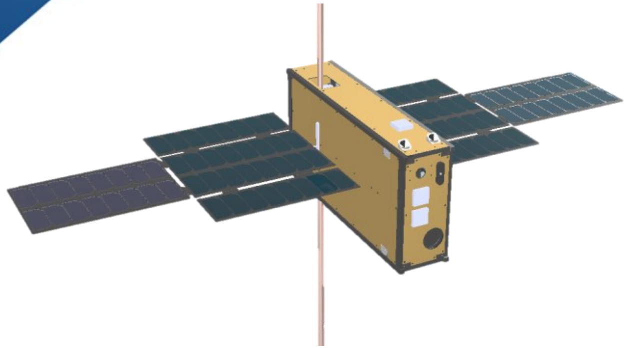
The 9th Mission Idea Contest: to the Moon

Intelligent Space Systems Laboratory
The University of Tokyo



CubeSat Mission Concept for TREED

The REceiver Exploring Dark-ages

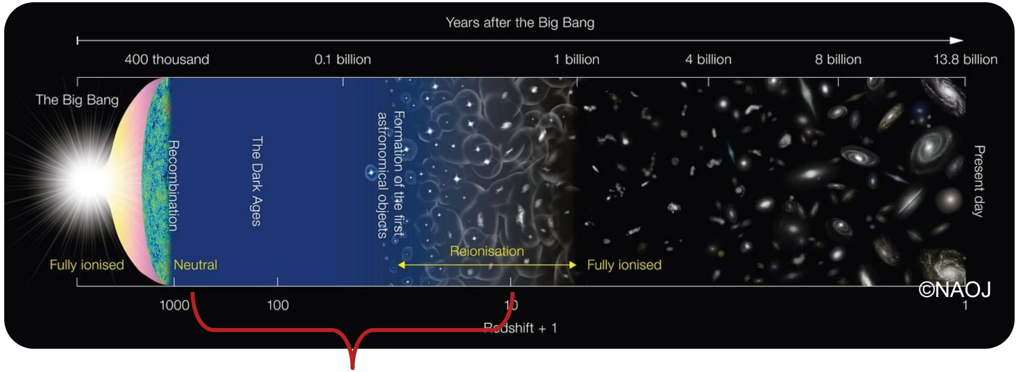
Takato Hatae (1), Yojiro Yamashiro (1), Shintaro Yoshiura (2), Yusuke Kono (2), Masaki Ito (1), Kazuya Fukuda (1), Shunta Oi (1), Hideki Takamoto (1), Satoshi Ikari (1), Kohei Kurahara (3), Tomo Takahashi (4), Fumiya Okamatsu (5), Hiroaki Misawa (6), Hajime Kita (7), Hiroyuki Nakanishi (8), Kazuyoshi Yamashita (2), Kiyotomo Ichiki (3), Taro Matsuo (9)

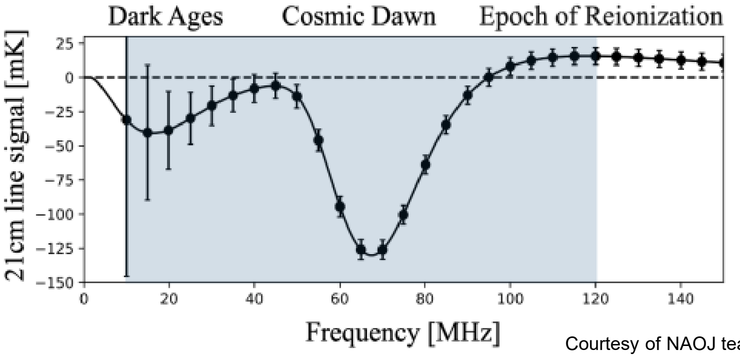
(1)The University of Tokyo (2)National Astronomical Observatory of Japan (3)Nagoya University (4)Saga University (5)Nihon University (6)Tohoku University (7)Tohoku Institute of Technology (8)Ishikawa Prefectural University (9)The University of Osaka

Observation of 21-cm Signal

The 21-cm global signal

The neutral-hydrogen 21-cm global signal, abundant before reionization, is a key probe of the early Universe. The 21-cm signal is redshifted by cosmic expansion and can be observed today as a faint low-frequency radio signal. The 21-cm signal provides virtually the only observational window into the cosmic dark ages and the birth of the first stars.



