Cialone et al. (2022) IEEE | Herique et al. (2016) DISCUS | 12U CubeSat standard (20×20×34 cm)

RADAR SPECIFICATIONS — CYCLE 1

Bandwidth Requirements

BANDWIDTH SPECIFICATIONS

$$\Delta r = v / (2B)$$

Δr = depth resolution v = velocity in medium B = bandwidth

Nominal Operating BW	**8.75 MHz**	Per mission requirement
Recommended Center BW	**4 MHz**	At 10 MHz center freq
Fractional Bandwidth	**40%**	At center frequency
Depth Res. in Basalt	**14.1 m**	With 4 MHz BW @ 10 MHz
Pulse Duration	**~250 ns**	For 4 MHz bandwidth
Modulation	**Chirp/SFCW**	Stepped-freq or linear FM

DEPTH RESOLUTION vs BANDWIDTH

IN LUNAR REGOLITH (v = 1.73×10^8 m/s)

Ctr Freq	BW	Frac. BW	Depth Res.
5 MHz	2 MHz	40%	43.3 m
10 MHz ★	4 MHz	40%	21.6 m
15 MHz	6 MHz	40%	14.4 m
20 MHz	8.75 MHz	44%	9.9 m

IN MARE BASALT (v = 1.13×10^8 m/s)

Ctr Freq	BW	Frac. BW	Depth Res.
5 MHz	2 MHz	40%	28.3 m
10 MHz ★	4 MHz	40%	14.1 m
15 MHz	6 MHz	40%	9.4 m
20 MHz	8.75 MHz	44%	6.4 m

★ 10 MHz recommended | 20 MHz nominal per mission spec → 9.9 m in regolith, 6.4 m in basalt

RADAR SPECIFICATIONS — CYCLE 1

Transmitter / Antenna Length Requirements

ANTENNA CONFIGURATION

Configuration	**Bistatic (TX/RX separated)**	Preferred for isolation
Alternative	**Monostatic w/ TX/RX switch**	
Antenna Type	**Half-wavelength dipole**	73 Ω impedance
Impedance Matching	**73 Ω → 50 Ω**	Requires matching network
Balun	**Required**	Coaxial feed transition
Orientation	**⊥ to nadir direction**	Linear polarization
Bistatic Separation	**0.5 – 2 m**	Frequency-dependent

TRANSMITTER POWER REQUIREMENTS

PEAK POWER	**10 – 30 W**	Duty cycle dependent
AVG POWER	**5 – 15 W**	During operation

ANTENNA COMPONENT MASS

Deployment Mechanism	**0.4 – 0.9 kg**	per antenna
Feed Structure	**0.1 – 0.2 kg**	per antenna
TX/RX Electronics	**1.5 – 2.5 kg**	total
Both Antenna Systems	**1.0 – 2.0 kg**	TX + RX total

Target vertical resolution: 10 m | Nominal freq: 20 MHz | BW: 8.75 MHz | Avg velocity assumed: 1.75×10^8 m/s through regolith

Radar Specifications - Cycle 2

RADAR SPECIFICATIONS

Timing & Power

Analysis Parameters:

- → Pulse Time
- → Power Requirements
- → Pulse Repetition Frequency (PRF)
- → Sample Rate

RADAR SPECIFICATIONS — CYCLE 2

Pulse Time & Pulse Repetition Frequency

PULSE TIME PARAMETERS

$\tau = 1/B \rightarrow \tau = 1/8.75\text{MHz} = 114.3\ \text{ns}$

τ = pulse duration B = bandwidth Unambiguous range: c·PRI/2

Pulse Duration (τ)

114.3 ns

GPR shall operate at this value

Wavelength (λ)

8.75 m

At 20 MHz nominal frequency

Vertical Resolution

10.0 m

Target depth resolution

Min. PRI (1 km depth)

5.71 µs

Unambiguous range window

Unambiguous Pulse Time

5.71 µs

GPR shall operate at this value

PULSE REPETITION FREQUENCY & SAMPLE RATE

$\text{PRF\_max} = 1/\text{PRI\_min} = 1/5.71\mu s \approx 175\ \text{kHz}$

PRF_mission = 2.95 kHz (GPR shall not exceed this)

MAX PRF (Physical)

175 kHz

1/PRI_min

MAX PRF (Mission Req.)

2.95 kHz

Shall not exceed

SAMPLE RATE

TBD

Sample rate requirement not yet specified.
Will be derived from bandwidth and Nyquist criterion: $f_s \geq 2B$

PRI = Pulse Repetition Interval | PRF = 1/PRI | Mission PRF requirement: 2.95 kHz max | Physical max: 175 kHz

RADAR SPECIFICATIONS — CYCLE 2

Power Requirements

POWER BUDGET PER PASS

ENERGY PER PASS

20.1 Wh

All onboard data shall be transmittable via DSN in < 3 hours

DSN Downlink Constraint

< 3 hours

All onboard data per pass

GPR Duty Cycle

> 20%

Power system must support for ≥ few days

Peak Transmit Power

10 – 30 W

Cycle 1 heritage value

Average Operating Power

5 – 15 W

Cycle 1 heritage value

DUTY CYCLE & SYSTEM CONTEXT

$DC = \tau \times PRF \rightarrow E = P\_avg \times t\_pass$

DC = duty cycle τ = pulse duration PRF = pulse rep. freq E = energy

DC at 2.95 kHz PRF, 114.3 ns τ

0.034%

τ × PRF = 114.3ns × 2.95kHz

Required minimum duty cycle

> 20%

Power system must sustain for days

Implication

PRF or τ must increase to meet duty cycle

Or chirp compression used

Energy per pass: 20.1 Wh | DSN downlink constraint: < 3 hours | Minimum duty cycle: > 20%

Radar Specifications - Cycle 3

RADAR SPECIFICATIONS

Observation & Pointing

Analysis Parameters:

- → Point of View for Data Collection
- → SNR (Signal-to-Noise Ratio)
- → Power Draw
- → Antenna Pointing Accuracy

RADAR SPECIFICATIONS — CYCLE 3

Point of View, Pointing Accuracy & SNR

ORBITAL DATA COLLECTION GEOMETRY

Orbital Inclination

> |57.03°|

Must exceed highest target latitude

Recommended Inclination

90°

For full coverage in < 1 lunar rotation

Swath Width (required)

> 25.1 km

To finish scan in < 1 lunar rotation

Swath Width (calculated)

81 km

Field of view at 100 km altitude

Safety Factor Swath

100 km

Used for antenna pointing ±5° spec

ANTENNA POINTING & SNR

ANTENNA POINTING ACCURACY

± 5°

At 100 km swath (safety factor from calculated 81 km FOV)

SNR — SIGNAL TO NOISE RATIO

69.8 dB

POWER DRAW

Peak

10–30 W

Average

5–15 W

Inclination req: > |57.03°| | Recommended: 90° | Swath req: > 25.1 km | Pointing accuracy: ±5° | SNR: TBD

Radar Specifications - Cycle 4

RADAR SPECIFICATIONS

Frequency, Size & Bandwidth (Final)

Analysis Parameters:

- → Nominal Frequency / Wavelength (final values)
- → Physical Size (final antenna)
- → Bandwidth (final)
- → Transmitter / Antenna Length (final)

RADAR SPECIFICATIONS — CYCLE 4

Final Frequency, Antenna & Bandwidth Values

FINAL FREQUENCY REQUIREMENTS

GPR Operating Frequency

30 MHz

Final nominal frequency

Bandwidth

8.75 MHz

Final operating bandwidth

Pulse Duration (τ)

114.3 ns

τ = 1/B = 1/8.75 MHz

Wavelength (λ)

8.75 m

At 30 MHz nominal

Vertical Resolution

10.0 m

Target met

Unambiguous Pulse Time

5.71 µs

Min. PRI for 1 km depth

Max PRF (mission)

2.95 kHz

Shall not exceed

FINAL ANTENNA SPECIFICATIONS

HALF-WAVE DIPOLE ANTENNA

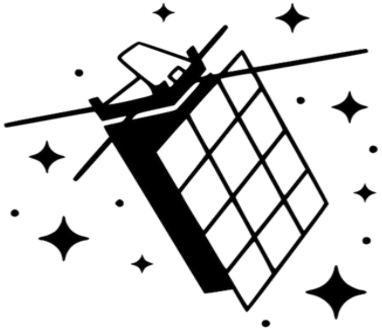
Each Arm: **2.5 m**

Total Length: **5.0 m**

Half-wave dipole | L_total = 142.65/30MHz = 4.76 m theoretical → 5.0 m deployed

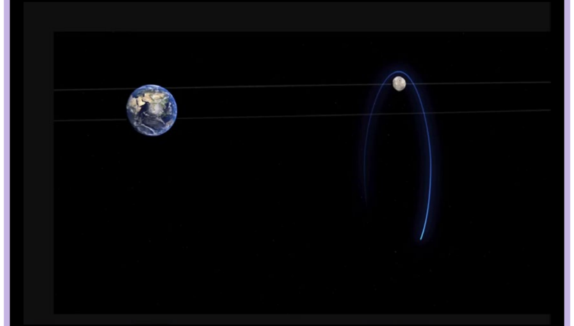
Antenna Type	**Half-wavelength dipole**	
Arm Length	**2.5 m each**	5.0 m total deployed
Frequency	**30 MHz**	Final nominal
Bandwidth	**8.75 MHz**	Final value
Energy / Pass	**20.1 Wh**	All onboard data ← 3 hr DSN
Pointing Accuracy	**± 5°**	100 km swath safety factor

Final values: 30 MHz | 8.75 MHz BW | τ = 114.3 ns | PRF ≤ 2.95 kHz | Antenna: 2.5 m per arm | Energy: 20.1 Wh/pass



Orbital Path & Requirements

Orbital Path and Stages



Deployed: Near Rectilinear Halo Orbit (NRHO - Gateway)

Transition: NRHO Perigee to Low Lunar Orbit (LLO)

TBD, STK ERROR

Final Orbit: LLO Science Orbit

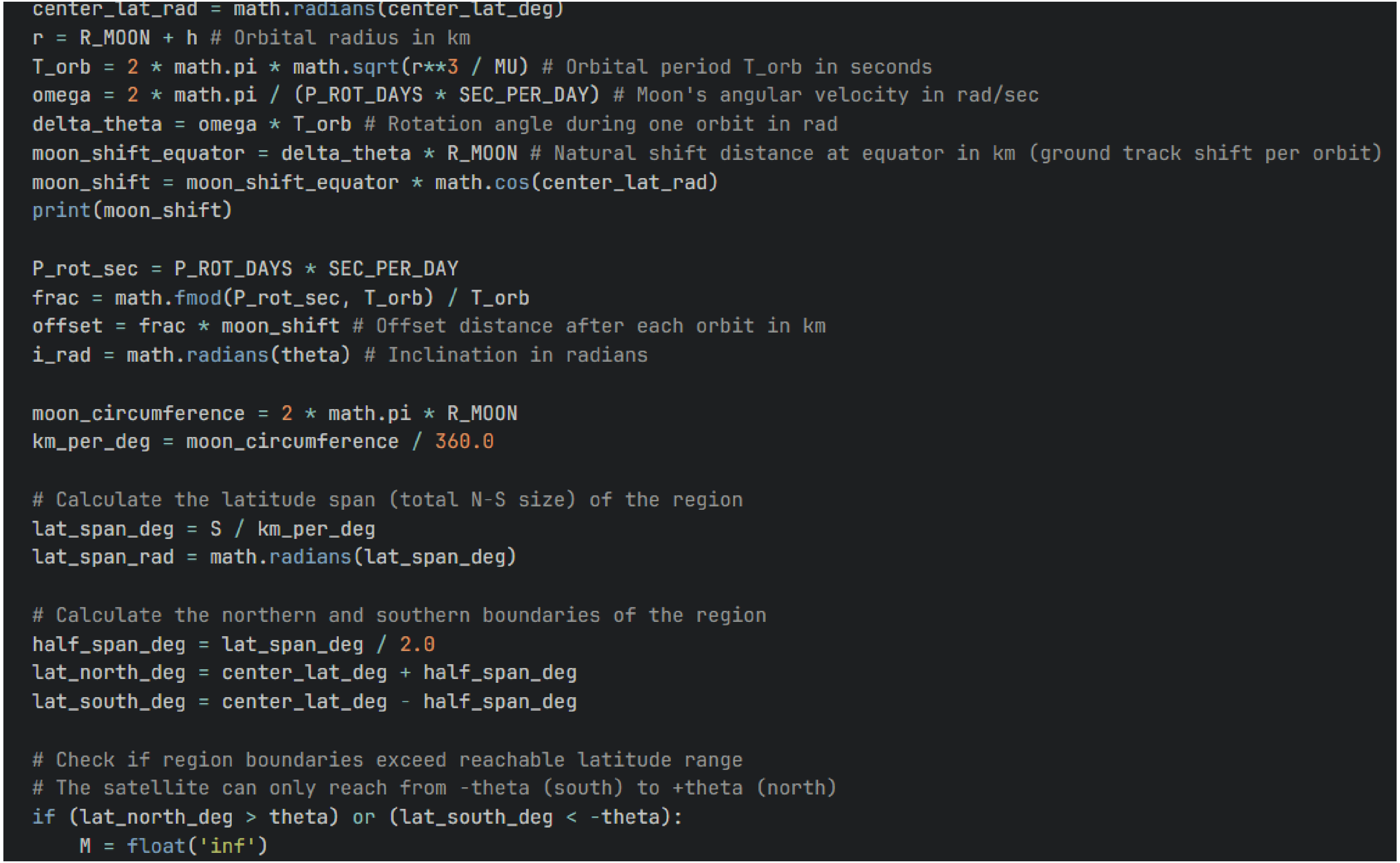
Transition: NRHO Perigee to Low Lunar Orbit (LLO)

