# *Exploring Lunar Ionosphere Characterization through Multi-CubeSat Occultation with Ranging Technology and Radiation Environment Analysis*

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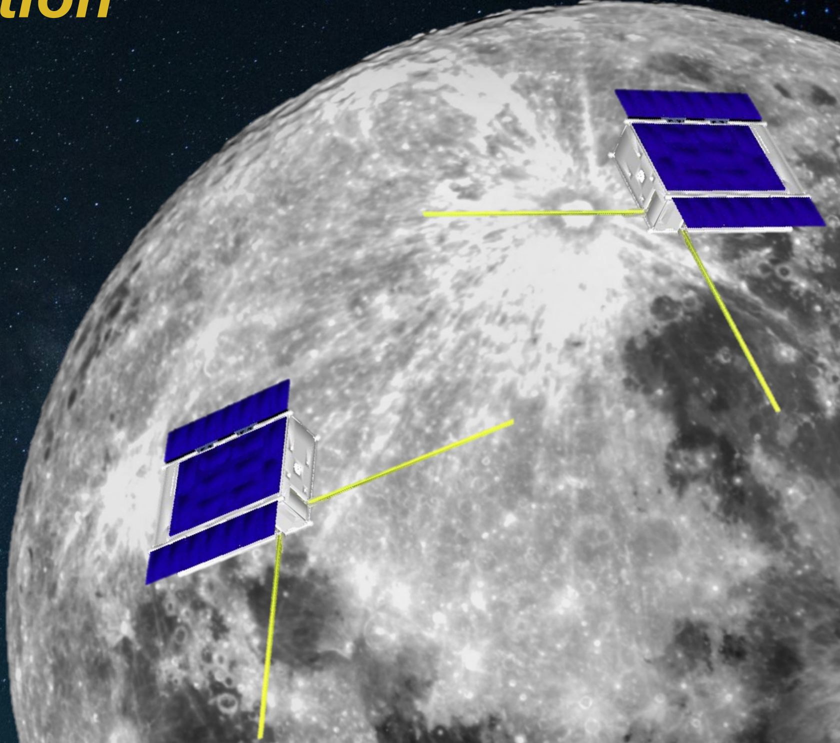
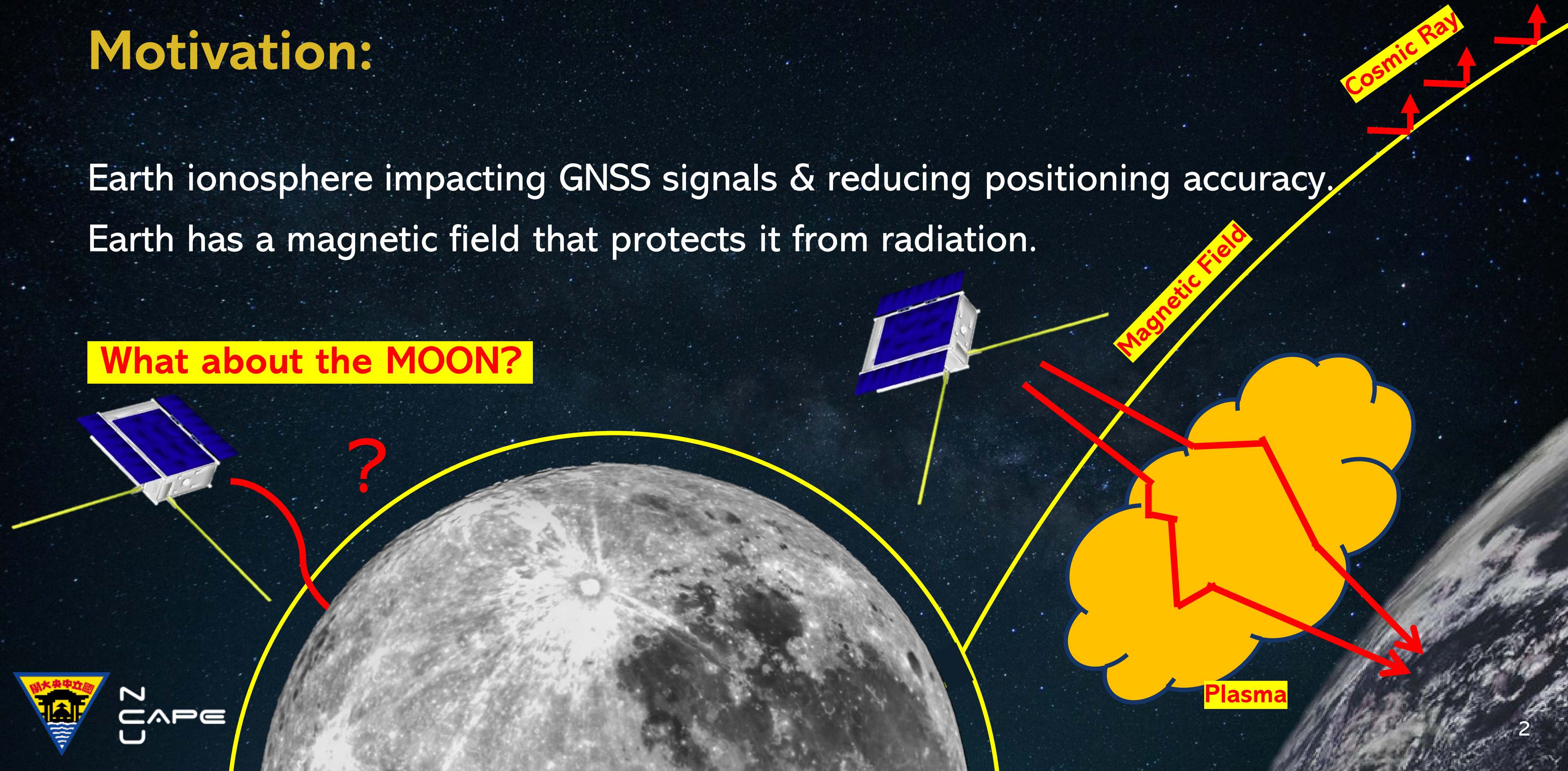
*National Central University,* **TAIWAN**.



# Motivation:

Earth ionosphere impacting GNSS signals & reducing positioning accuracy.

Earth has a magnetic field that protects it from radiation.



# Mission Overview:

Total mass for a CubeSat: **11.7 kg.**

Our mission includes **two 6U CubeSats** into **low lunar orbit.**

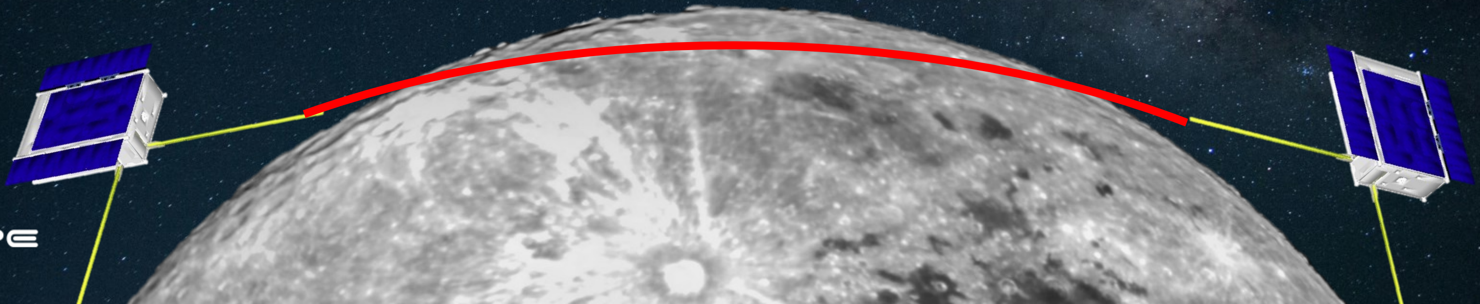
Mission Objective 1 – Radio Occultation

Mission Objective 2 – Radiation Environment

Extend Mission Objective 1 – Radiation with the space weather and ionosphere.