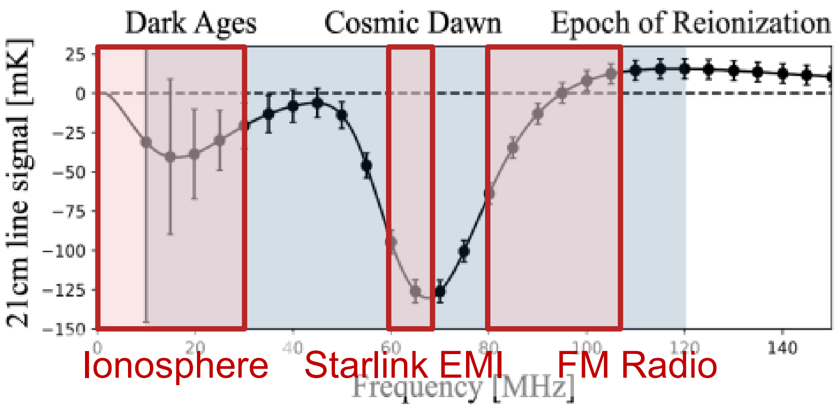


Courtesy of NAOJ team

Filled with neutral hydrogen in the early universe ⇨ **Observe the 21-cm signal emitted or absorbed by neutral hydrogen**

Challenges of Ground-based 21-cm Observations

- **Reflection by the Ionosphere**
    - 21-cm signal from the Dark Ages requires observations **beyond** the ionosphere
- **Anthropogenic Radio Frequency Interference (RFI)**
    - Observations of the Cosmic Dawn 21-cm signal are strongly affected by interference from RFI such as **FM radio and Starlink EMI (**Electromagnetic Interference**)**.

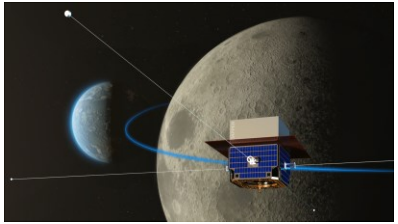


The Moon's Far Side

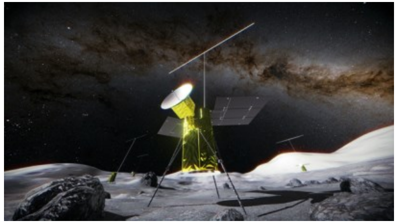
- **No Ionosphere**
- **Blocks Radio Interference from the Earth**
  - The lunar far side is naturally shielded from Earth's radio emissions.

⇩

- **Missions Aim to Observe the 21-cm Signal**
  - Multiple missions employing both orbital and surface approaches are in progress worldwide; however, a full observation has yet to be realized.



DAPPER ©NASA



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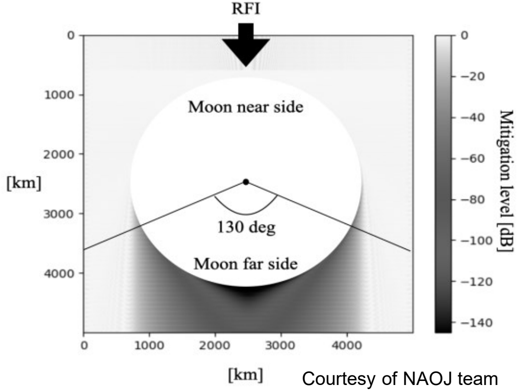
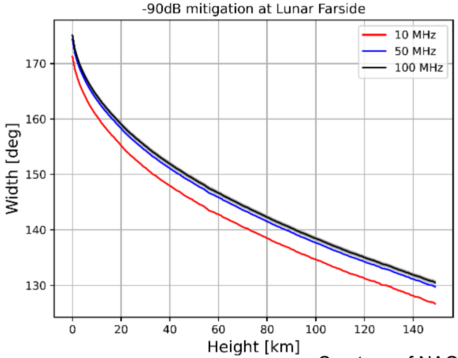
Lunar shielding effect evaluated by using a code developed in Bassett *et al.* (2020)



Courtesy of NAOJ team



Courtesy of NAOJ team

Bassett Neil, *et al.* "Characterizing the radio quiet region behind the lunar farside for low radio frequency experiments." *Advances in Space Research* 66.6 (2020): 1265-1275.