Orbital Parameters - LLO

Low Lunar Orbit (LLO)

🟥	Unconfirmed
🟧	TBR
🟩	Confirmed

Orbit Type	Circular (e~0)
Orbit Location	On eclipse line, always facing the sun
Inclination (i)	86 [degree]
Min altitude	30 [km]
Max altitude	70 [km]
Max Eccentricity	0.0112
Delta E change per day	TBD
Lunar Radius	1737[km]
Experimental altitude	1787 [km]
Passes per day	25 times
Average Time Over Period	27 minutes
Time of Scientific research	Reach LLO at 07/20/2026-07/20/2026



```
center_lat_rad = math.radians(center_lat_deg)
r = R_MOON + h # Orbital radius in km
T_orb = 2 * math.pi * math.sqrt(r**3 / MU) # Orbital period T_orb in seconds
omega = 2 * math.pi / (P_ROT_DAYS * SEC_PER_DAY) # Moon's angular velocity in rad/sec
delta_theta = omega * T_orb # Rotation angle during one orbit in rad
moon_shift_equator = delta_theta * R_MOON # Natural shift distance at equator in km (ground track shift per orbit)
moon_shift = moon_shift_equator * math.cos(center_lat_rad)
print(moon_shift)

P_rot_sec = P_ROT_DAYS * SEC_PER_DAY
frac = math.fmod(P_rot_sec, T_orb) / T_orb
offset = frac * moon_shift # Offset distance after each orbit in km
i_rad = math.radians(theta) # Inclination in radians

moon_circumference = 2 * math.pi * R_MOON
km_per_deg = moon_circumference / 360.0

# Calculate the latitude span (total N-S size) of the region
lat_span_deg = S / km_per_deg
lat_span_rad = math.radians(lat_span_deg)

# Calculate the northern and southern boundaries of the region
half_span_deg = lat_span_deg / 2.0
lat_north_deg = center_lat_deg + half_span_deg
lat_south_deg = center_lat_deg - half_span_deg

# Check if region boundaries exceed reachable latitude range
# The satellite can only reach from -theta (south) to +theta (north)
if (lat_north_deg > theta) or (lat_south_deg < -theta):
    M = float('inf')
```

Orbital Parameters - Transfer Orbit

Transfer Orbit (Xfer)

🟥 Unconfirmed

🟧 TBR

🟩 Confirmed

Orbit Type	2 phase transfer	Erika 01/27/26 From BLT
Transfer Days	TBD	
Number of burns to completion	TBD	
Minimum Delta V Required	TBD	
Transfer Date	Reach LLO at 07/20/2026	

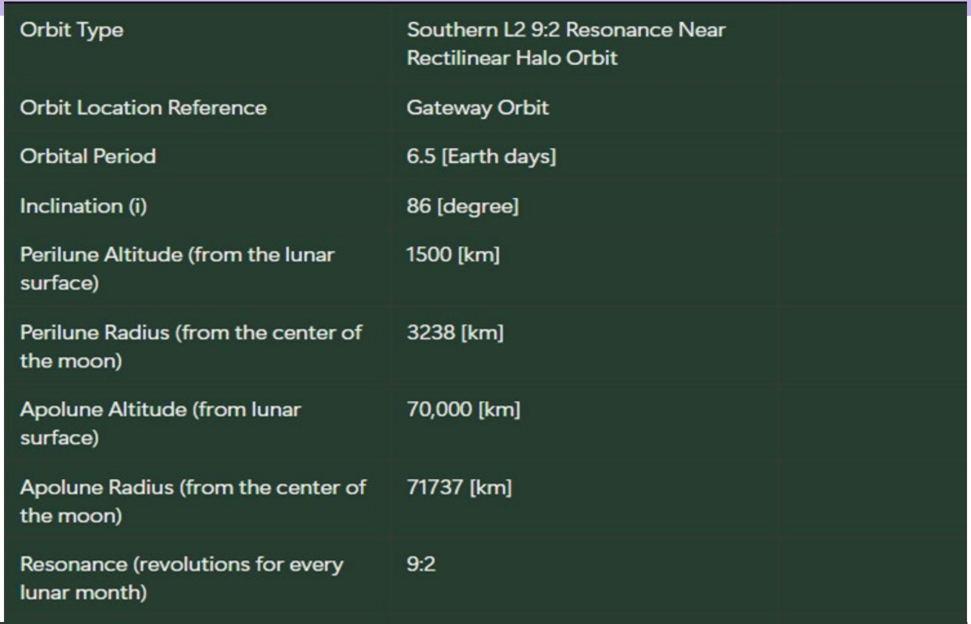
Orbital Parameters - NHRO Orbit

Near Rectilinear Halo Orbit (NRHO)

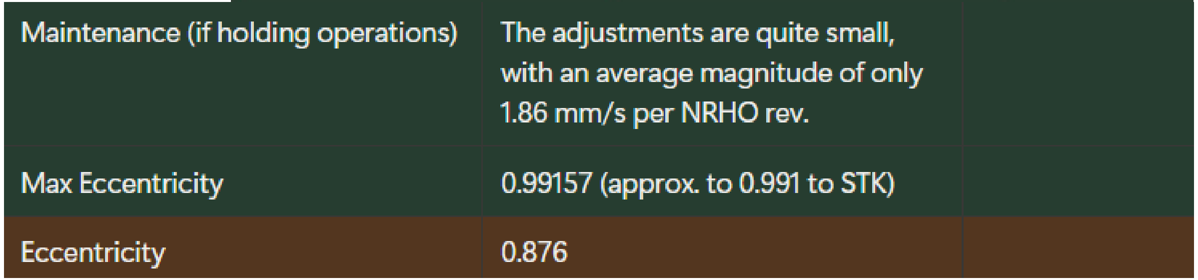
🟥 Unconfirmed

🟧 TBR

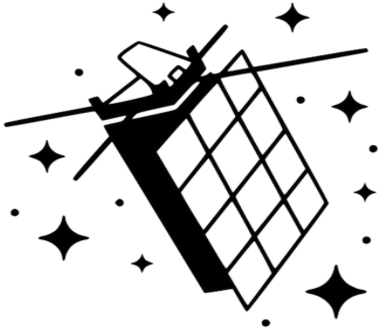
🟩 Confirmed



Orbit Type	Southern L2 9:2 Resonance Near Rectilinear Halo Orbit
Orbit Location Reference	Gateway Orbit
Orbital Period	6.5 [Earth days]
Inclination (i)	86 [degree]
Perilune Altitude (from the lunar surface)	1500 [km]
Perilune Radius (from the center of the moon)	3238 [km]
Apolune Altitude (from lunar surface)	70,000 [km]
Apolune Radius (from the center of the moon)	71737 [km]
Resonance (revolutions for every lunar month)	9:2



Maintenance (if holding operations)	The adjustments are quite small, with an average magnitude of only 1.86 mm/s per NRHO rev.
Max Eccentricity	0.99157 (approx. to 0.991 to STK)
Eccentricity	0.876

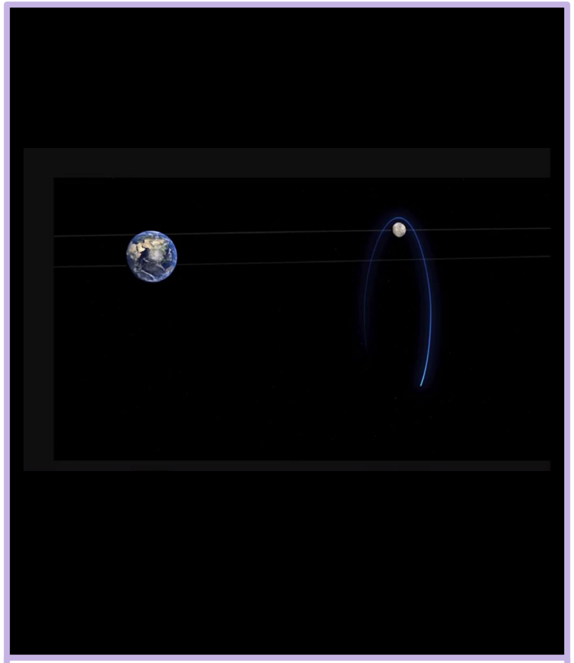


Propulsion

Requirements Overview - Propulsion

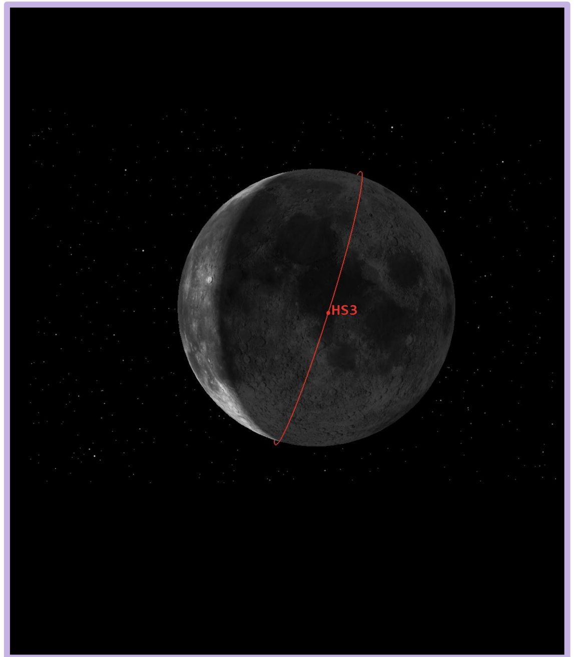
Requirement Name	Shall Statement	Rationale	Parent Shall Statements	Child Shall Statements	Verification Strategy
PROP.1	The propulsion system shall be capable of achieving 20 m/s of delta-v during Science Phase	Driven by max eccentricity allowed in the final orbit and time taken before the eccentricity is reached.	The Satellite's orbital eccentricity shall not exceed 0.0112 The Satellite's orbital altitude shall be 50km nominally		Testing & Analysis
PROP.2	The propulsion system shall be capable of achieving 900 m/s of delta-v during Maneuver Phase	Driven by Hohmann transfer trajectory from Gateway down to Science orbit.	The Satellite's orbital altitude shall be 50km nominally The satellite shall launch off of NASA's Gateway Station		Testing & Analysis

Orbital Path and Stages



Deployed: Near Rectilinear Halo Orbit (NRHO - Gateway)