Extend Mission Objective 2 – Orbit determination

Extend Mission Objective 3 – Range measurement



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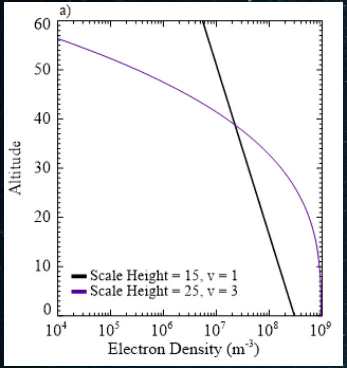
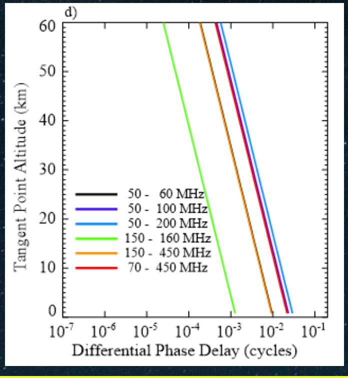
# Objective 1 – Radio Occultation

## Theory of Lunar Ionosphere

1. The lower the frequency, the more significant the phase delay.
2. Simulating lunar ionospheric Total Electron Content (TEC).




Electron Density




Different Phase Delay

(*C. Watson et al*, 2023)

$$I = (40.3/f^2) \cdot TEC \qquad ---(1)$$

$$\delta\phi(t) = \Delta\phi_1(t) - \frac{f_1}{f_2}\Delta\phi_2(t)$$

$$= \frac{40.3}{c} f_1 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \text{ TEC} \qquad -----(2)$$

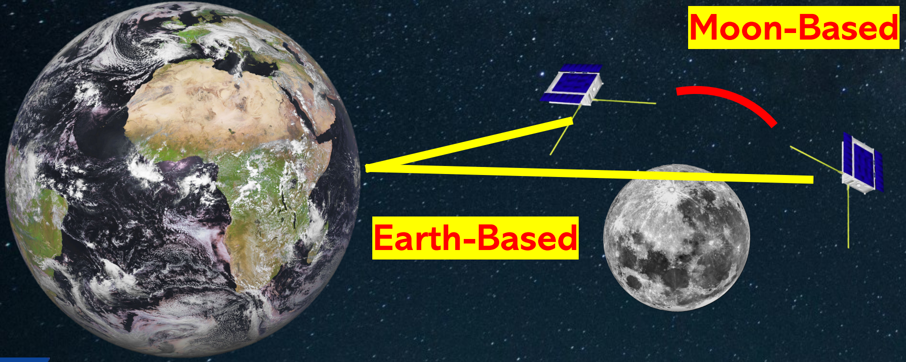
$$\text{LOS TEC} = \int N_e \, dl \qquad -----(3)$$

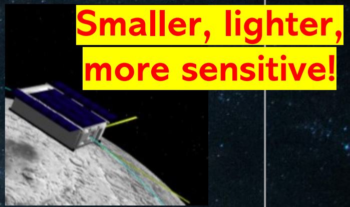
| | |
|---|---|
| $I$ | Phase delay |
| $f$ | Freq. of electromagnetic wave |
| TEC | Representing the number of electrons in a column along the signal path |
| $Ne$ | Electron density |

# Objective 1 – Radio Occultation (cont.)

## Advanced

Our mission can take broader measurements over the Lunar without interference from Earth's ionosphere.



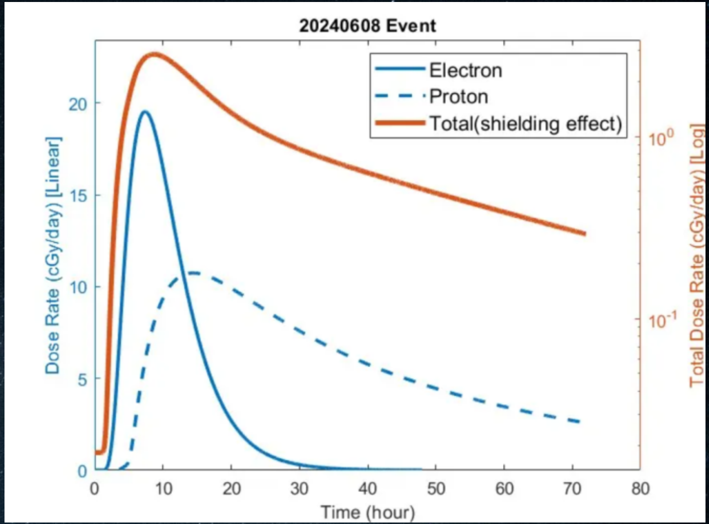

| | | |
|---|---|---|
| **Missions** |  **Luna 19 and 22** |  **Kaguya** |
| **TEC** | 400–2000 $cm^{-3}$ | Approx. 300 $cm^{-3}$ |
| **Freq.** | S-band | S-band |
| **Missions** |  **Chandrayaan-1** |   **Our Mission** |
| **TEC** | Approx. 300 $cm^{-3}$ | ? |
| **Freq.** | S-band | VHF, UHF |

# Objective 2 – Radiation Environment

For example, on June 8, 2024, an M9.7-class solar flare and the associated CME occurred.

Based on particle propagation modeling, the figure shows dose rate of electrons and protons.

The red curve represents the combined dose rate, taking into account the shielding effect.




**Our simulation model predicts DSRP performance under solar events and improves accuracy by comparing with real data.**

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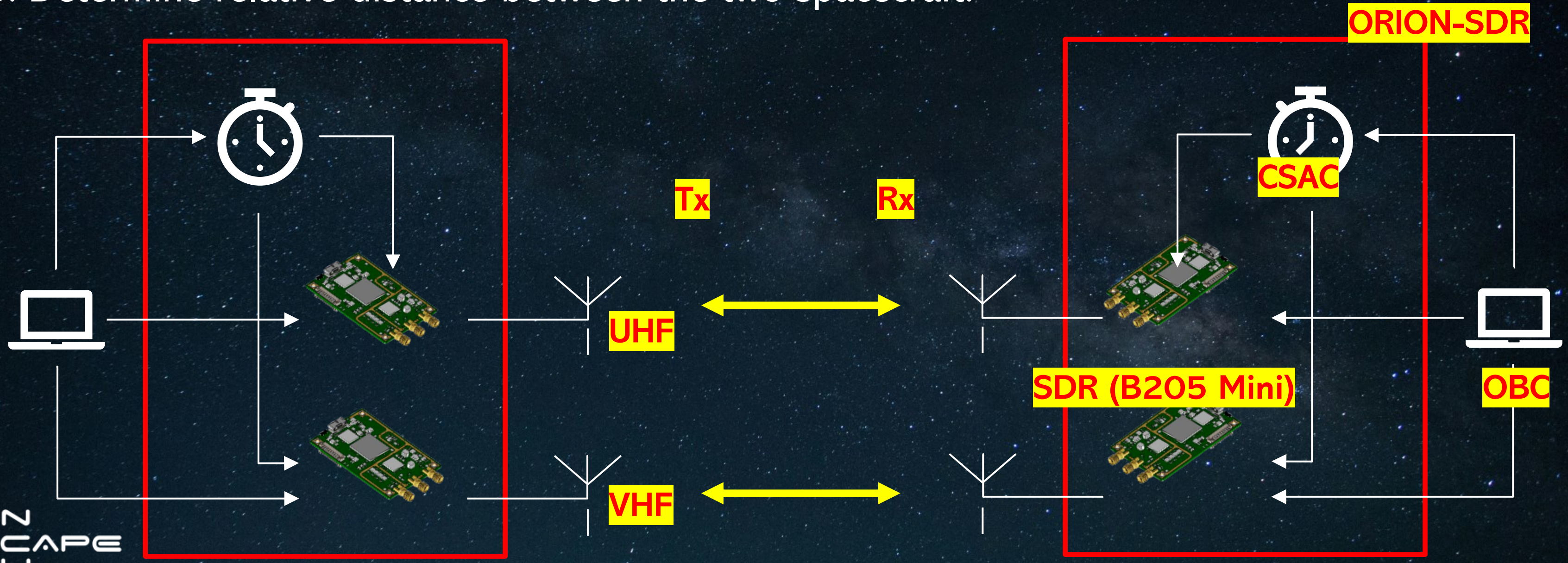
# Payload 1: ORION-SDR