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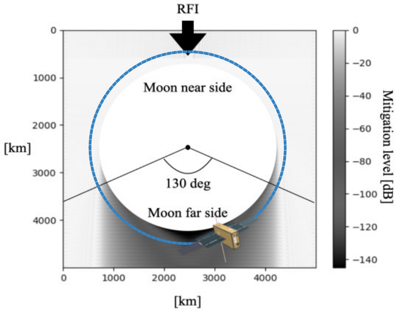
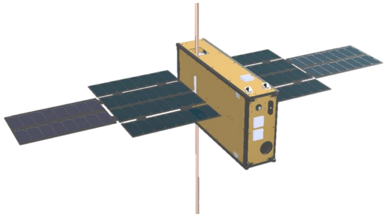
Mission: Observation of 21-cm Signal at the Moon's Far Side

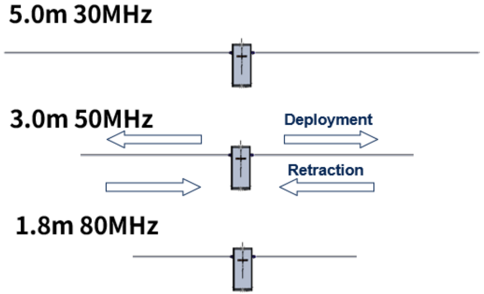
Low Lunar Orbit:



CubeSat:



Variable-Length Dipole Antenna:



Priority	Objective	Impact
1. Minimum	Observe 21-cm signal in 50–120 MHz band (5 MHz steps) using optimized dipoles	Validate ground-based measurements and test star formation models
2. Full	**Accumulate 1,500 hours of total observation time**	Detect global 21-cm signal from the cosmic dawn
3. Extra	Expand observational frequency range down to 10 MHz	Enable detection of 21-cm signal from the dark ages
4. Extra	Extend observation time to 6,000 hours	Improve signal quality and reduce uncertainty

Low Lunar Orbit

- **Observable Area**
  - @100 km ≦130 deg
  - -90dB shielding effect
- **Insertion Orbit**
  - Altitude of Perilune: Ø rp: 100 km
  - Altitude of Apolune: Ø ra: 100 km
  - Inclination: 80° or 100°
- **Quasi-Frozen Orbit**
  - Stable for up to 4 years with ideal insertion
  - 1 year for full success
  - +3 years for extra success

Bassett Neil, *et al.* "Characterizing the radio quiet region behind the lunar farside for low radio frequency experiments." *Advances in Space Research* 66.6 (2020): 1265-1275.

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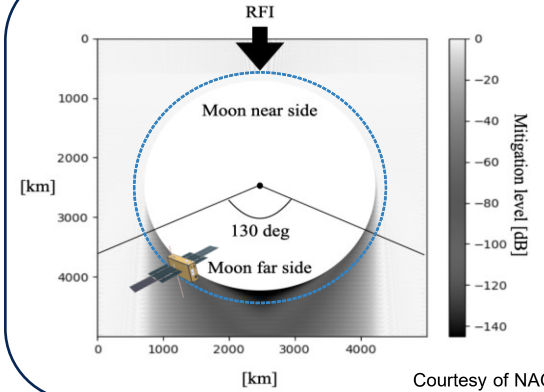
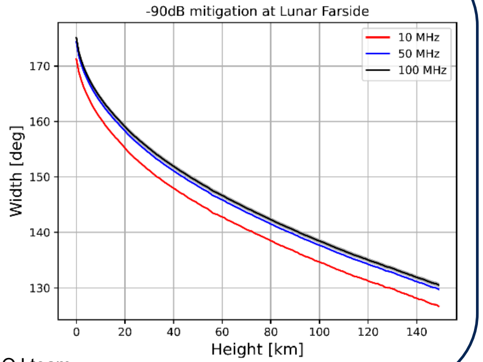
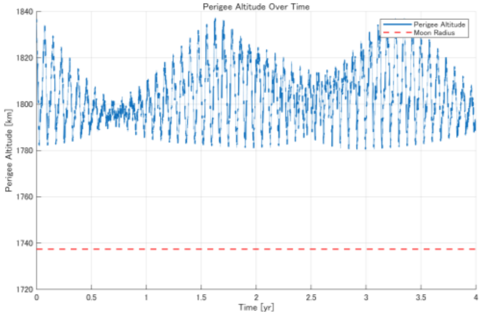


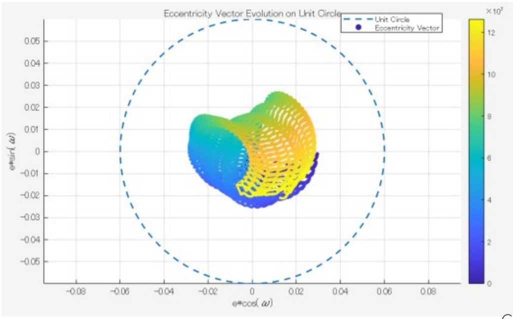


Courtesy of NAOJ team

Perigee Altitude (4 years)