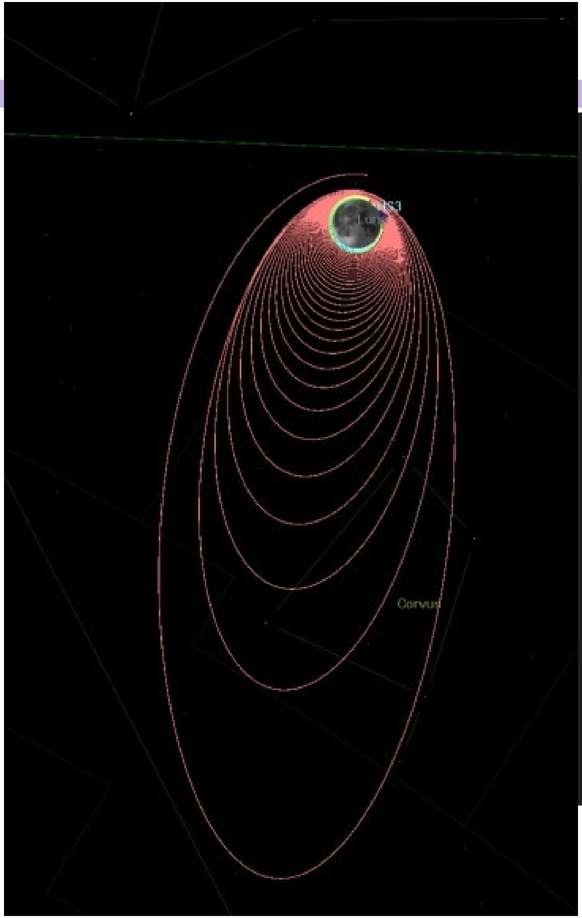
Transition: NRHO Perigee to Low Lunar Orbit (LLO)

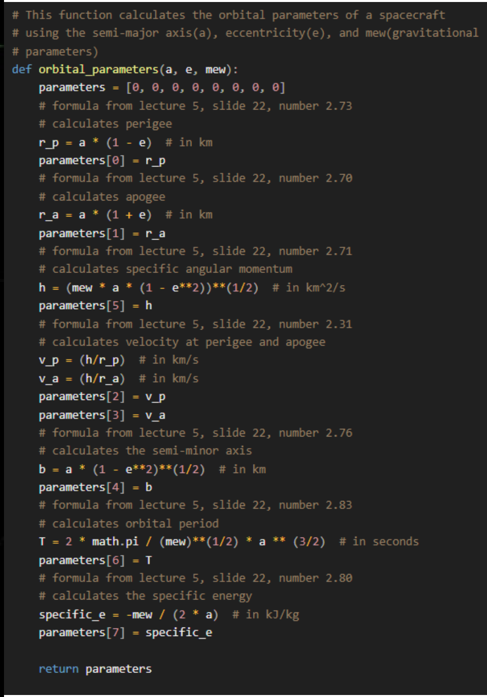


Final Orbit: LLO Science Orbit

Propulsion Analysis

- Current trajectory assumes impulsive hohmann transfer burns and disregards the 3-body problem
- Burn locations:
    1. Perigee of orbit until new perigee becomes the final altitude
    2. Perigee of new orbit until the orbit is circularized at final altitude
- Roughly 890 m/s of delta-v is required for the maneuver down the final orbit with roughly 24 days as the total transfer time

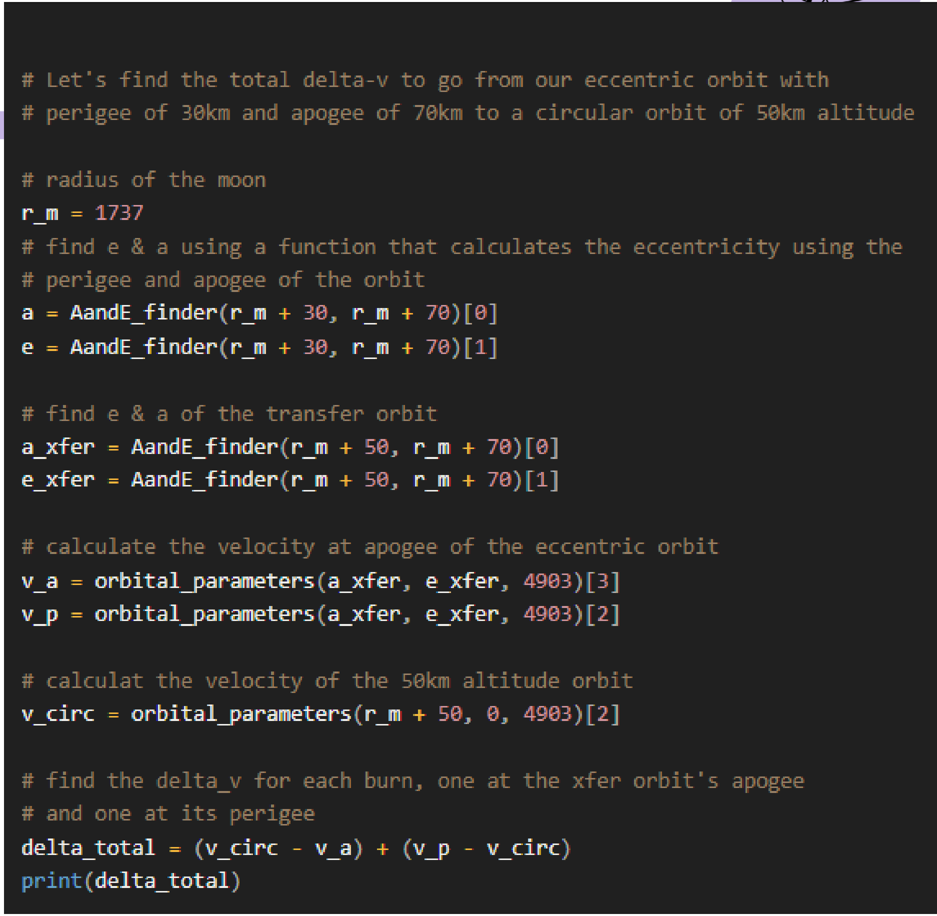




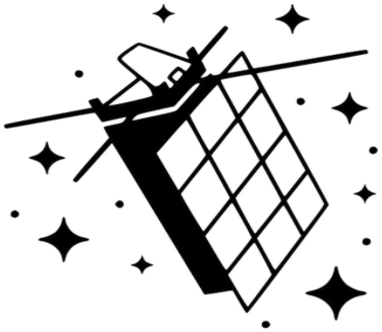
```python
# This function calculates the orbital parameters of a spacecraft
# using the semi-major axis(a), eccentricity(e), and mew(gravitational
# parameters)
def orbital_parameters(a, e, mew):
    parameters = [0, 0, 0, 0, 0, 0, 0, 0]
    # formula from lecture 5, slide 22, number 2.73
    # calculates perigee
    r_p = a * (1 - e)  # in km
    parameters[0] = r_p
    # formula from lecture 5, slide 22, number 2.70
    # calculates apogee
    r_a = a * (1 + e)  # in km
    parameters[1] = r_a
    # formula from lecture 5, slide 22, number 2.71
    # calculates specific angular momentum
    h = (mew * a * (1 - e**2))**(1/2)  # in km^2/s
    parameters[5] = h
    # formula from lecture 5, slide 22, number 2.31
    # calculates velocity at perigee and apogee
    v_p = (h/r_p)  # in km/s
    v_a = (h/r_a)  # in km/s
    parameters[2] = v_p
    parameters[3] = v_a
    # formula from lecture 5, slide 22, number 2.76
    # calculates the semi-minor axis
    b = a * (1 - e**2)**(1/2)  # in km
    parameters[4] = b
    # formula from lecture 5, slide 22, number 2.83
    # calculates orbital period
    T = 2 * math.pi / (mew)**(1/2) * a ** (3/2)  # in seconds
    parameters[6] = T
    # formula from lecture 5, slide 22, number 2.80
    # calculates the specific energy
    specific_e = -mew / (2 * a)  # in kJ/kg
    parameters[7] = specific_e

    return parameters
```

Propulsion Analysis

- For station-keeping, we have an altitude envelope of [30km, 70km] driven by the GPR
- Calculating eccentricity of this orbit and the time required to reach this eccentricity as a function of the lunar perturbations, we arrive at a 20m/s delta-v requirement for stationkeeping *per month*.



```
# Let's find the total delta-v to go from our eccentric orbit with
# perigee of 30km and apogee of 70km to a circular orbit of 50km altitude

# radius of the moon
r_m = 1737
# find e & a using a function that calculates the eccentricity using the
# perigee and apogee of the orbit
a = AandE_finder(r_m + 30, r_m + 70)[0]
e = AandE_finder(r_m + 30, r_m + 70)[1]

# find e & a of the transfer orbit
a_xfer = AandE_finder(r_m + 50, r_m + 70)[0]
e_xfer = AandE_finder(r_m + 50, r_m + 70)[1]

# calculate the velocity at apogee of the eccentric orbit
v_a = orbital_parameters(a_xfer, e_xfer, 4903)[3]
v_p = orbital_parameters(a_xfer, e_xfer, 4903)[2]

# calculat the velocity of the 50km altitude orbit
v_circ = orbital_parameters(r_m + 50, 0, 4903)[2]

# find the delta_v for each burn, one at the xfer orbit's apogee
# and one at its perigee
delta_total = (v_circ - v_a) + (v_p - v_circ)
print(delta_total)
```



Communications

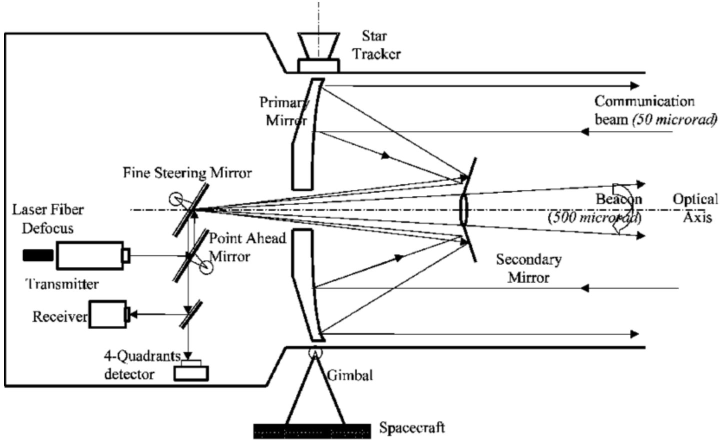
Optical Communication

Advantages

- Short wavelength → High Frequency → Large Bandwidth → High Data Rate

Disadvantages

- Extraordinarily complex
  - Requires vibration stabilization
  - Thermal fluctuation accommodation
- Systems requires high precision
  - Microradian pointing accuracy
- High likelihood of failure
- Expensive
- Limited access to guidance



Why Ka-band over S or X Band

Frequency Ranges

- S-Band: 2→4 GHz
  - Long heritage of use
  - “Common” hardware
  - Crowded Bandwidth → Low data rate
- X-Band: 8→12 GHz
  - Used in previous lunar cubesat missions
  - “Common” hardware
  - Crowded Bandwidth → Low data rate
- Ka-Band: 26.5→40 GHz
  - Higher carrier frequency → larger bandwidth and higher data rates
  - Limited pre existing hardware

Ka-Band

- Not a completely novel technology
  - Gateway and JWST utilize Ka-Band for data downlink
  - Many LEO and GEO satellites have moved to Ka-Band
- Extensive ground infrastructure exists
  - The NSN and DNS support Ka-Band communication
  - High data throughput is possible on the NSN