**(Occultation & Ranging Integrated Orbital DeterminatioN – SDR) – TRL3**

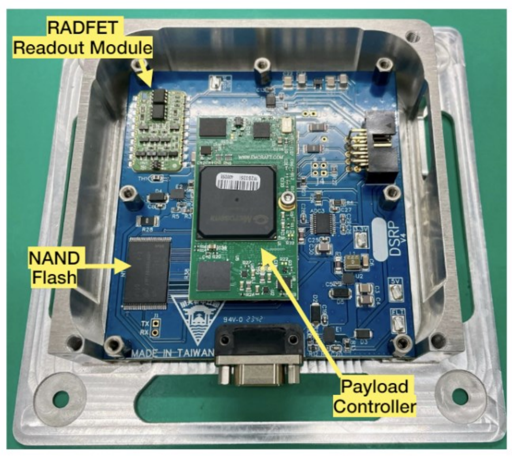
M1. Characterize spatial and temporal distribution of lunar ionosphere.
M2. Determine spacecraft's orbital dynamics with respect to the lunar environment.
M3. Determine relative distance between the two spacecraft.

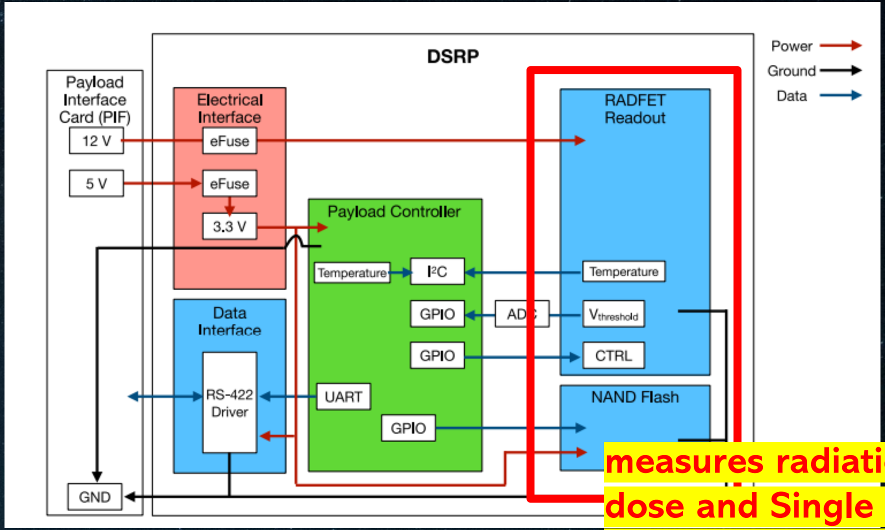


# Payload 2: Deep Space Radiation Probe (DSRP)

M1. Understand the lunar radiation environment and high-energy particles.

M2. Understand the link between space-weather events and radiation.




measures radiation dose and Single Event Upset (SEU) rate

# Orbit Design:

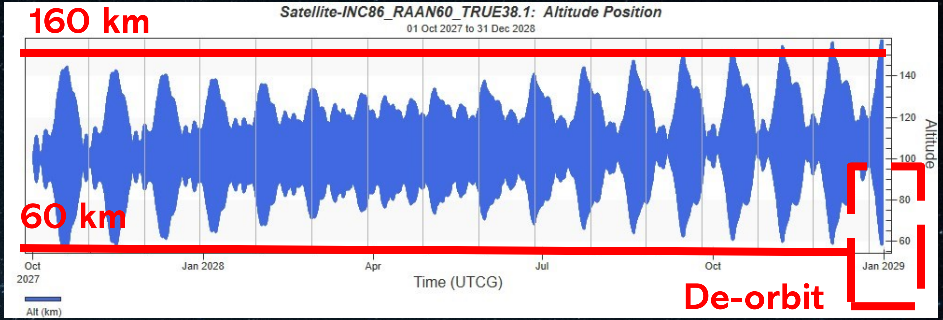
We choose a Quasi-frozen orbit to ensure that relative distance between two satellites remains as stable as possible. The high inclination enables the coverage of lunar polar regions.

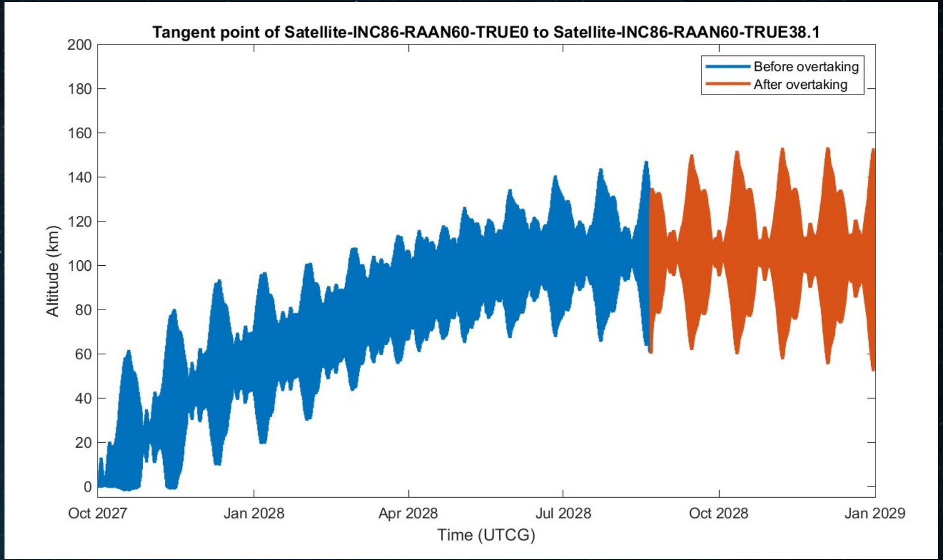
| Orbit Parameters | Reason |
|---|---|
| Inclination<br>(i = 86~90,<br>Quasi-frozen Orbit) | Longer time for communication |
| Range between the satellite = 1000 km | Simulation result |
| a = 100 km | |
| e = 0 | |
| Gravity LP100 | Worst case (STK) |
| Same orbital plane | Forward-and-aft configuration |

# STK Altitude Analysis:

The altitude of CubeSats changes due to the Moon's uneven gravitational field, varying between 160 km and 60 km without crashing into the Moon.

The tangent-point altitude varies from about 0 km at the start to roughly 100 km by the end without maneuver.