Eccentricity Vector (4 years)



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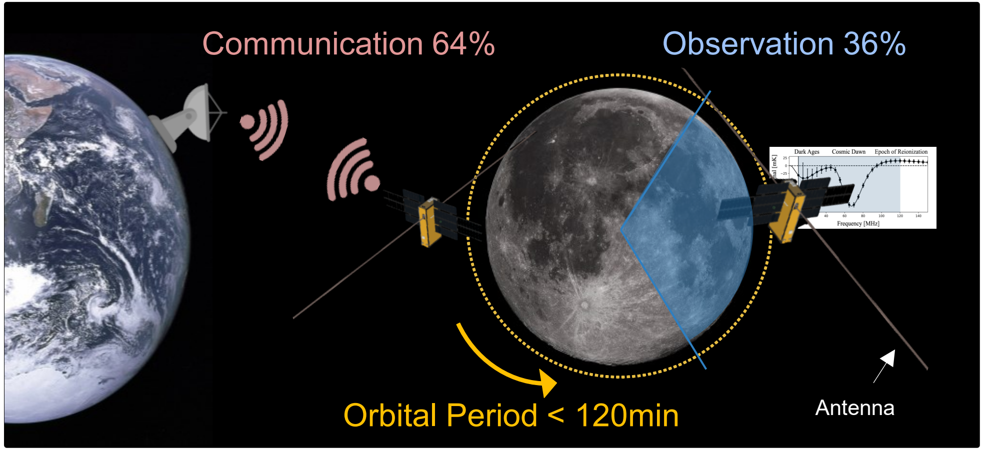
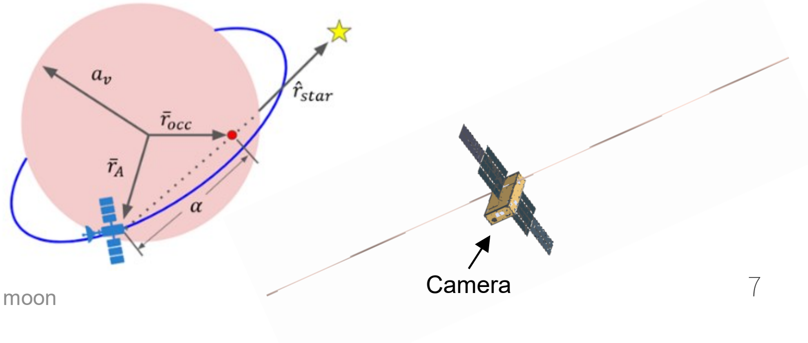
Mission Phase

- ## Main Mission
  - Alternate communication (near side) and observation (far side) phases
  - Total observation time is key for detecting the sky-averaged 21-cm signal (longer time, more precise data)



- ## Sub Mission
  - Star Occultation Method
  - Demonstrate orbit determination using an optical navigation during communication phases



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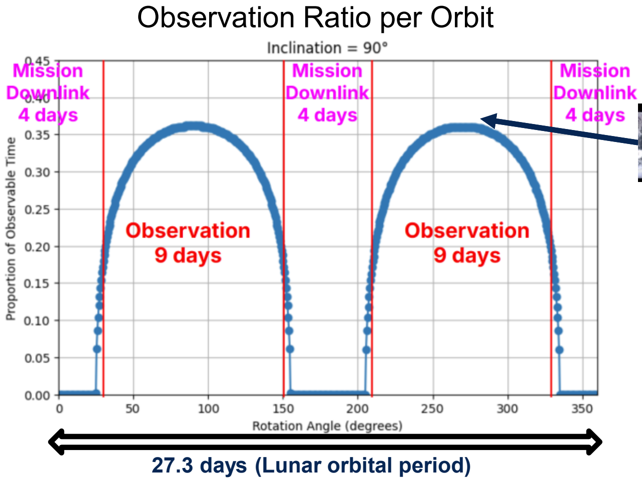
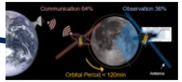
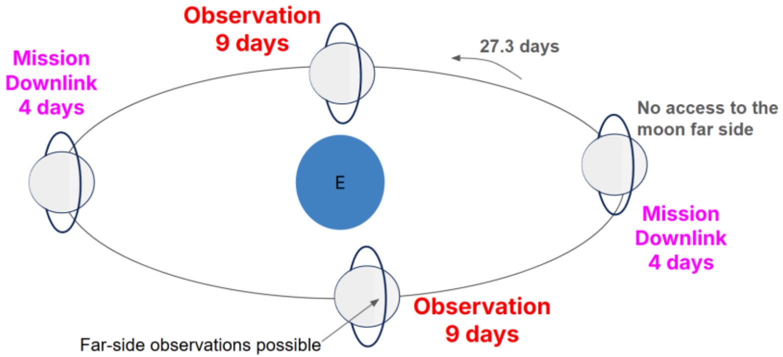
Operation Term