Transmission Window

Orbital Velocity: $1.66\ \frac{km}{s}$

Orbital Radius: 1787.4 km

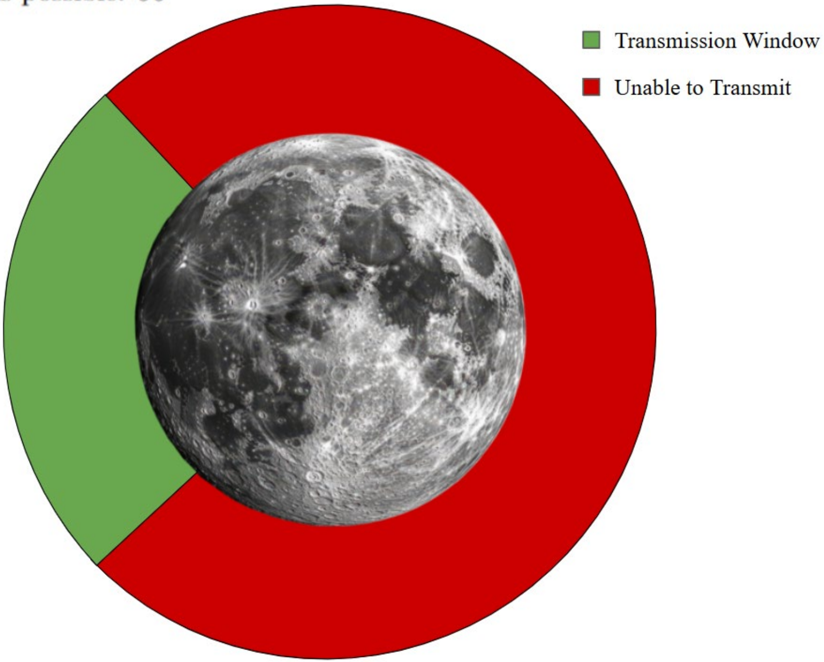
Assumed arc in which transmission is possible: 90°

$$L_{arc} = \text{radians} \cdot r$$

$$L_{arc} = 2807.64\,\text{km}$$

$$T_{transfer} = \frac{2807.64}{1.66} = 1691\,\text{s}$$

$$\boxed{\approx 28\,\text{min}}$$

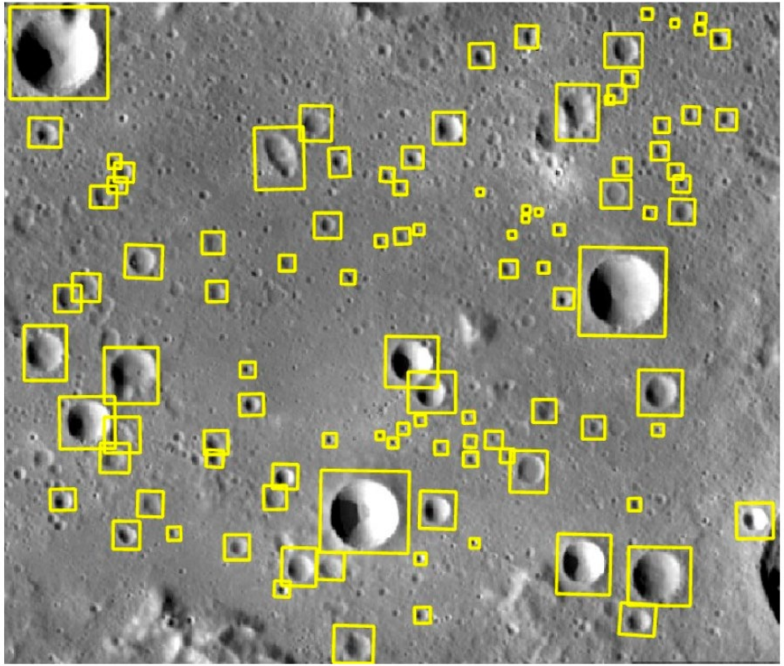


Transmission Window

- Determined by how maneuverable our antenna is
- For a somewhat fixed antenna- transmission window is a few degrees → few minute transmit time

How to Point Antenna

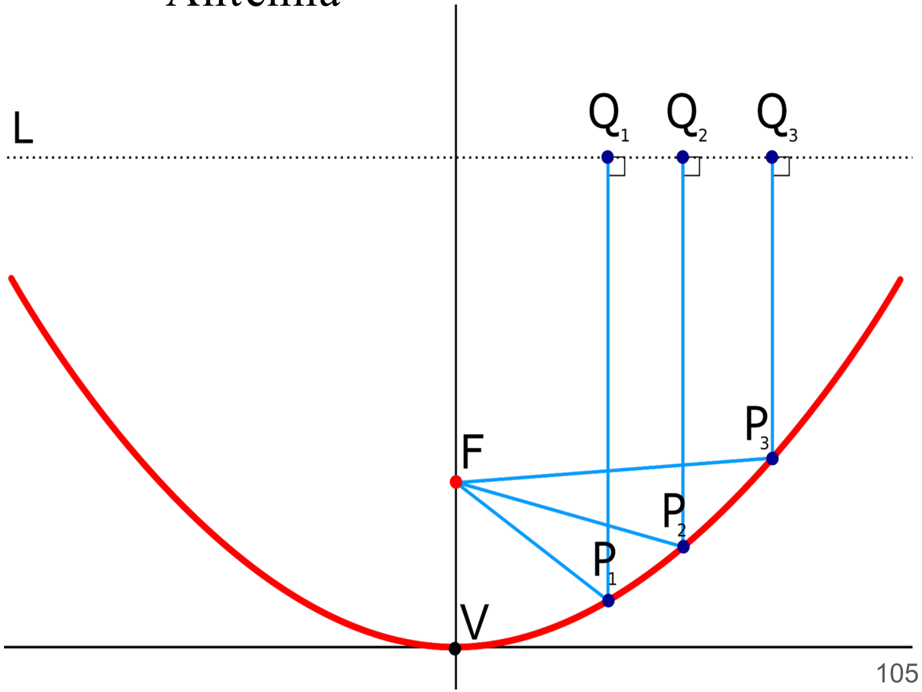
- A lunar positioning system is already required for lava tube mapping
- The satellite knows where it is above the moon
- The position of the earth relative to the moon is known
- Therefore the position of the satellite relative to the ground station is known
- Beacon pointing can aid in acquiring a stable satellite link



Determining Antenna Type

- Ka-Band patch antennas generally have large beam divergences
- Antenna needs to fit in 1U of space
- Parabolic antennas offer focused beams for better data transmission
  - More compact than horn antennas
  - Commonly used for high gain space communication applications

Parabolic Reflector Antenna



Antenna Pointing Accuracy

- Pointing accuracy increases for larger antenna diameters
- The pointing of the antenna will need to take refraction into account

$$\theta_{\text{HPBW}} \approx \frac{70\lambda}{D}$$

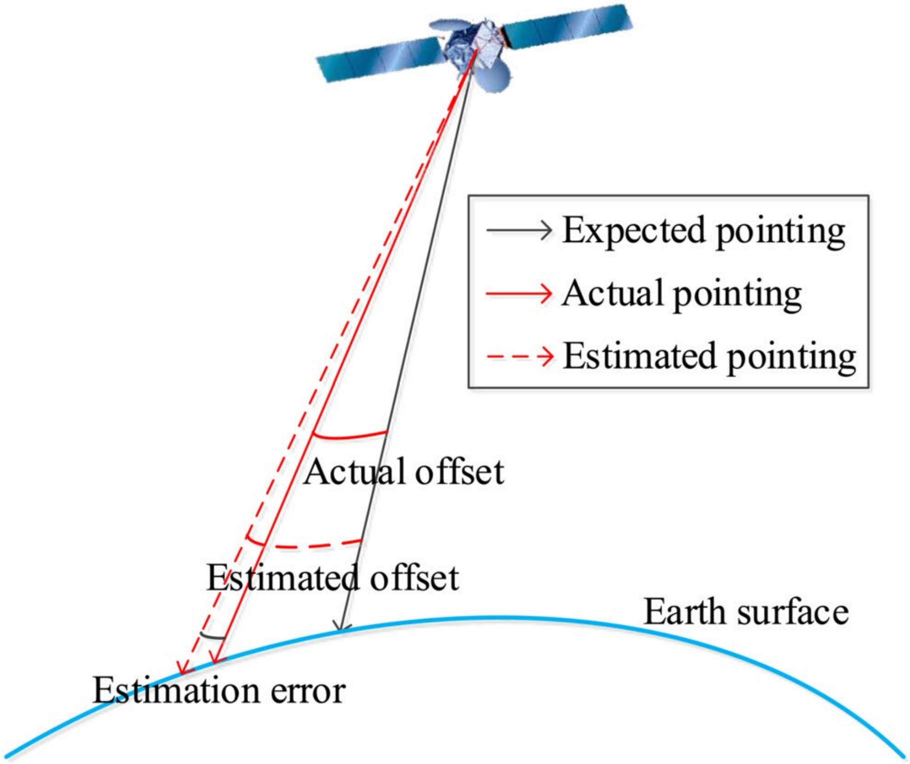
$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{30 \times 10^9} = 1 \times 10^{-2}\,\text{m}$$

$$\theta_{\text{HPBW}} \approx \frac{70(1 \times 10^{-2})}{0.2}$$

$$\theta_{\text{HPBW}} \approx 3.5^\circ$$

$$\text{Pointing Accuracy} = \frac{1}{10} \cdot \theta_{\text{HPBW}}$$

$$\boxed{\text{Pointing Accuracy} = 0.35^\circ}$$



Signal Losses

$$L_{\text{total}} = L_{\text{FS}} + L_{\text{atm}} + L_{\text{rain}} + L_{\text{pol}} + L_{\text{pointing}} + L_{\text{hardware}}$$

$$L_{\text{FS}} = \left(\frac{4\pi d}{\lambda}\right)^2$$

$$L_{\text{FS}} = \left(\frac{4\pi \cdot 3.84 \times 10^8\,\text{m}}{1.00 \times 10^{-2}\,\text{m}}\right)^2$$

$$L_{\text{FS}} \approx 2.33 \times 10^{23}$$

$$L_{\text{FS}} \approx -234\,\text{dB}$$

Values below are based on collected data[4]

$$L_{\text{atm}} \approx -2\,dB$$

$$L_{\text{rain}} \approx -3\,dB$$

$$L_{\text{pol}} \approx -1\,dB$$

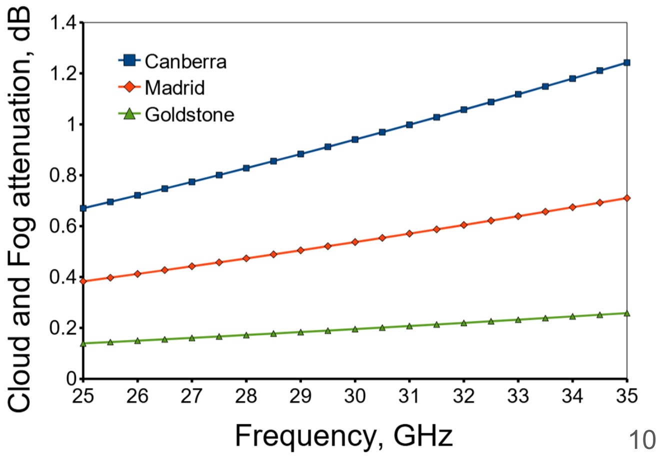
$$L_{\text{pointing}} \approx -1\,dB$$

$$L_{\text{total}} = -234 - 2 - 3 - 1 - 1$$

$$\boxed{L_{\text{total}} = -241\,\text{dB}}$$

- Rain attenuation poses a significant risk
- Free space loss accounts from majority of signal weakening
- Losses due to hardware are potentially large

On the left is an estimate of the total signal losses. On the right is a graph of water vapor attenuation for DSN sites



Link Budget

Transmit Power:

$$P_t = 35\ \text{W} = 35{,}000\ \text{mW}$$

$$P_t(\text{dBm}) = 10\log_{10}(35000) = 45.44\ \text{dBm}$$

Wavelength:

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{30\times10^9} = 0.01\ \text{m}$$

Antenna Gain Formula:

$$G = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

$$G_{\text{dBi}} = 10\log_{10}(G)$$

Transmit Antenna Gain $(D_t = 0.2\ \text{m}, \eta = 0.6)$:

$$G_t = 0.6\left(\frac{\pi(0.2)}{0.01}\right)^2 = 0.6(62.83)^2 = 2368.7$$

$$G_t(\text{dBi}) = 10\log_{10}(2368.7) = 33.75\ \text{dBi}$$

Ground Station Gain $(D_r = 13\ \text{m}, \eta = 0.6)$:

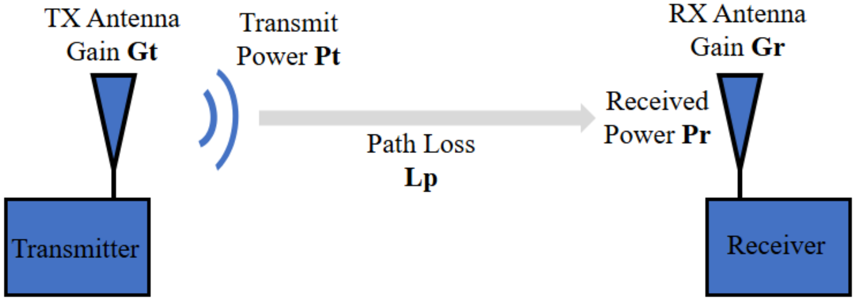
$$G_r = 0.6\left(\frac{\pi(13)}{0.01}\right)^2 = 0.6(4084.07)^2 = 1.001\times10^7$$

$$G_r(\text{dBi}) = 10\log_{10}(1.001\times10^7) = 70.01\ \text{dBi}$$

Link Budget $(L = 241\ \text{dB})$:

$$\begin{aligned} P_r &= P_t + G_t + G_r - L \\ &= 45.44 + 33.75 + 70.01 - 241 \\ &= -91.8\ \text{dBm} \end{aligned}$$