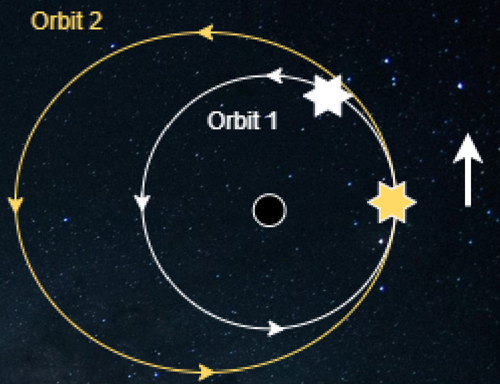
# Maneuver:

**Conditions:**

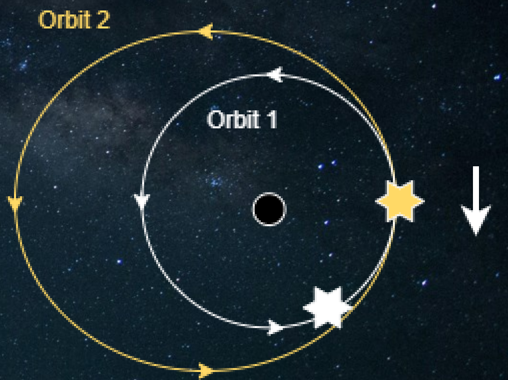
1. When the satellites move too close to each other, there is a potential risk of collision.
2. When they drift too far apart, occultation cannot be achieved.

The rear satellite (in yellow) executes dual burns of 5.15 m/s at perigee over 11 lunar orbits (≈21.6 hr). Temporarily changing its orbit into an elliptical one. Afterward, it returns to the original circular orbit to complete precise phasing and move ahead of the leading satellite.

**Phase 1**



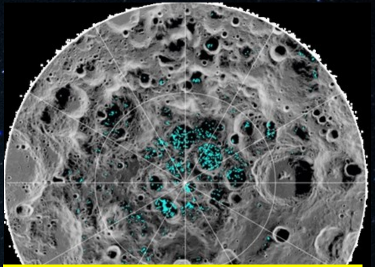

**Phase 2**



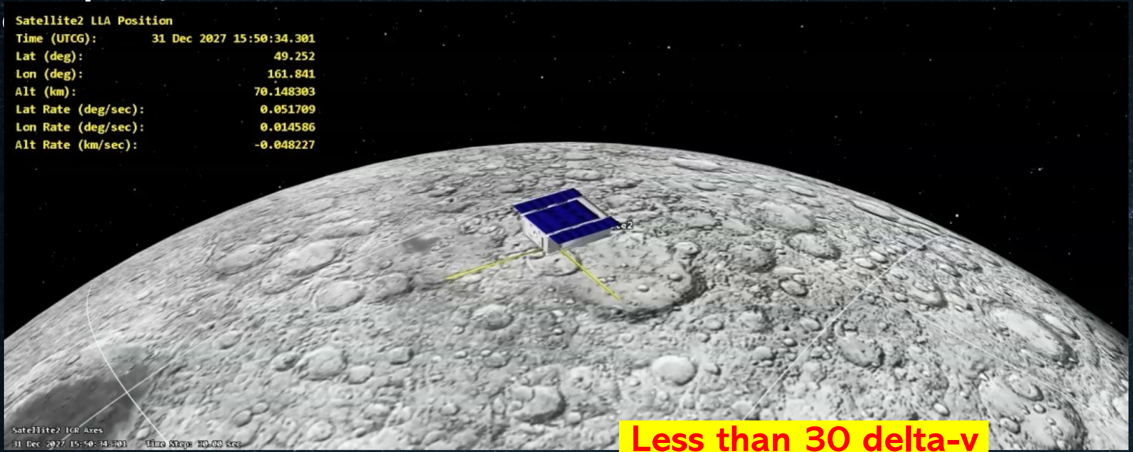
# De-orbit:

## COSPAR Planetary Protection Policy CATEGORY IIA:

Spacecraft control should align with planetary protection



lunar poles which are defined as locations in 79°S and 86°N latitude.




Less than 30 delta-v
De-orbit and crash in 51°N latitude

Permanently Shadowed Region (PSR)

# Concept of Operation:

Science Mode

TT&C Mode

Heating Mode

Proportion Mode

| | Emergency | | Normal | | | | | |
|---|---|---|---|---|---|---|---|---|
| Subsystem | Phoenix | Safe | Charging | TT&C | Science | Proportion | Heating | Maneuver |
| CDH | ON | ON | ON | ON | ON | ON | ON | ON |
| EPS | ON | ON | ON | ON | ON | ON | ON | ON |
| ADCS | OFF | Coarse sun pointing | Fine sun pointing | Target pointing | Target pointing | Momentum unload | OFF | Maneuver |
| TCS | OFF | OFF | OFF | OFF | OFF | OFF | ON | OFF |
| X-Band Tx | OFF | OFF | OFF | ON | OFF | OFF | OFF | OFF |
| X-Band Rx | ON | ON | ON | ON | ON | ON | ON | ON |
| ORION-SDR | OFF | OFF | OFF | OFF | ON | OFF | OFF | OFF |
| DSRP | OFF | OFF | ON | ON | ON | ON | ON | ON |

Charging Mode

Safe Mode

Phoenix Mode

Maneuver Mode

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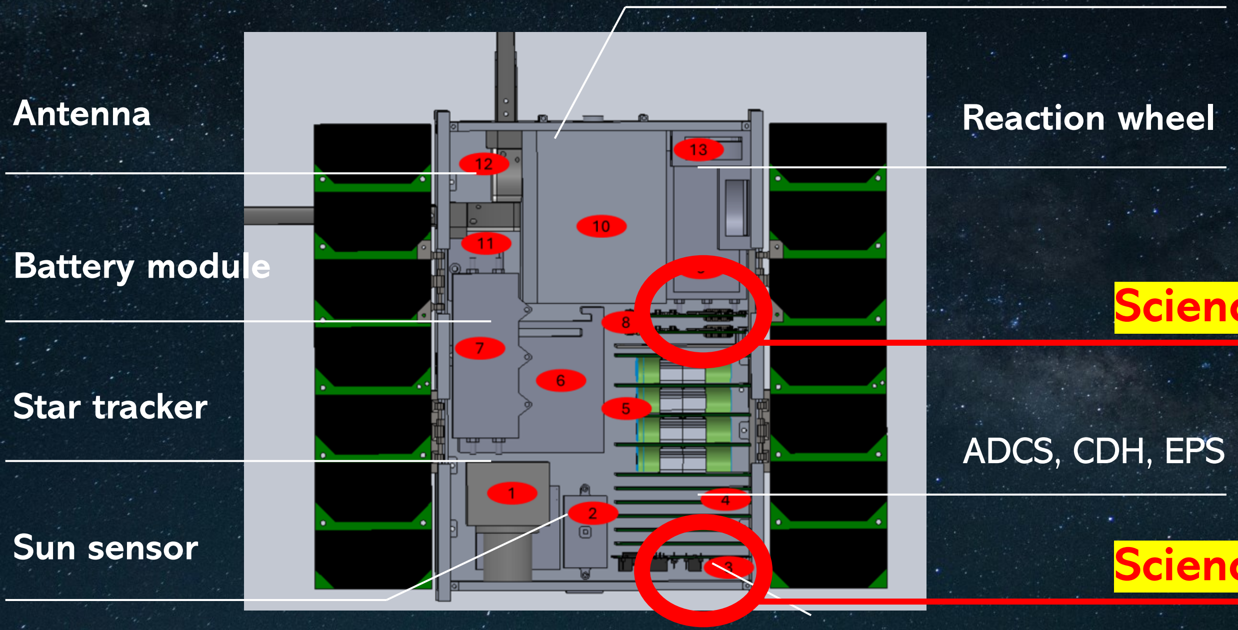
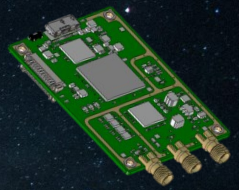
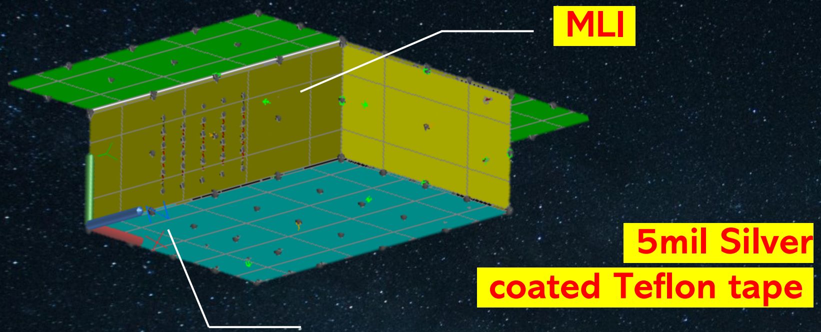
# Spacecraft Interior:

**Based on** 2024 State-of-the-Art Small Spacecraft Technology Report,
**all subsystems have achieved** **TRL >7**



## Thermal



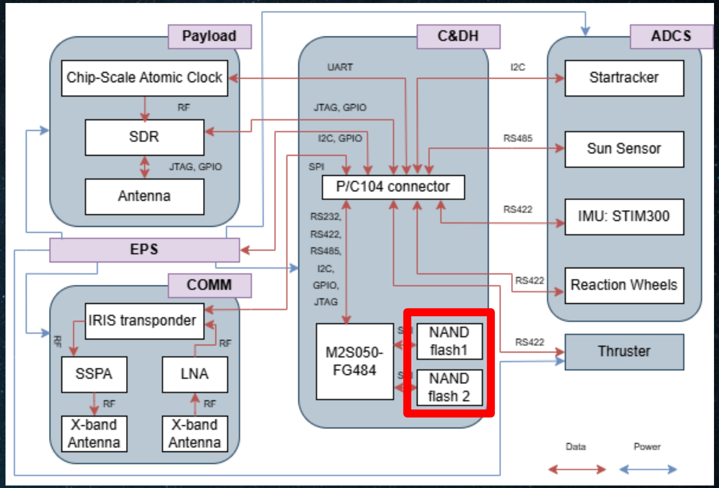

## Propulsion

| Mode | Cold Gas | Green Monopropellant |
|---|---|---|
| Purpose | Momentum Unloading | Maneuver and Orbit Adjustment |
| Propellant/ Event (g) | 0.665 | 50.9 |
| Annual Usage (g/yr) | 69.16 | 203.6 |
| **Propellant Margin** | **67.83%** | **48.9%** |

## EPS

| Item | Power (Wh) |
|---|---|
| Total Consumption | 19.027 |
| Power Generation | 28.333 |
| **Margin** | **32.85%** |

## CDH



# Implementation Plan:

| IMPLEMENTATION PLAN | 2024 | | | 2025 | | | | 2026 | | | | 2027 | | | | 2028 | | | | 2029 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 |
| PrePhase-A | | | | | | | | | | | | | | | | | | | | |
| Phase-A | | | | | | | | | | | | | | | | | | | | |
| Phase-B | | | | | | | | | | | | | | | | | | | | |
| Phase-C | | | | | | | | | | | | | | | | | | | | |
| Purchase | | | | | | | | | | | | | | | | | | | | |
| Product Test | | | | | | | | | | | | | | | | | | | | |
| Phase-D | | | | | | | | | | | | | | | | | | | | |
| Vibration Test | | | | | | | | | | | | | | | | | | | | |
| Radiation Test | | | | | | | | | | | | | | | | | | | | |
| Thermal Vacuum Test | | | | | | | | | | | | | | | | | | | | |
| Test Margin | | | | | | | | | | | | | | | | | | | | |
| Launch | | | | | | | | | | | | | | | | | | | | |
| Phase-E | | | | | | | | | | | | | | | | | | | | |
| Mission Operation | | | | | | | | | | | | | | | | | | | | |
| Data analyze | | | | | | | | | | | | | | | | | | | | |
| Phase-F | | | | | | | | | | | | | | | | | | | | |

3 Eclipses

## Human Resources: Students

| | Number of people | Time [Q] | Cost [USD] |
|---|---|---|---|
| | | | |
| PrePhase-A | 3 | 1 | 2700 |
| Phase-A | 5 | 1 | 4500 |
| Phase-B | 5 | 1 | 4500 |
| Phase-C | 5 | 3 | 13500 |
| Purchase | | | 0 |
| Product | | | 0 |
| Phase-D | 10 | 3 | 27000 |
| Vibration | | | 1500 |
| Radiation | | | 120 |
| Thermal Vacuum | | | 3700 |
| Margin | | | 0 |
| Launch | | | 0 |
| Phase-E | 5 | 5 | 22500 |
| Operation | | | 0 |
| Data | | | 0 |
| Phase-F | 5 | 1 | 4500 |
| CubeSats Components (x2) | | | 345932 |
| Total Cost | | | 430452 |

# Implementation Plan:

Assemble 3D model

Air-bearing table test

# Risk Matrix:

| ID | Risk | Consequence | Likelihood | Risk Score | Solution |
|---|---|---|---|---|---|
| 1 | Loss of Position Information | 4 | 4 | 22 | Transmit ground station signal to inform satellite position and time |
| 2 | Insufficient Funding | 5 | 3 | 21 | Participate in competitions to capture exposure levels |
| 3 | Gravity | 5 | 2 | 17 | Simulate lunar gravitational field on the 100th order |
| 4 | Technical Knowledge Transferred | 4 | 2 | 14 | Manage using a note-taking application and record in accordance with ECSS standards. |
| 5 | Lunar Eclipse Occurrence | 5 | 1 | 12 | Add a heater to prevent instrument damage |
| 6 | No lunar flight heritage | 2 | 3 | 10 | Perform radiation testing (TID) and thermal vacuum tests for components without lunar flight heritage. |
| 7 | Power <100% duty cycle | 2 | 2 | 8 | Implement reduced-duty-cycle mission modes or switch to safe mode. |

# Exploring Lunar Ionosphere Characterization through Multi-CubeSat Occultation with Ranging Technology and Radiation Environment Analysis.

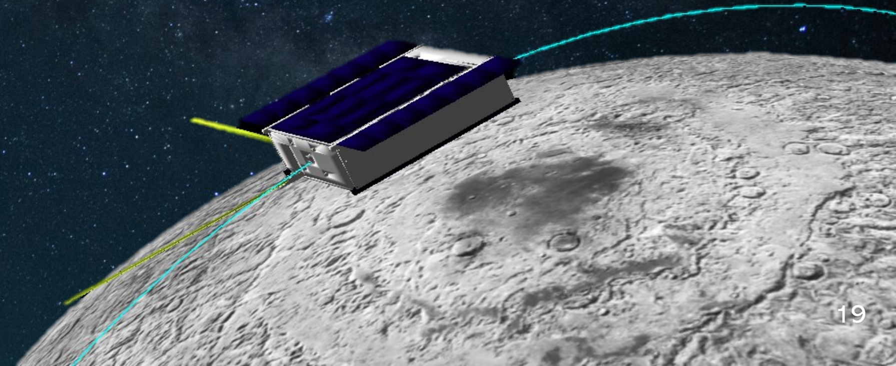
**Spacecrafts:** 2 six-unit CubeSats.

**Objectives:** Radio Occultation and Radiation Environment.

**SDG:** 4 Quality Education; 9 Industry, Innovation and Infrastructure; 17 Partnerships for the Goals

Designing the payload **in-house** allows for greater customization and control.

Student advance: Highly creative and passionate



4 QUALITY EDUCATION

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

17 PARTNERSHIPS FOR THE GOALS

*“Exploring Lunar Ionosphere Characterization through Multi-CubeSat Occultation with Ranging Technology and Radiation Environment Analysis”,*

National Central University, TAIWAN.