- **Observation Term**
  - ~9 days dominated by far side observations
- **Communication Term**
  - ~4 days dominated by Earth visibility, used for data downlink and maintenance
- **Cycle Characteristics**
  - Repeating operation cycle driven by the Moon’s orbital period and geometry
  - Durations vary slightly due to precession and seasonal effects.



36% 130deg





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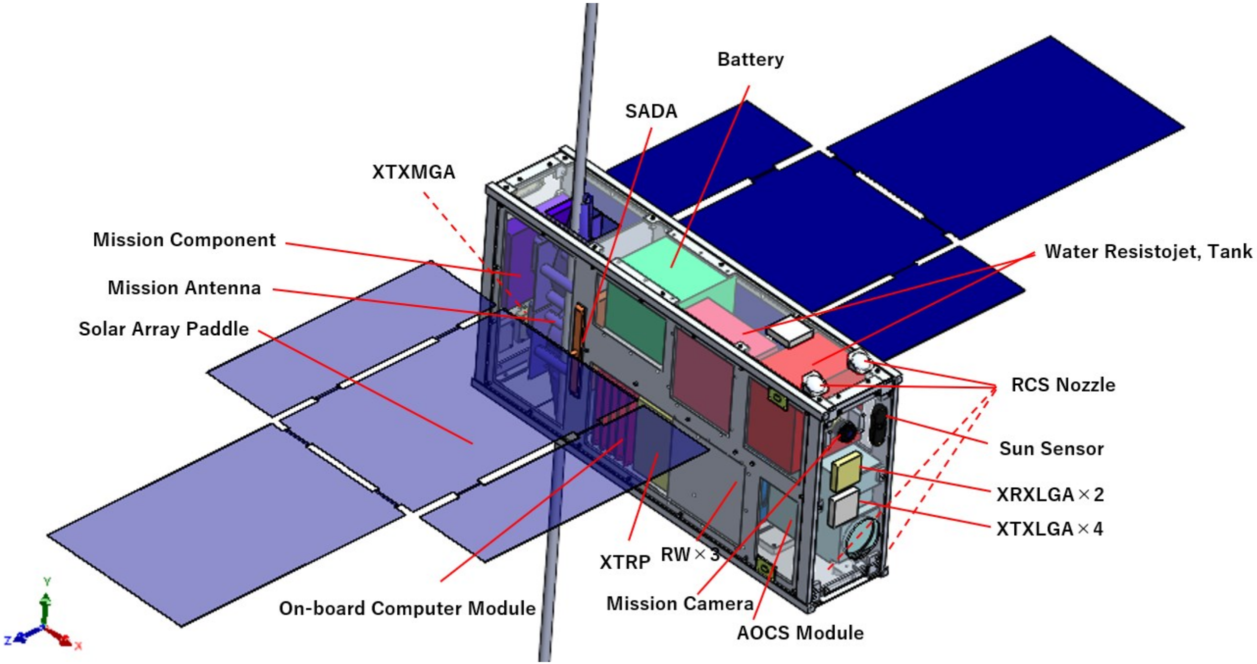
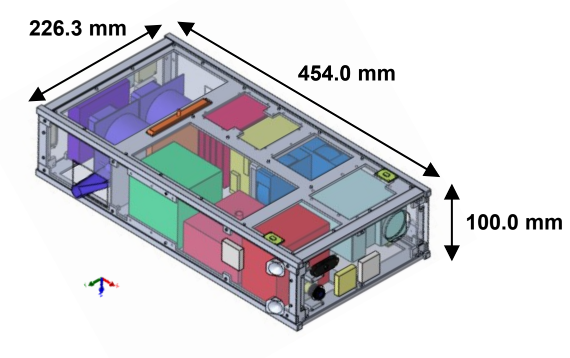
Satellite Design



Parameter	Value / Description
Mass	**13.0 kg** (with 10% margin)
Volume	**Wide 8U** (454 × 226 × 100 mm)
Communication Band	**X-band** (LGA + MGA)
Mission Life	**1+3 years**