- Link margin is at least 5 dB
- NSN minimum signal strength for detection -100 dBm

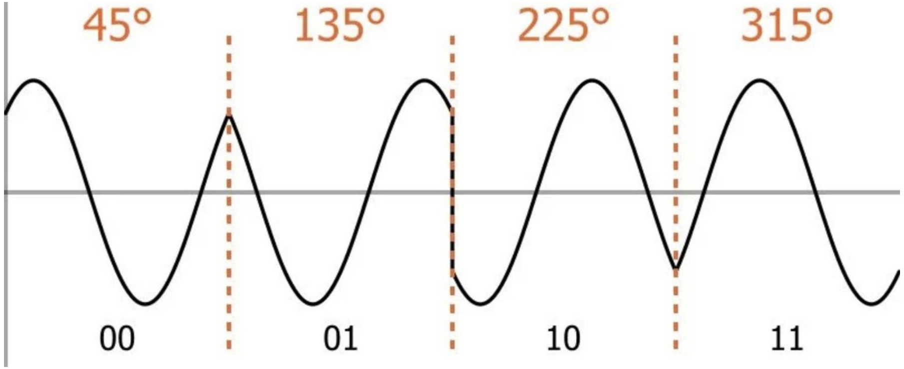


Frequency Modulation

- GMSK is a possibility
  - Power efficient
  - Struggles in high S/N
- QPSK is an ideal
  - Decent data rate
  - Efficient use of bandwidth
  - Common in transceivers
  - Resilient in high S/N environments
- QAM-16 for high data rates
  - Offers high data rates (4 bits/sym)
  - Struggles in high S/N

QPSK Modulation

Slightly misleading, each symbol should stretch over several periods



Data Transmission Rates

$$R_{\text{info}} = B_{\text{ch}}\,\eta_{\text{eff}}$$

$$\eta_{\text{eff}} = \frac{\log_2(M)\,r_c\,\gamma}{1+\alpha}$$

$$R_{\text{info}} = B_{\text{ch}}\,\frac{\log_2(M)\,r_c\,\gamma}{1+\alpha}$$

Assumed Values:

$$M = 4 \quad \text{(QPSK)}$$
$$B_{\text{ch}} = 41 \times 10^6\ \text{Hz}$$
$$\alpha = 0.25 \quad \text{(RRC rolloff)}$$
$$r_c = \frac{1}{2} \quad \text{(FEC code rate)}$$
$$\gamma = 0.95 \quad \text{(framing efficiency)}$$

Numerical Result:

$$\begin{aligned} R_{\text{info}} &= (41 \times 10^6)\,\frac{\log_2(4)\,\left(\frac{1}{2}\right)(0.95)}{1+0.25} \\ &= (41 \times 10^6)\,\frac{(2)(0.5)(0.95)}{1.25} \\ &\approx 3.12 \times 10^7\ \text{bps} \\ &\approx 31.2\ \text{Mbps} \end{aligned}$$

- Data rate is largely determined by
  - Allowed bandwidth
  - Modulation scheme
- Terms
  - Rolloff → how much extra bandwidth signal occupies
  - FEC → transmitting a copy of the data
  - Framing efficiency → percent of transmitted bits that are payload
- 3.9 MBps
- 6 hour 25 min transmit time

System Noise

Noise Spectral Density $(T = 400 \text{ K})$ **:**

$$\begin{aligned} N_0 &= kT \\ N_0 &= (1.38 \times 10^{-23})(400) \\ &= 5.52 \times 10^{-21} \text{ W/Hz} \end{aligned}$$

Energy Per Bit:

$$\begin{aligned} R_b &= 32.1 \times 10^6 \text{ bps} \\ E_b &= \frac{P_r}{R_b} \\ &= \frac{6.61 \times 10^{-13}}{32.1 \times 10^6} \\ &\approx 2.06 \times 10^{-20} \text{ J} \end{aligned}$$

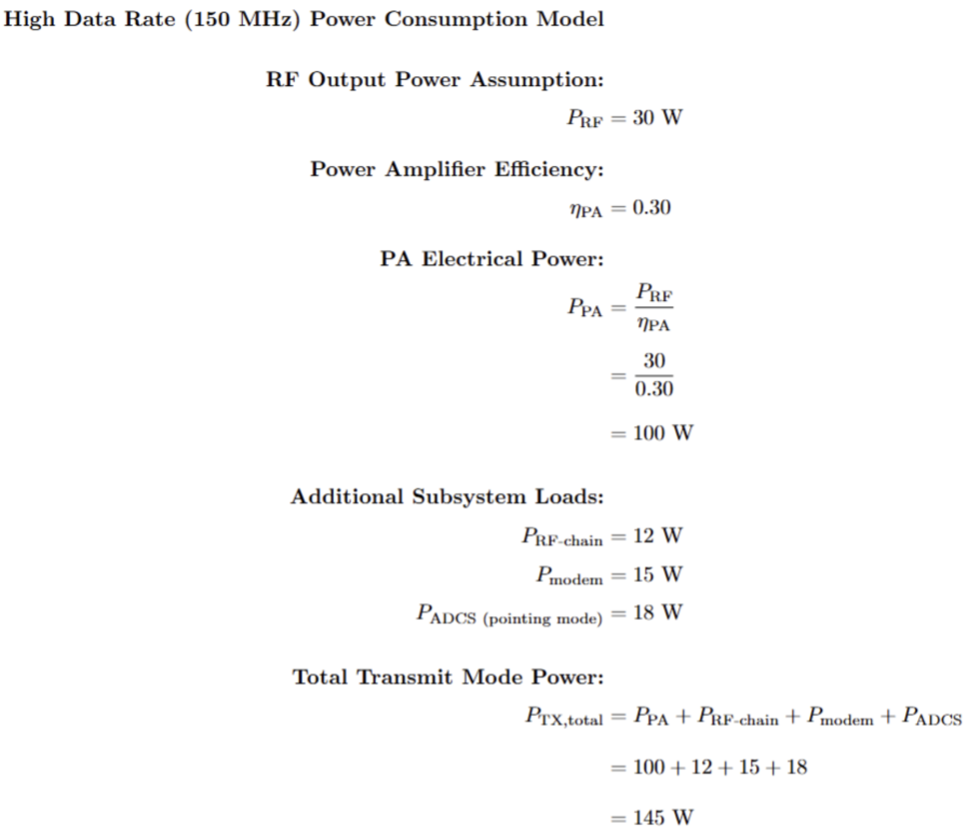
Energy per Bit to Noise Density Ratio:

$$\begin{aligned} \frac{E_b}{N_0} &= \frac{2.06 \times 10^{-20}}{5.52 \times 10^{-21}} \\ &\approx 3.73 \end{aligned}$$

$$\begin{aligned} \left(\frac{E_b}{N_0}\right)_{\text{dB}} &= 10 \log_{10}(3.73) \\ &\approx 5.72 \text{ dB} \end{aligned}$$

- Eb/N0 → Energy per bit to noise power spectral density ratio
- Measure of how much energy a bit has compared to noise of channel
- Thermal noise at 400K assumed for calculations
- Eb/N0 must be at least 4 dB for coded QPSK

Power Usage of Comms System



High Data Rate (150 MHz) Power Consumption Model

RF Output Power Assumption:

$$P_{\mathrm{RF}} = 30\ \mathrm{W}$$

Power Amplifier Efficiency:

$$\eta_{\mathrm{PA}} = 0.30$$

PA Electrical Power:

$$\begin{aligned} P_{\mathrm{PA}} &= \frac{P_{\mathrm{RF}}}{\eta_{\mathrm{PA}}} \\ &= \frac{30}{0.30} \\ &= 100\ \mathrm{W} \end{aligned}$$

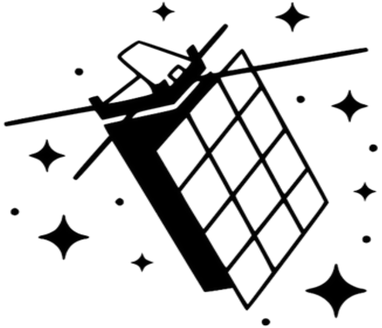
Additional Subsystem Loads:

$$\begin{aligned} P_{\mathrm{RF\text{-}chain}} &= 12\ \mathrm{W} \\ P_{\mathrm{modem}} &= 15\ \mathrm{W} \\ P_{\mathrm{ADCS\ (pointing\ mode)}} &= 18\ \mathrm{W} \end{aligned}$$

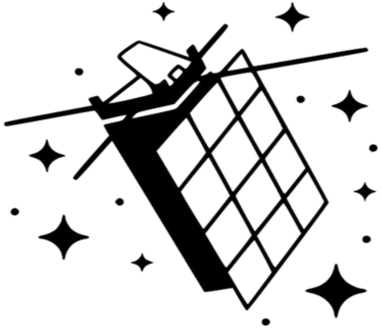
Total Transmit Mode Power:

$$\begin{aligned} P_{\mathrm{TX,total}} &= P_{\mathrm{PA}} + P_{\mathrm{RF\text{-}chain}} + P_{\mathrm{modem}} + P_{\mathrm{ADCS}} \\ &= 100 + 12 + 15 + 18 \\ &= 145\ \mathrm{W} \end{aligned}$$

- High power amplifier accounts for majority of energy usage
- Higher frequencies → amplifier less efficient
- The communication system on JWST is 170 W
    - HS-3’s comm system has similar energy usage
- Cubesat Ka-Band transceivers are available

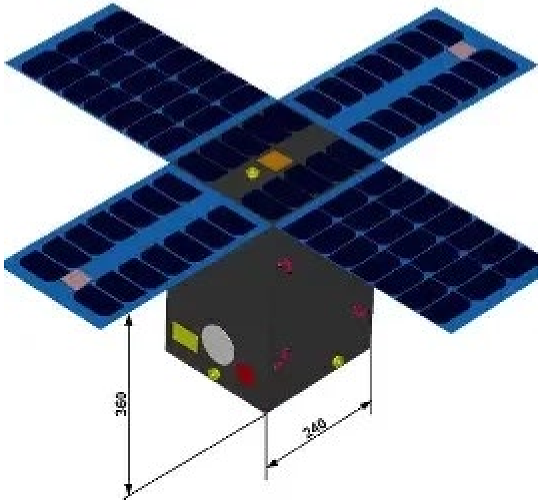


Budgets



Power Budget

Power



Area = ~2000cm^2 for a 12U satellite

Formula for peak instantaneous power:

$$P_{peak} = G * A * \eta * cos(\theta)$$

G = Solar constant (1361 W/m^2 at 1AU)

η = Cell conversion efficiency

A = Area (m^2)

θ = incidence angle to the Sun

Formula for average usable power through orbit:

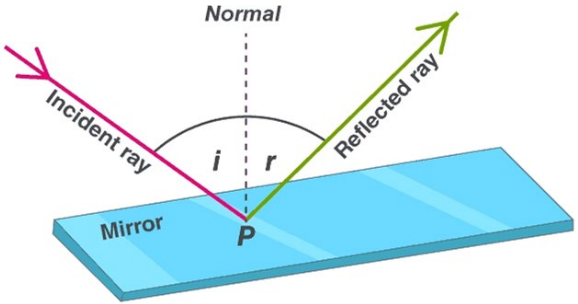
$$P_{avg} = P_{peak} * f_{sun} * f_{loss}$$

$$P_{peak} = (1361W/m^2) * (0.28m^2) * (0.2) * cos(0) - - > P_{peak} = 76.216W$$

Assuming a F_loss of 0.6 (conservative), we get the following:

$$P_{avg} = (76.216W) * (1) * (0.6) - - > P_{avg} = 45.7W$$

Power Generation



$$P(\theta) = P_m cos(\theta) \qquad \theta_{max} = 10^{\circ}$$

Source: https://www.pumpkinspace.com/uploads/8/2/6/7/82676946/s288672987626690703_p198_i5_w6016.jpeg?width=2560

Capacity: 2500mAh, 72Wh

Orbit-averaged usable power

$P_{avg} = P_{max} * f_{sun} * F_{loss}$

Using $f_{sun} \approx 0.85$ in LLO

and a conservative $F_{loss} \approx 0.6$

$P_{avg} = 76.2 * 0.85 * 0.6 \approx 38.9W$ instantaneous power generation on average.