Thank You 謝謝大家 Dankie Teşekkürler Na gode

ありがとう Grazie Terima kasih शुक्रिया благодаря

# Appendix

# Our Team:

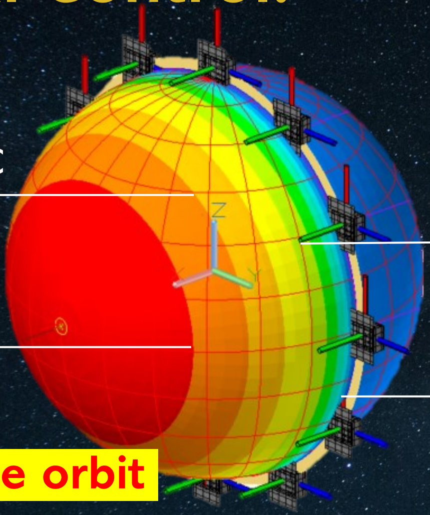
We are a student team from the Department of Space Science and Engineering, National Central University (NCU), Taiwan, and supported by the Center for Astronautical Physics and Engineering (CAPE), NCU, Taiwan.

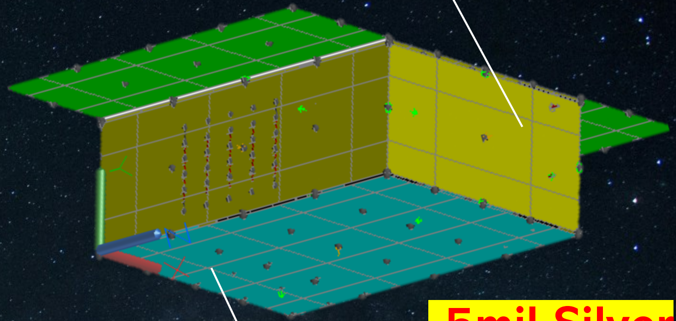
| Name | Degree | Affiliation | Work | Expertise |
|---|---|---|---|---|
| YiYu Chang | Master Student | NCU<br>Tron Future | PM<br>Science, COMM | COMM |
| Yuhsiu Tien | Master Student | NCU | ADCS, Orbit | ADCS |
| Terry Chen | Bachelor Student | NCU | Science | COMM |
| Jason Yu | Master Student | NCU | STR | STR |
| Roger Tsai | Bachelor Student | NCU<br>HEX20 | CDH, Modes | FSW |
| Chieh Lung | Master Student | NCU | Thermal Control | Thermal Control |
| Dr. Yi Duann | Postdoc | NCU | Instructor | |
| Prof. Loren Chang | Professor/<br>Dept. Chair | NCU | Instructor | |

# More Lunar RO Missions:

| Satellite Name | Launch Year | Volume | Weight | RO Experiment Time | Measured TEC Density Range | Observation Features |
|---|---|---|---|---|---|---|
| Pioneer 7 | 1966 | 20.8 $m^3$ | 146 kg | 1966 (Lunar flyby) | Upper limit around 40 $cm^{-3}$ | Provided the first data on the lunar ionosphere, indicating a low ionospheric density upper limit. |
| Luna 19 & 22 | 1971, 1974 | 82.4 $m^3$ | 5,700 kg | 1971, 1974 | Range 400–2000 $cm^{-3}$ | Detected ionosphere above the lunar dayside, with density decreasing exponentially with altitude; peak ionospheric density observed at 2–10 km altitude. |
| SMART-1 | 2003 | 1.57 $m^3$ | 367 kg | 2003–2006 | Around 100 $cm^{-3}$ | Dual-frequency measurements using S-band and X-band showed low ionospheric TEC. |
| Kaguya | 2007 | 21.2 $m^3$ | 2,914 kg | 2007–2009 | Average around 300 $cm^{-3}$, local peaks up to 1000 $cm^{-3}$ | Dual-frequency technique observed lower-than-expected ionospheric density, mainly at high latitudes; occasional higher densities in certain local areas. |
| Chandrayaan-1 | 2008 | 3.375 $m^3$ | 1,380 kg | 2008–2009 | Around 300 $cm^{-3}$ | Two-way radio occultation measurements in polar regions indicated ionospheric density near the terminator. |
| ARTEMIS | 2011 | 2.057 $m^3$ | 77 kg | 2011–now | Specific TEC values not provided, showing ionospheric density variations | Dual-satellite partial RO experiments mainly observed plasma conditions, providing limited lunar ionospheric data. |

# Thermal Control:




| | Orbit cold | Orbit hot | Eclipse | Unit |
|---|---|---|---|---|
| Beta angle | 65 | 90 | 65 | degree |
| Solar Flux | 1315 | 1421 | 581.2 | $W/m^2$ |
| Albedo | 0.07 | 0.2 | 0 | |

| | Thermal Control Design |
|---|---|
| +y, +x, -x, +z chassis | MLI |
| Battery box | MLI |
| Battery mounting | isolated mount |
| -y, -z chassis | silver coated teflon tape (5mil) |

# RO Link Budget:

| Fundamental Parameter | |
|---|---|
| Bandwidth | $10^7$ |
| Modulation | BPSK |
| Frequency [MHz] | 450 |
| Require BER | $10^{-5}$ |
| **Power Parameter** | |
| USRP Tx Power [dBm] | 10 |
| Pass Loss [dB] | -149 |
| Rx System Gain [dB] | 65 |
| **Noise Parameter** | |
| Noise Floor [dBm/Hz] | -174 |
| **CNR Calculation** | |
| Require CNR | 9.6 |
| Final CNR | 31 |
| Margin | 21.4 |

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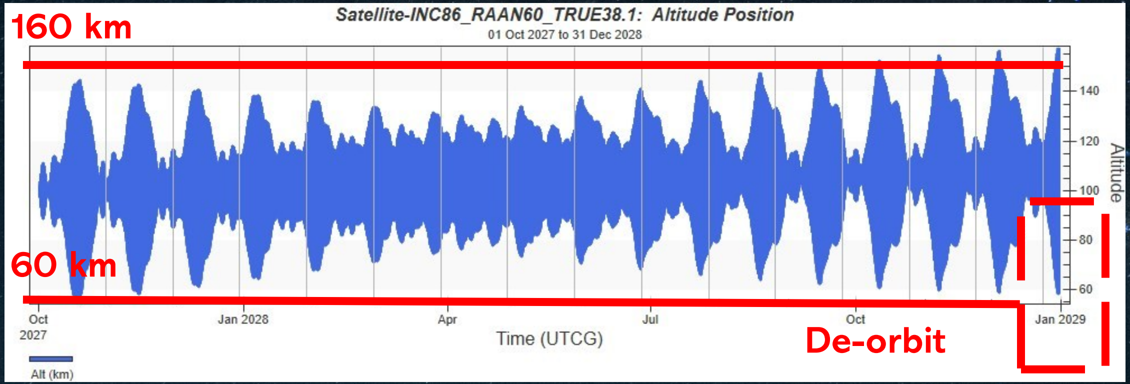
# STK Altitude Analysis:

- Start time: 2027/10/01 04:00:00 UTCG.
- Duration: About 1 year.
- Propagator: High Precision Orbit Propagator (HPOP), Coord system: International Celestial Reference Frame (ICRF) and Mean Earth (ME) Reference System.
- Perturbations: LP165P (48,48), Three body (Earth, Sun gravity), Solar Radiation Pressure (SRP).