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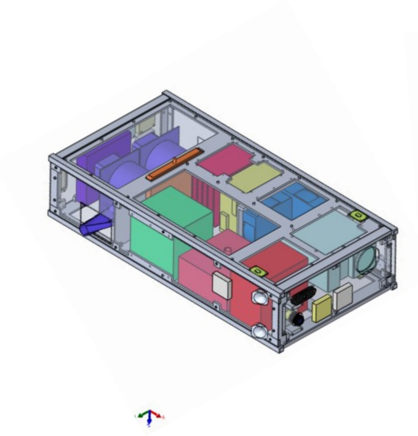
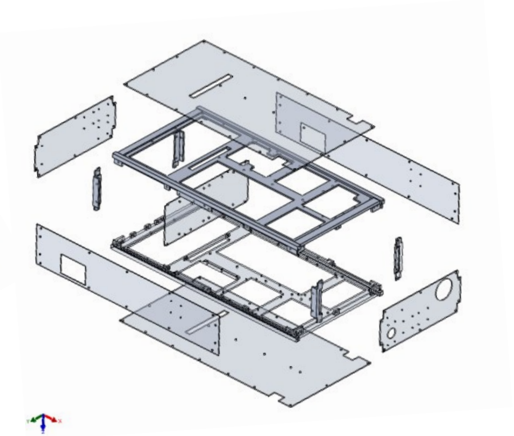
Structure Design and Analysis

Heritage-Based 8U CubeSat Structure:

- Follows established CubeSat mechanical standards
- Ensures interface compatibility and ease of integration





Compliant with Launch Environments:

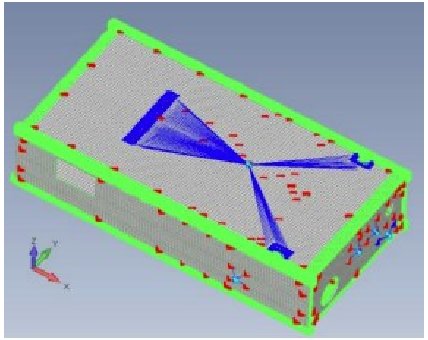
- The first natural frequency

⇒ 110 HZ (req. ≧40Hz)

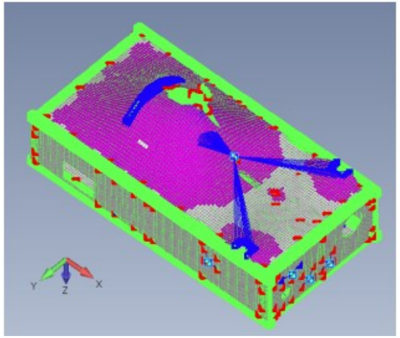
- Quasi-static loads
- Random vibration

M.S. = 2.49

Condition: SpaceX Falcon9



Finite element model



First natural vibration mode

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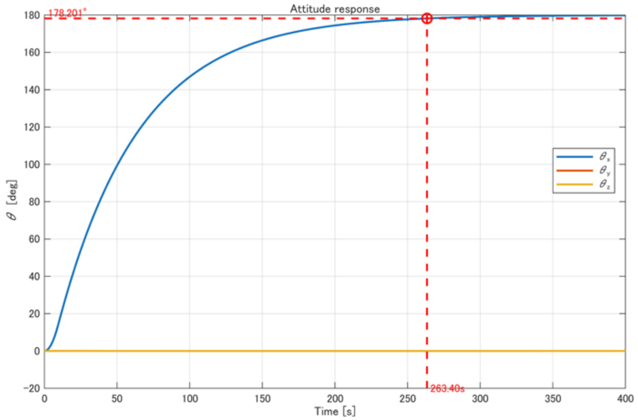
ADCS Design and Analysis

- **ADCS Module：XACT-100**
  - RW×3, STT, IMU, Sun Sensor×4
  - Easy to integrate
- **RCS Module：PBR-10**
  - Water resistojet
  - Green propellant — safe and easy to handle in lab conditions

XACT-100
©Blue Canyon Technologies LLC

PBR-10
©Pale Blue



180° reorientation achieved in 263s (PD feedback control)

Parameter	Value
SRP Disturbance Torque	1.89×10^{-7} N·m
Gravity-Gradient Torque	7.86×10^{-7} N·m
RW Unloading Interval	**3.56 days**
RCS Propellant Mass (3 years)	**0.809 kg**