If we use that average to calculate the total amount of energy we can generate per orbit:

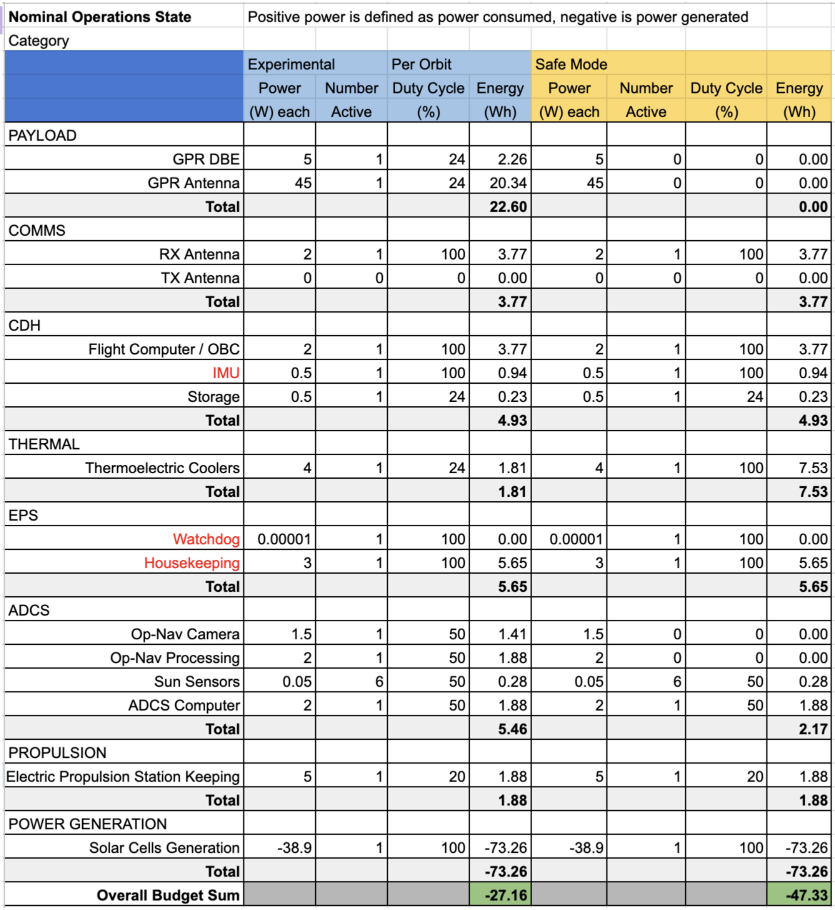
$E_{orbit} \approx P_{avg} * T_{orbit}$

$T_{orbit} \approx 112.96min = 1.883h$

$E_{orbit} = 38.9W * 1.883h = 73.25Wh/orbit$

This is the amount of energy we can generate and store per orbit.

Power Budget Nominal Operations

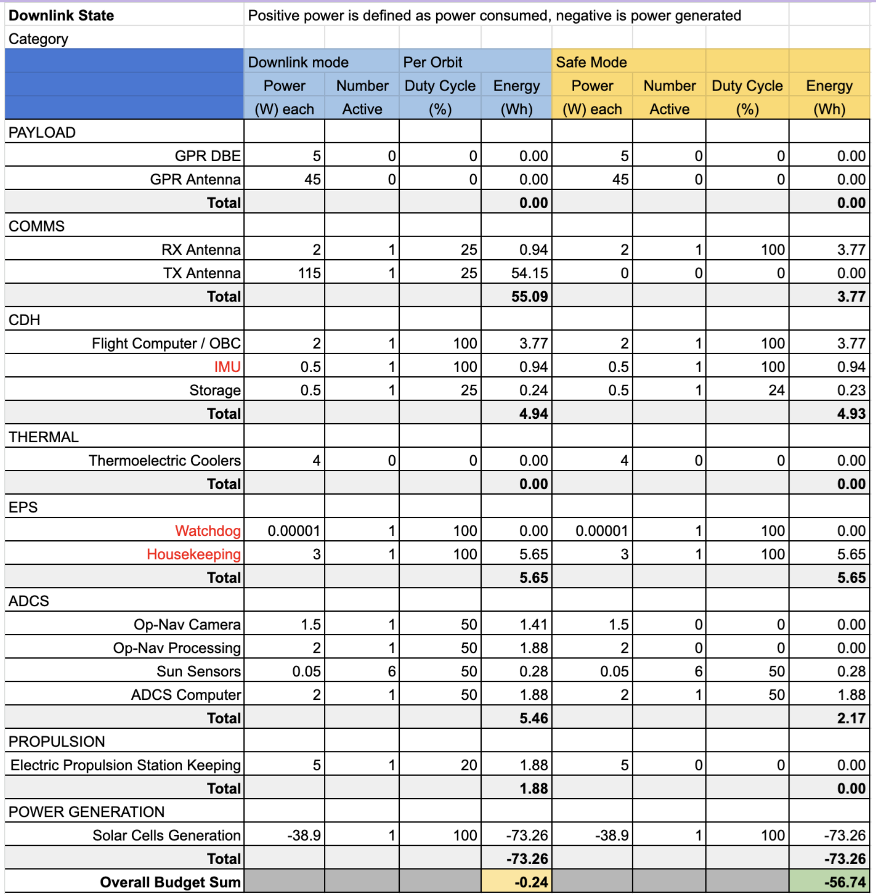


Nominal Operations State	Positive power is defined as power consumed, negative is power generated							
Category								
	Experimental		Per Orbit		Safe Mode			
	Power (W) each	Number Active	Duty Cycle (%)	Energy (Wh)	Power (W) each	Number Active	Duty Cycle (%)	Energy (Wh)
PAYLOAD								
GPR DBE	5	1	24	2.26	5	0	0	0.00
GPR Antenna	45	1	24	20.34	45	0	0	0.00
Total				**22.60**				**0.00**
COMMS								
RX Antenna	2	1	100	3.77	2	1	100	3.77
TX Antenna	0	0	0	0.00	0	0	0	0.00
Total				**3.77**				**3.77**
CDH								
Flight Computer / OBC	2	1	100	3.77	2	1	100	3.77
IMU	0.5	1	100	0.94	0.5	1	100	0.94
Storage	0.5	1	24	0.23	0.5	1	24	0.23
Total				**4.93**				**4.93**
THERMAL								
Thermoelectric Coolers	4	1	24	1.81	4	1	100	7.53
Total				**1.81**				**7.53**
EPS								
Watchdog	0.00001	1	100	0.00	0.00001	1	100	0.00
Housekeeping	3	1	100	5.65	3	1	100	5.65
Total				**5.65**				**5.65**
ADCS								
Op-Nav Camera	1.5	1	50	1.41	1.5	0	0	0.00
Op-Nav Processing	2	1	50	1.88	2	0	0	0.00
Sun Sensors	0.05	6	50	0.28	0.05	6	50	0.28
ADCS Computer	2	1	50	1.88	2	1	50	1.88
Total				**5.46**				**2.17**
PROPULSION								
Electric Propulsion Station Keeping	5	1	20	1.88	5	1	20	1.88
Total				**1.88**				**1.88**
POWER GENERATION								
Solar Cells Generation	-38.9	1	100	-73.26	-38.9	1	100	-73.26
Total				**-73.26**				**-73.26**
Overall Budget Sum				**-27.16**				**-47.33**

Main Takeaways:

- Orbital period of 113 minutes
- GPR Antenna: 45W
- Electric Propulsion
- All other numbers are based on assumptions from other CubeSat missions / HS-2
- Power Positive

Power Budget Downlink Phase

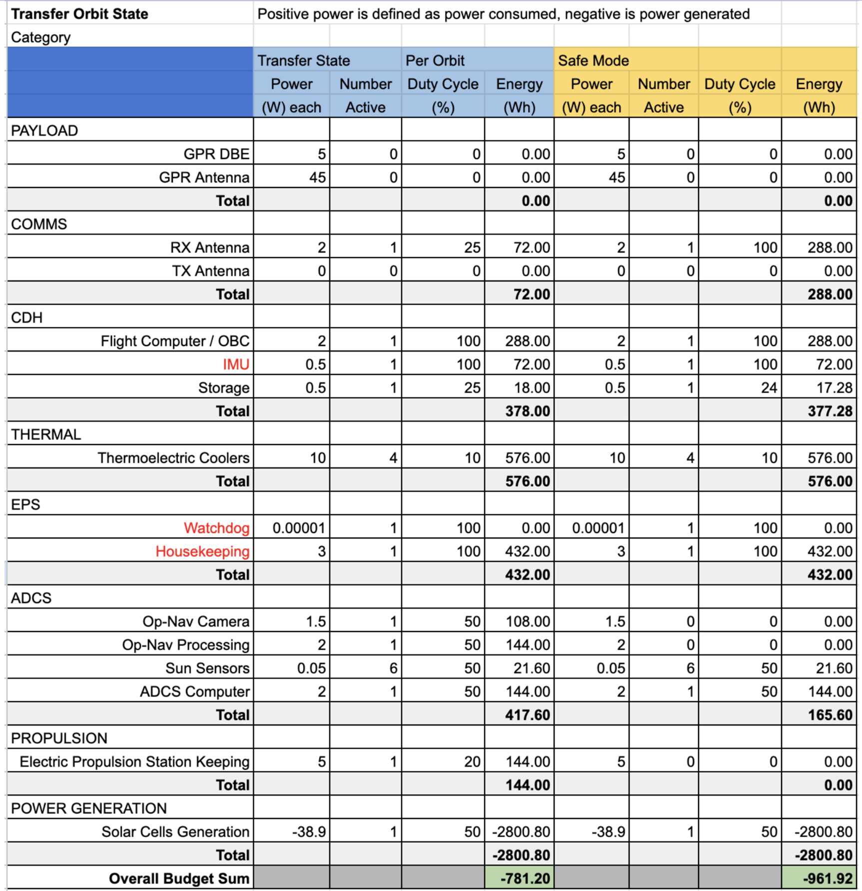


Downlink State	Positive power is defined as power consumed, negative is power generated							
Category								
	Downlink mode		Per Orbit		Safe Mode			
	Power (W) each	Number Active	Duty Cycle (%)	Energy (Wh)	Power (W) each	Number Active	Duty Cycle (%)	Energy (Wh)
PAYLOAD								
GPR DBE	5	0	0	0.00	5	0	0	0.00
GPR Antenna	45	0	0	0.00	45	0	0	0.00
Total				**0.00**				**0.00**
COMMS								
RX Antenna	2	1	25	0.94	2	1	100	3.77
TX Antenna	115	1	25	54.15	0	0	0	0.00
Total				**55.09**				**3.77**
CDH								
Flight Computer / OBC	2	1	100	3.77	2	1	100	3.77
IMU	0.5	1	100	0.94	0.5	1	100	0.94
Storage	0.5	1	25	0.24	0.5	1	24	0.23
Total				**4.94**				**4.93**
THERMAL								
Thermoelectric Coolers	4	0	0	0.00	4	0	0	0.00
Total				**0.00**				**0.00**
EPS								
Watchdog	0.00001	1	100	0.00	0.00001	1	100	0.00
Housekeeping	3	1	100	5.65	3	1	100	5.65
Total				**5.65**				**5.65**
ADCS								
Op-Nav Camera	1.5	1	50	1.41	1.5	0	0	0.00
Op-Nav Processing	2	1	50	1.88	2	0	0	0.00
Sun Sensors	0.05	6	50	0.28	0.05	6	50	0.28
ADCS Computer	2	1	50	1.88	2	1	50	1.88
Total				**5.46**				**2.17**
PROPULSION								
Electric Propulsion Station Keeping	5	1	20	1.88	5	0	0	0.00
Total				**1.88**				**0.00**
POWER GENERATION								
Solar Cells Generation	-38.9	1	100	-73.26	-38.9	1	100	-73.26
Total				**-73.26**				**-73.26**
Overall Budget Sum				**-0.24**				**-56.74**

Main Takeaways:

- Orbital period of 113 minutes
- Similar to Experimental Phase
- TX Antenna requires all available power