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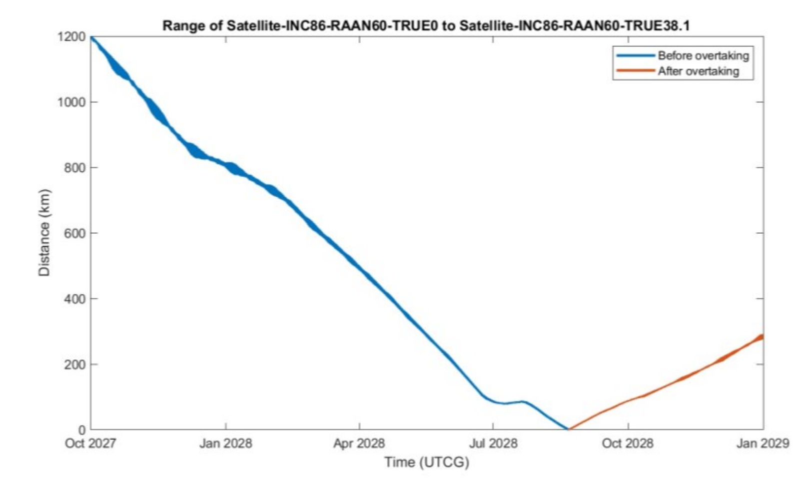
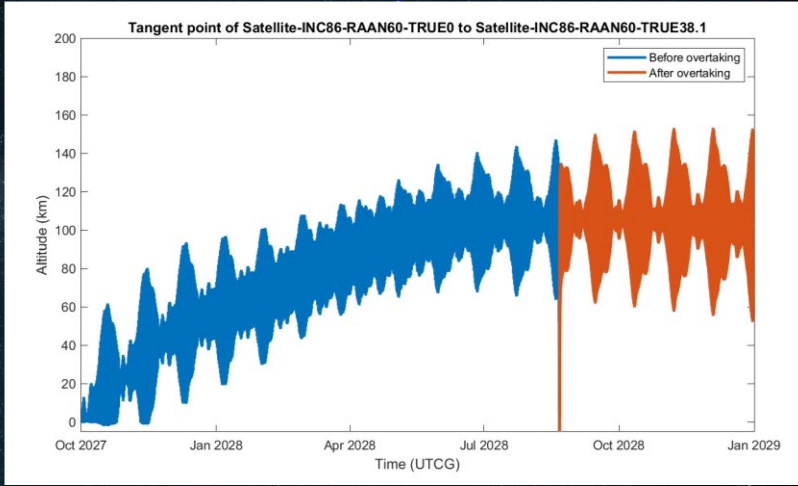
# STK Altitude Analysis:

The tangent-point altitude varies from about 0 km at the start to roughly 100 km by the end without maneuver.



# ADCS & Propulsion

- ArgoMoon Micro Propulsion System (MiPS)
- Cold Gas Mode (Isp ≈ 60 s) is used for momentum unloading, triggered ~2 times per week (~104/year), consuming only ~69 g annually.
- Green Monopropellant Mode (Isp ≈ 230 s) is used for larger maneuvers, here planned at 4 per year (10.145 m/s each), consuming ~214.4 g annually.

| Mode | Cold Gas | Green Monopropellant |
|---|---|---|
| Purpose | Momentum Unloading | Maneuver / Orbit Adjustment |
| ΔV / Event (m/s) | 0.00875 | 10 |
| Event Frequency | 2 per week → 104/year | 4 per year |
| Isp (s) | 60 | 230 |
| Propellant / Event (g) | 0.665 | 53.6 |
| Annual Usage (g/yr) | 69.16 | 214.4 |
| **Remaining Propellant (g)** | **145.84** | **205.6** |

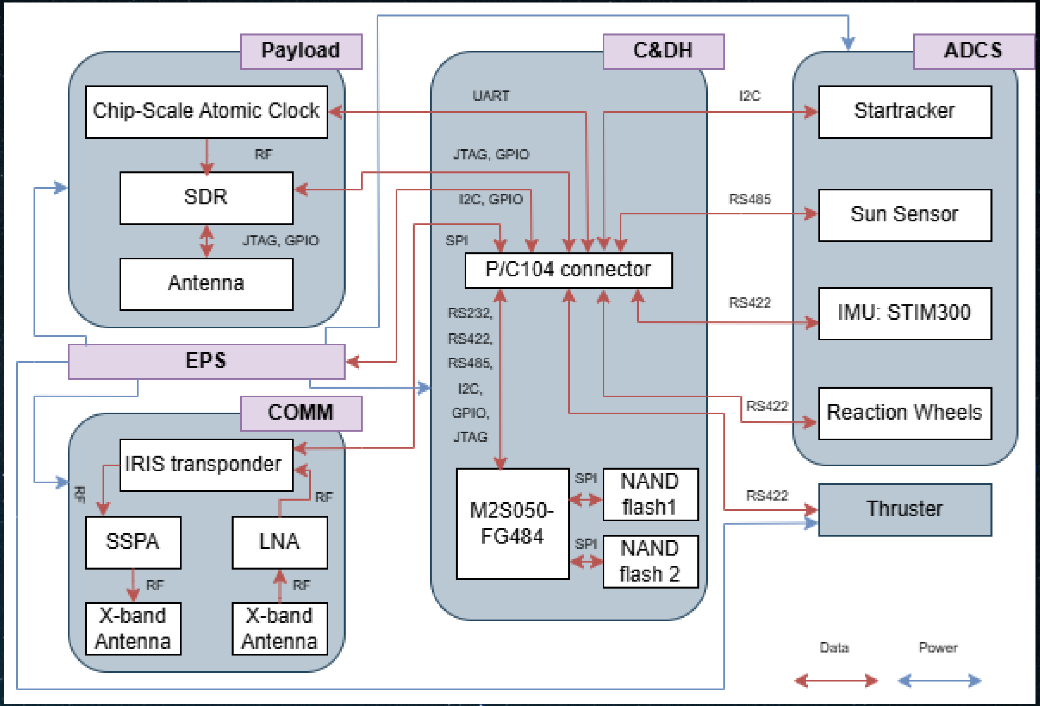
# EPS

- Battery Type: Panasonic NCR18650GA (3.6V, 3500mAh)
- Battery Pack: 4S × 3P = 12 cells
- Nominal Voltage: 14.4 V
- Pack Capacity: 10.5 Ah → 151.2 Wh total, 121 Wh usable (80% DoD)
- Orbit Condition: 100 km LLO, ~1.96 hours/orbit
- Orbit Energy Demand: ~42.2 Wh
- System Margin: ~**2.9× per orbit**
- Peak Load Supported: Up to 30 W with ≥20% SOC
- Charging Method: Body-mounted solar arrays + MPPT converters

| ITEM | POWER (Wh) | DUTY CYCLE |
|---|---|---|
| EPS Consumption | 1.78 | 100% |
| Momentum Unload | 20.00 | 0.80% |
| Command & data | 1.40 | 100% |
| ADCS | 11.545 | 100% |
| Telecom | 7.20 | 1% |
| Payload-dsrp | 0.40 | 100% |
| Payload-usrp | 4.50 | 50% |
| Payload-iris | 12.80 | 10% |
| Payload-atomic Clock | 0.14 | 100% |
| Total | 19.027 | |
| Power Generation | 28.333 | |
| Margin | | 32.85% |

# CDH Architecture

- **Two NAND flash ICs** for data storage to mitigate radiation-induced damage to the hardware.
- Currently assume the use of the NASA JPL IRIS transponder to support deep-space navigation and data downlink, together with its associated amplifier equipment.
- An SDR is equipped with an external **chip-scale atomic clock (CSAC)**, which serves as a stable oscillator.