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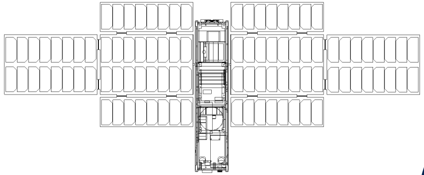
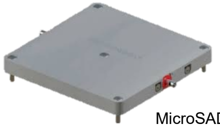
Electric Power Design and Analysis

- **SAP**
  - 96 cells arranged in 8 series and 12 parallel
  - 2 wings



- **SADA : MicroSADA-10**
  - Actively point the panels toward the Sun



MicroSADA-10
©DHV Technology

- **Batteries : NCR18650B**
  - Lithium-ion cells
  - 3400mAh
  - 3 series and 3 parallel, 9 cells

NCR18650B
©Panasonic

Parameter	Value
Power Generation @ 1 AU (BOL)	111 W
Power Generation @ 1 AU (EOL)	93 W
Power Consumption (X-band downlink)	36 W
Power Storage	112 Wh
DoD (allowable)	40%

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Communication

Parameter	Value
Frequency	X-band (7145 MHz, 8400 MHz)
Antenna	MGA×1 (downlink) LGA×4 (downlink) LGA×2 (uplink)
X-band Transceiver	RF output: 1.1 W
Ground Station	54m antenna, 13.5m antenna

54m e.g. Misasa GS
©JAXA

13.5m e.g. Awara GS
©Fukui University of Technology

Direction	GS	Antenna	Bitrate [bps]	Gain [dBi]	Margin [dB]
Uplink	54m GS	LGA	1024	-15 (Boresight:±90[deg])	Data: 48.6 Carrier: 62.2
Downlink	54m GS	LGA	4096	0 (Boresight:±12[deg])	Data: 9.3 Carrier: 15.0
		MGA	32768	8 (Boresight:±12[deg])	Data: 8.2 Carrier: 23.1
	13.5m GS	LGA	512	0 (Boresight:±12[deg])	Data: 3.7 Carrier: 3.4
		MGA	2028	8 (Boresight:±12[deg])	Data: 5.7 Carrier: 11.4

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Thermal Design and Analysis

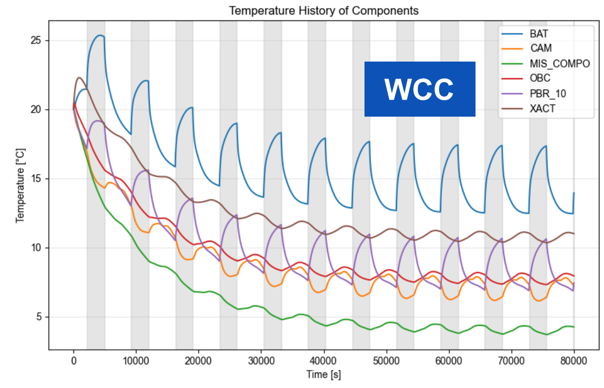
- **Design**
  - Radiator area: 30% of each panel (Ag Teflon)

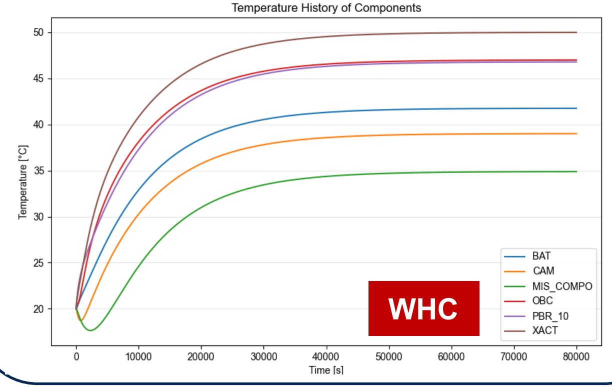
absorptivity(α) and emissivity(ε)

Panel	PX	MX	PY	MY	PZ	MZ
α	0.158	0.134	0.134	0.134	0.134	0.134
ε	0.175	0.332	0.297	0.297	0.244	0.244