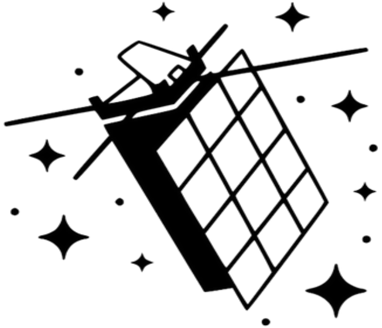
Power Budget Transfer Orbit



Transfer Orbit State	Positive power is defined as power consumed, negative is power generated							
Category								
	Transfer State		Per Orbit		Safe Mode			
	Power (W) each	Number Active	Duty Cycle (%)	Energy (Wh)	Power (W) each	Number Active	Duty Cycle (%)	Energy (Wh)
PAYLOAD								
GPR DBE	5	0	0	0.00	5	0	0	0.00
GPR Antenna	45	0	0	0.00	45	0	0	0.00
Total				**0.00**				**0.00**
COMMS								
RX Antenna	2	1	25	72.00	2	1	100	288.00
TX Antenna	0	0	0	0.00	0	0	0	0.00
Total				**72.00**				**288.00**
CDH								
Flight Computer / OBC	2	1	100	288.00	2	1	100	288.00
IMU	0.5	1	100	72.00	0.5	1	100	72.00
Storage	0.5	1	25	18.00	0.5	1	24	17.28
Total				**378.00**				**377.28**
THERMAL								
Thermoelectric Coolers	10	4	10	576.00	10	4	10	576.00
Total				**576.00**				**576.00**
EPS								
Watchdog	0.00001	1	100	0.00	0.00001	1	100	0.00
Housekeeping	3	1	100	432.00	3	1	100	432.00
Total				**432.00**				**432.00**
ADCS								
Op-Nav Camera	1.5	1	50	108.00	1.5	0	0	0.00
Op-Nav Processing	2	1	50	144.00	2	0	0	0.00
Sun Sensors	0.05	6	50	21.60	0.05	6	50	21.60
ADCS Computer	2	1	50	144.00	2	1	50	144.00
Total				**417.60**				**165.60**
PROPULSION								
Electric Propulsion Station Keeping	5	1	20	144.00	5	0	0	0.00
Total				**144.00**				**0.00**
POWER GENERATION								
Solar Cells Generation	-38.9	1	50	-2800.80	-38.9	1	50	-2800.80
Total				**-2800.80**				**-2800.80**
Overall Budget Sum				**-781.20**				**-961.92**

Main Takeaways:

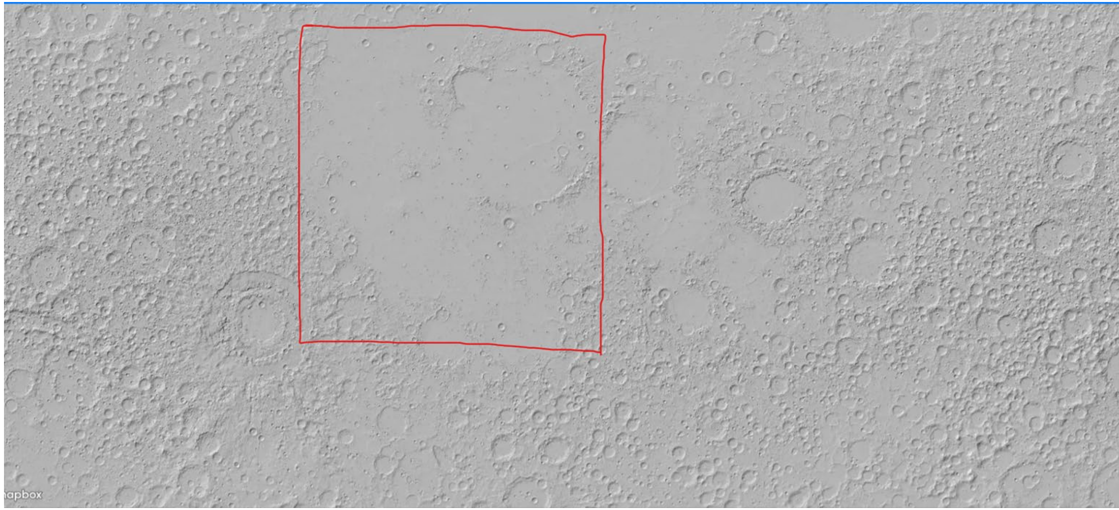
- Max orbital period 6 days
- Worst-case 50% sun-pointing
- Propulsion chemical w/ occasional input from electric propulsion system
- Mainly CDH, ADCS, RX Antenna
- Cooling for Propulsion



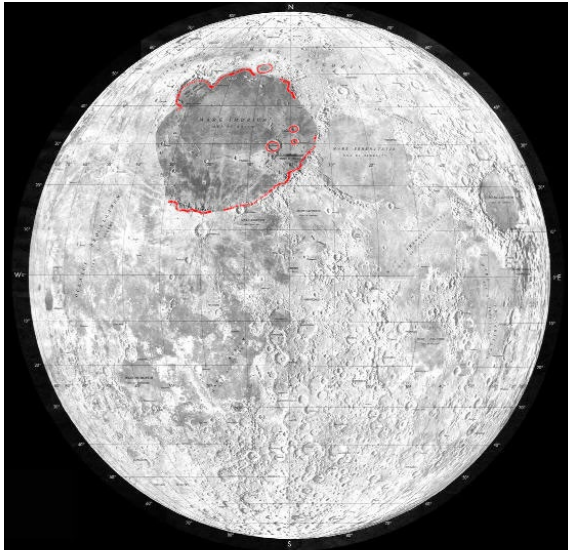
Data Budget

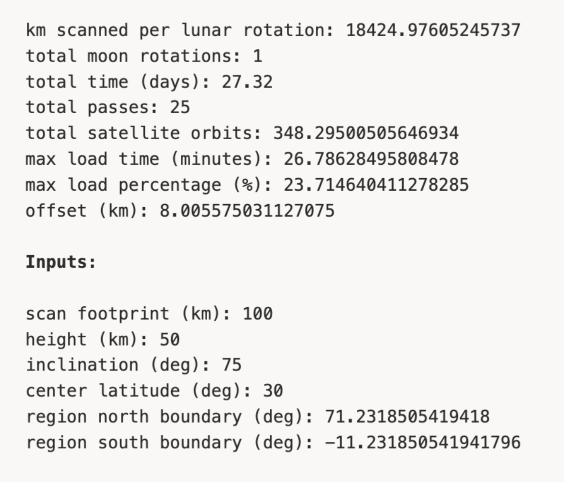
Data

- Assume bounding box around area of interest for max (worst case) condition
- Assume 8 repetitions of total passes (doable in one lunar rotation)
- Math flow:
    - Calculate data per each kilometer of tracing
    - Calculate data per each second of radar being operational
    - Find total amount of second the radar is operational
    - Find total amount of data collected



Data





```
km scanned per lunar rotation: 18424.97605245737
total moon rotations: 1
total time (days): 27.32
total passes: 25
total satellite orbits: 348.29500505646934
max load time (minutes): 26.78628495808478
max load percentage (%): 23.714640411278285
offset (km): 8.005575031127075

Inputs:

scan footprint (km): 100
height (km): 50
inclination (deg): 75
center latitude (deg): 30
region north boundary (deg): 71.2318505419418
region south boundary (deg): -11.231850541941796
```

bytes per trace = bits/8:

- low-band: $2{,}400 \div 8 = 300\ \text{bytes/trace}$.
- high-band: $12{,}000 \div 8 = 1{,}500\ \text{bytes/trace}$.

bytes per second (raw) = bytes/trace × PRF (1000):

- low-band: $300 \times 1000 = 300{,}000\ \text{bytes/s}$.
- high-band: $1{,}500 \times 1000 = 1{,}500{,}000\ \text{bytes/s}$.

Worst-case overall passes required over the region: 198

Time for each pass: ~ 26 minutes

Total time in seconds:

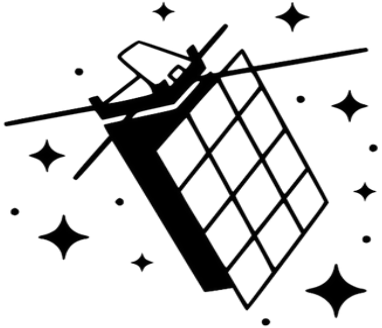
$$T = 26 \cdot 60 \cdot 198 = 308880\ sec$$

Total data:

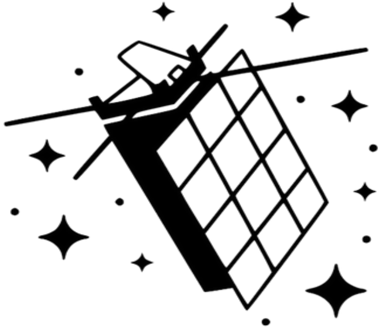
$$Data_{total} = \left(0.2894415563\ \frac{MB}{s}\right) \cdot 308880\ s$$

$$Data_{total} = 89402.70791\ MB = 89.4\ GB$$

Pictures:
https://upload.wikimedia.org/wikipedia/commons/f/f3/Imbrium_location.jpg



Optical Navigation

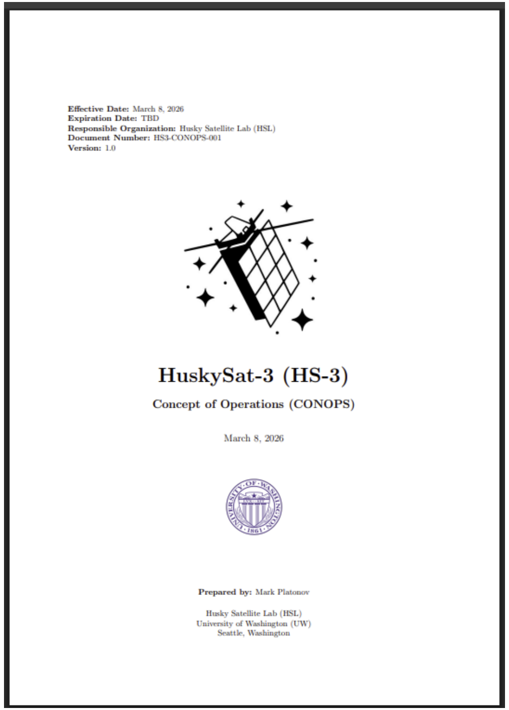


CONOPS

CONOPS

Culminating Stage in Mission Development

- Analyze for *functional* requirements of subsystems
- Establish detailed order of actions
- Gain insight into operational risks and management
- Set the stage for the satellite's state machine and flight software development



Effective Date: March 8, 2026
Expiration Date: TBD
Responsible Organization: Husky Satellite Lab (HSL)
Document Number: HS3-CONOPS-001
Version: 1.0

HuskySat-3 (HS-3)