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# Science Matrix – ORION SDR

| Science/Mission Objectives | Objectives<br>Measurement | Instrumentation | Measurement Requirements (Capabilities) |
|---|---|---|---|
| Mission-ORION SDR | | | |
| M1. Characterize the spatial and temporal distribution of the lunar ionosphere.<br><br>M2. Determine the spacecraft's orbital dynamics (position, velocity, acceleration) with respect to the lunar environment.<br><br>M.3 To determine, in real time, the relative distance between the two spacecraft. | Dual-frequency carrier-phase and group-delay measurements on the intersatellite-link.<br><br>Continuous Doppler tracking radio link.<br><br>Code-phase offset of the GPS-style Gold PRN embedded in the inter-satellite link | 1. B205-mini SDR x2<br>2. VHF deployed antenna<br>3. UHF deployed antenna<br>4. CASA(chip scale atomic clock) | Dual Frequency: 450 MHz & 75MHz<br><br>Modulation: BPSK<br><br>Chip Rate: 1.023 Mcps (MHz chips $s^{-1}$)<br><br>Sequence Structure: Gold Code |

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# Science Matrix – DSRP

| Science Traceability Matrix | | | |
|---|---|---|---|
| Science/Mission Objectives | Objectives<br>Measurement | Instrumentation | Measurement Requirements (Capabilities) |
| Mission-DSRP | | | |
| M1. Understand the lunar radiation environment and high-energy particles.<br><br>M2. Understand the link between space-weather events and radiation. | Radiation dose and dose rate.<br><br>SEU Rate | RADFET<br>NAND Flash | Power: < 0.9 W<br><br>Maximum Data Rate: 50 bytes/min<br><br>Dose Resolution: <1 mRad<br><br>Spatial resolution ≤4° in latitude and longitude |

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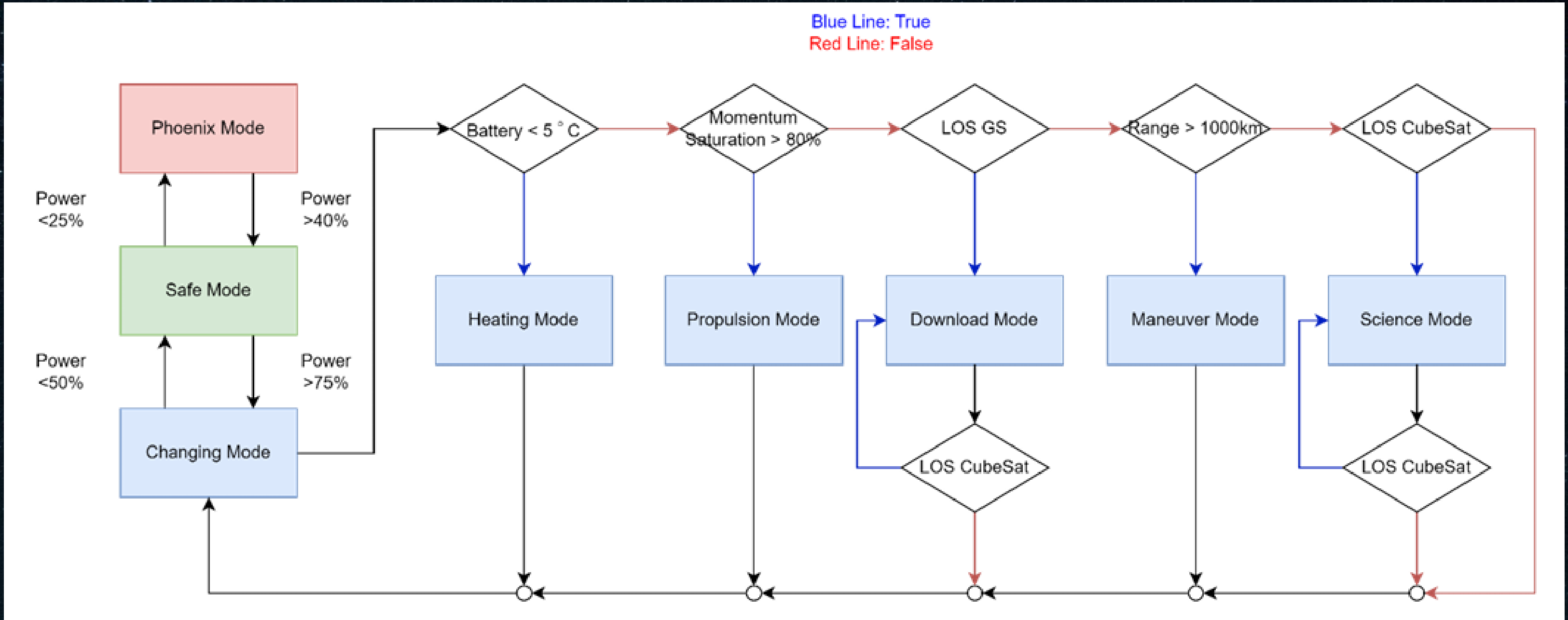
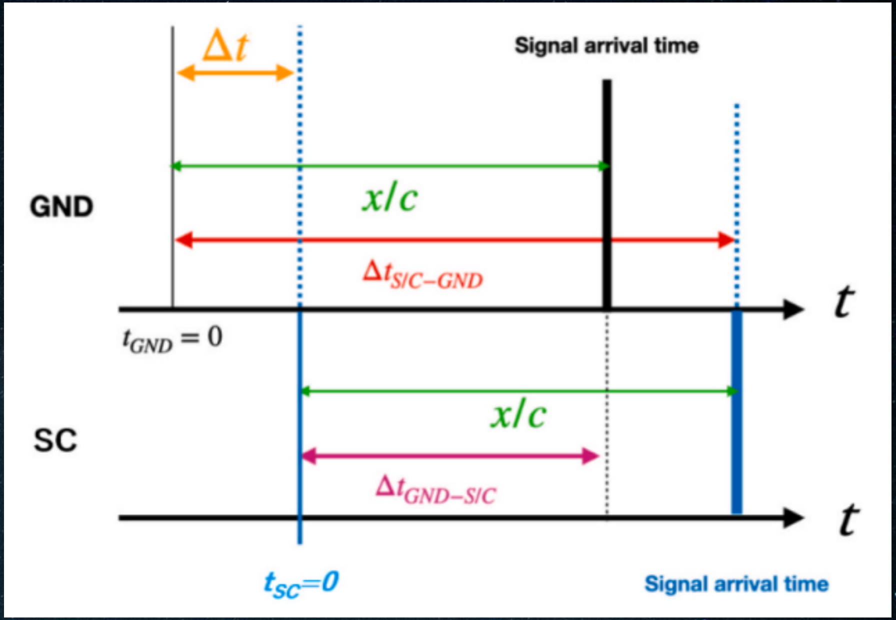
# Operation Logic:



# Asynchronous one-way range measurement method:

- The ground station (GND/GS) and the spacecraft (S/C/SC)—each continuously transmits a time-stamped sequence
- Key point: adding the two pseudoranges and dividing by two cancels the clock offset, yielding the true range
- If the S/C clock runs ahead of the ground clock ($\Delta t$>0, defined as S/C clock minus ground clock).
- The pseudorange measured at the S/C is biased long, and the pseudorange measured at the ground is biased short.




(*J. Kawaguchi et al*, 2024)

# Appendix

## Maneuver:

- Isp: 230 s
- Satellite mass (m0): 11.77 kg
- Δv per maneuver (total): 10.291 m/s
- Propellant per maneuver (approx): ≈ 53.6 g
- Tank usage: ≈ 38% of 420 g

| Number of Waiting Orbits | Single Δv (m/s) | Total Δv (m/s) | New Semi-Major Axis (km) | New Orbital Period (hr) | Waiting Time (hr) | Propellant Mass (g) |
|---|---|---|---|---|---|---|
| 10 | 5.66 | 11.32 | 1850.2 | 1.9838 | 19.6 | 68 |
| **11** | **5.145** | **10.29** | **1849.0** | **1.9819** | **21.5** | **63** |
| 12 | 4.717 | 9.433 | 1848.0 | 1.9803 | 23.5 | 53 |
| 13 | 4.354 | 8.707 | 1847.2 | 1.979 | 25.5 | 49 |