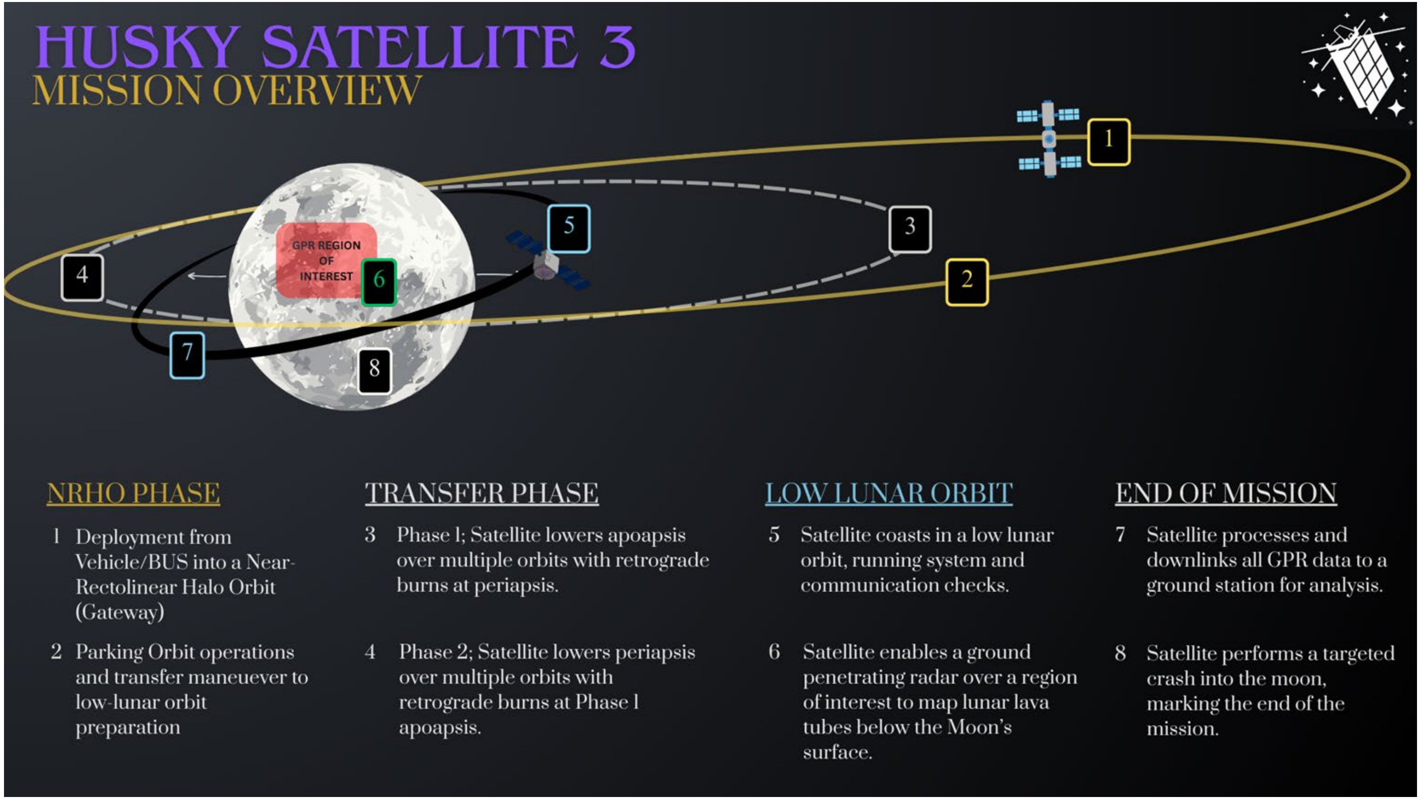
Concept of Operations (CONOPS)

March 8, 2026

Prepared by: Mark Platonov

Husky Satellite Lab (HSL)
University of Washington (UW)
Seattle, Washington

CONOPS



HUSKY SATELLITE 3
MISSION OVERVIEW

NRHO PHASE

1 Deployment from Vehicle/BUS into a Near-Rectolinear Halo Orbit (Gateway)

2 Parking Orbit operations and transfer maneuever to low-lunar orbit preparation

TRANSFER PHASE

3 Phase 1; Satellite lowers apoapsis over multiple orbits with retrograde burns at periapsis.

4 Phase 2; Satellite lowers periapsis over multiple orbits with retrograde burns at Phase 1 apoapsis.

LOW LUNAR ORBIT

5 Satellite coasts in a low lunar orbit, running system and communication checks.

6 Satellite enables a ground penetrating radar over a region of interest to map lunar lava tubes below the Moon's surface.

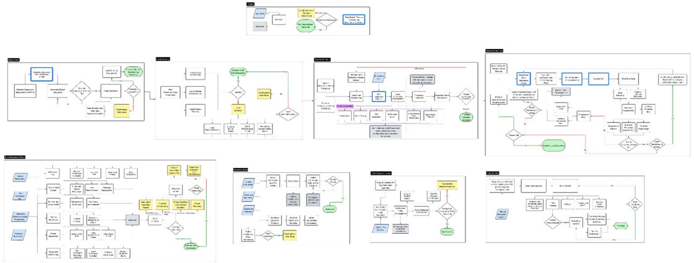
END OF MISSION

7 Satellite processes and downlinks all GPR data to a ground station for analysis.

8 Satellite performs a targeted crash into the moon, marking the end of the mission.

Design Philosophy

- The HS-3 mission targets a fully autonomous configuration for all operational stages
    - ➢ Allows for prioritization of communication link budgets for high-bandwidth science operations
- Steps taken:
    1. Evaluate basic requirements
    2. Determine available operational margin
    3. Push a chain of constraints



Initial Wireframe Mapping

Operational Philosophy

Our concept is based on three principles expressed in order of importance:

1. Deploy and operate the spacecraft safely in the cislunar and lunar environments
2. Acquire and disseminate spacecraft telemetry, GPR instrument data, and mapping products to meet mission requirements
3. Operate as efficiently as possible, optimizing the cost and resource usage while meeting data availability and latency requirements

Fault Management

- **Tier 1:** Faults handled automatically by redundant systems. These do not disrupt the main operations flow and are resolved transparently to the primary operational sequence.
- **Tier 2:** Anomalies requiring an active change or branch in operations (e.g., executing a correction burn, adjusting a timeline). This is accounted for in the mission operations flow.
- **Tier 3:** Critical failures (e.g., low battery, lost attitude/state, stuck thruster, or persistent unresolvable faults) that immediately halt current operations and trigger an autonomous Safe Mode.

Mission Phases/Modes

- **Primary Phases:**
    - Transfer Phase (NRHO to LLO)
        - Time between deployment and arrival at the final orbit.
    - Science Operations (LLO)
        - Time spent in final orbit.
- **Auxiliary Phases:**
    - Pre-Launch & Integration
    - Deployment & Initial Acquisition
    - End of Mission Decommissioning

- **Operational Modes:**
    - Coasting/Stationkeeping
    - Propulsive Maneuver
    - Science Observation
    - Data Processing & Communications
    - Safe Mode

Transfer Phase

- **Deployment:** Team monitors satellite array deployment and initial detumble metrics until nominal separation distance is achieved
- **Orbit Characterization:** The Optical Navigation system runs the Initial Orbit Determination (IOD) sequence until navigation uncertainty is within the strict threshold
- **Transfer Planning:** Evaluates phase constraints, finalizes the trajectory, and generates a Burn Index List with phase-level abort criteria
  - Two Phase: (1, 17.5 days) Lower apoapsis to target LLO altitude, (2, 5.5 days) Lower periapsis to target LLO Altitude
- **Burn Readiness Check:** Verifies tank and feed system pressure, thruster and valve health, thermal readiness, and battery state of charge prior to the burn epoch
- **Transfer Execution:** Initiates the burn, tracks real-time trajectory, and performs a post-burn assessment to estimate predicted new radius and remaining propellant

Science Phase

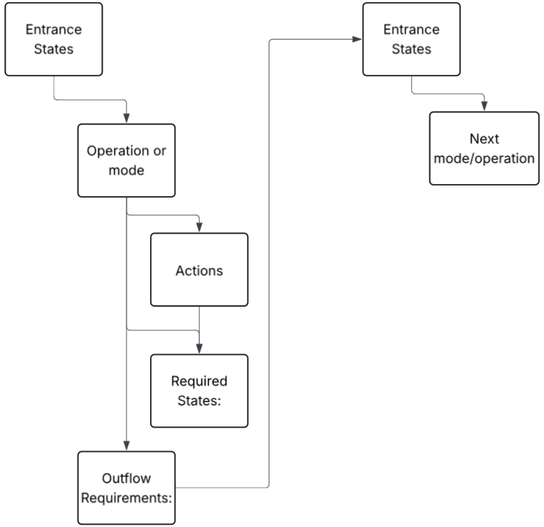
Critical flow of operations:

- **System switchover:** Switch over optical navigation system to begin obtaining latitude and longitude and switch over source of orbital maneuver from chemical to electrical propulsion

- **Stability check:** Ensure orbital stability [enter orbital correction branch if unstable]
- **Op-nav on:** Track the time it takes to reach area of interest, turn on navigation within 10 minutes of reaching the region.
- **Radar on:** Turn on the radar within 1 minute of reaching the region. Collect data until region is passed.
- **Downlink**: Triple redundant method of checking when the radar's data collection is "done". Move into establishing ground link and transmitting data

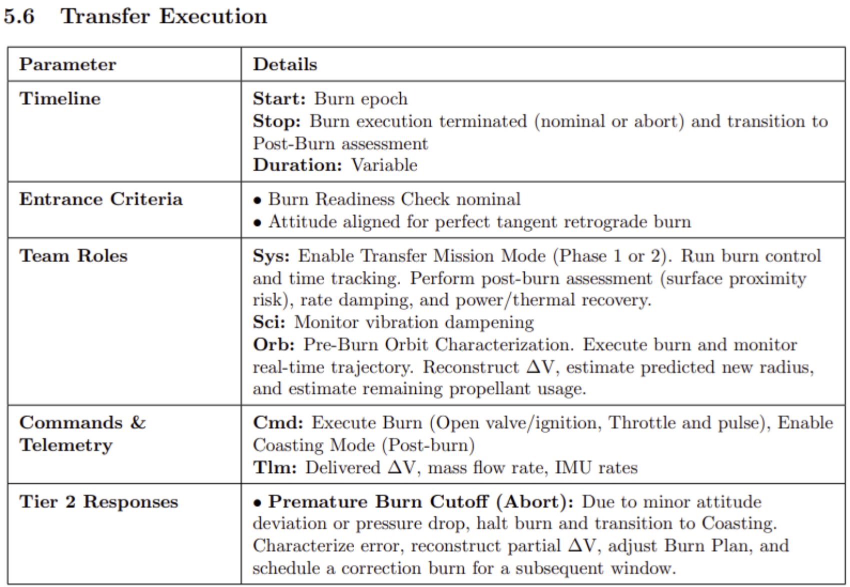
Standardization

- Every step contains Parameter & Details:
  - **Timeline:** start, stop, and duration of each operation
  - **Team roles:** what each team member needs to be doing for each operation
  - **Commands and Telemetry:** what commands are being sent and what telemetry should be reading
  - **Tier 2 responses:** diversions in the case of an off nominal event
- Each mode/operation shall have:
  - Required "steps/actions"
  - Required states
  - Outflow requirements



Operation Flow

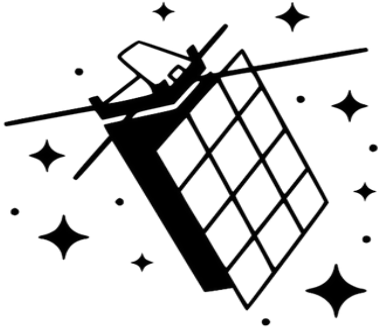
Standardization



5.6 Transfer Execution

Parameter	**Details**
Timeline	**Start:** Burn epoch **Stop:** Burn execution terminated (nominal or abort) and transition to Post-Burn assessment **Duration:** Variable
Entrance Criteria	• Burn Readiness Check nominal • Attitude aligned for perfect tangent retrograde burn
Team Roles	**Sys:** Enable Transfer Mission Mode (Phase 1 or 2). Run burn control and time tracking. Perform post-burn assessment (surface proximity risk), rate damping, and power/thermal recovery. **Sci:** Monitor vibration dampening **Orb:** Pre-Burn Orbit Characterization. Execute burn and monitor real-time trajectory. Reconstruct ΔV, estimate predicted new radius, and estimate remaining propellant usage.
Commands & Telemetry	**Cmd:** Execute Burn (Open valve/ignition, Throttle and pulse), Enable Coasting Mode (Post-burn) **Tlm:** Delivered ΔV, mass flow rate, IMU rates
Tier 2 Responses	• **Premature Burn Cutoff (Abort):** Due to minor attitude deviation or pressure drop, halt burn and transition to Coasting. Characterize error, reconstruct partial ΔV, adjust Burn Plan, and schedule a correction burn for a subsequent window.

Example Block in CONOPS Document



Path Forward

Path Forward

- Program-wide:
  - We’ll be recruiting more engineers to begin design of systems already analyzed
  - We’ll continue analysis cycles and iterating on requirement development (requirements will continue to change)
  - Mission Design Document
  - Risk management matrix
- Communications
  - Continue to put real world considerations into the calculations
  - Create a way to fold the antenna
  - Minimize the power needs of the comms system

Path Forward

- Power:
  - Further refine power budget with more accurate numbers based on hardware and software
  - Thermals / propulsion estimates
- Science:
  - Recruit for Power and Thermal specific positions
  - Review GPR with different altitudes and conditions
  - Continue to solve SNR parameters
  - Continue Thermal and Radiation simulations
- Orbit:
  - Continue gathering reports from simulations and refine orbital elements to ensure mission works.
- Propulsion:
  - RCS propulsion analysis for pointing is yet to happen. That'll be a primary focus from now.
  - Orbital maneuver allocations for thrust minimization

Questions?