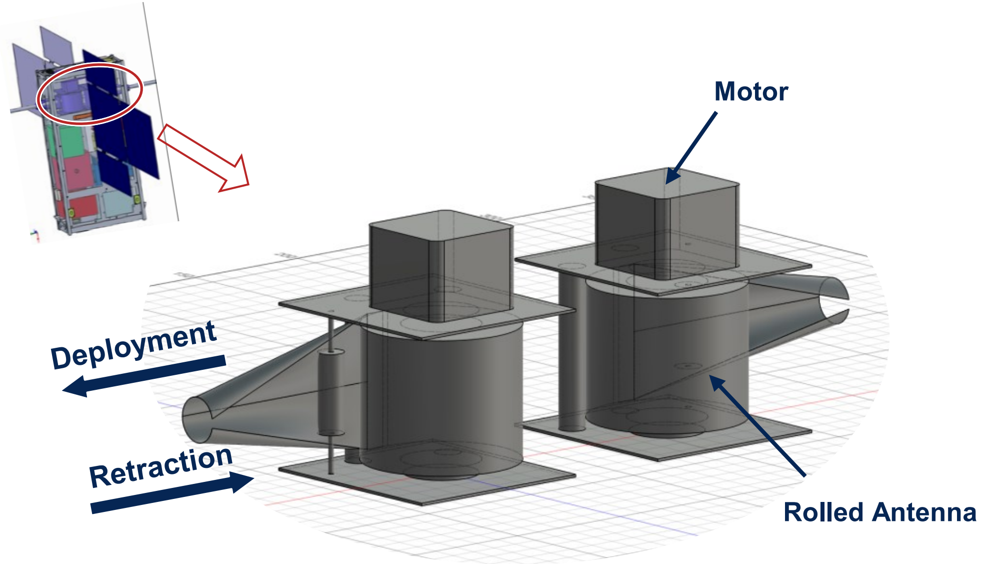
- **Thermal Model**
  - Node: 6 external panels (PX~MZ) and components
  - Conduction, radiation, solar/albedo/planetary IR was modeled in python scripts
- **Cases**
  - Worst Cold Case (WCC): $\beta = 0°$, Eclipse, 10W Heater
  - Worst Hot Case (WHC): $\beta = 90°$, Full Sunlight

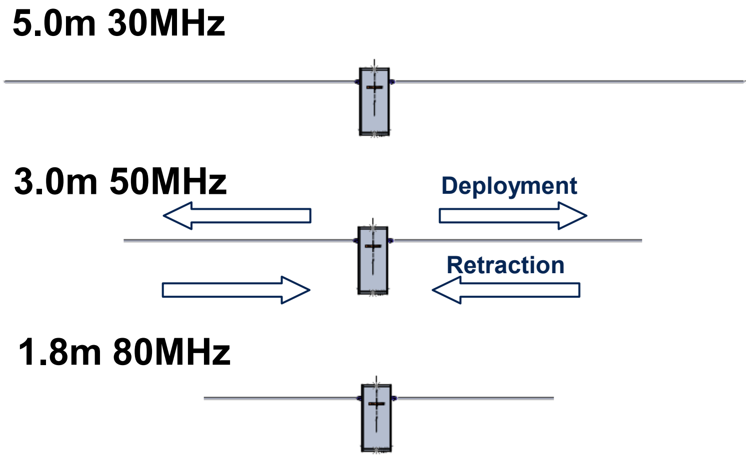
All Components within limits (BAT: 10~45°C)





Payload Design





Antenna Material: Beryllium copper
Shape-memory characteristics, allowing the antenna to retain its deployed form

Convex tape structure:
Roll-stowed design allowing deployment and retraction

Variable-Length Dipole Antenna:
Adjusts antenna length to achieve optimal performance for each observation wavelength

Risk Analysis

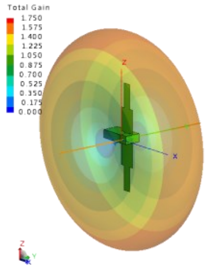
1. EMI from Bus Systems
- Possible contamination of low-frequency observations
- Requires strict control and testing.

2. Antenna Deployment Failure
- Critical mechanism
- Needs high reliability and validation.

3. Unintentional Radio Emission from other Satellites
- Increasing lunar activity may cause interference
- Early mission execution is essential.

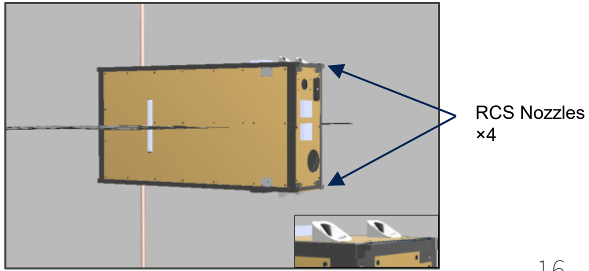
4. Launch and Orbit Injection
- Dependent on transfer vehicle
- Coordination and flexibility required.

Antenna pattern at 70 MHz
(sensitive to EMI effects)



Courtesy of NAOJ team

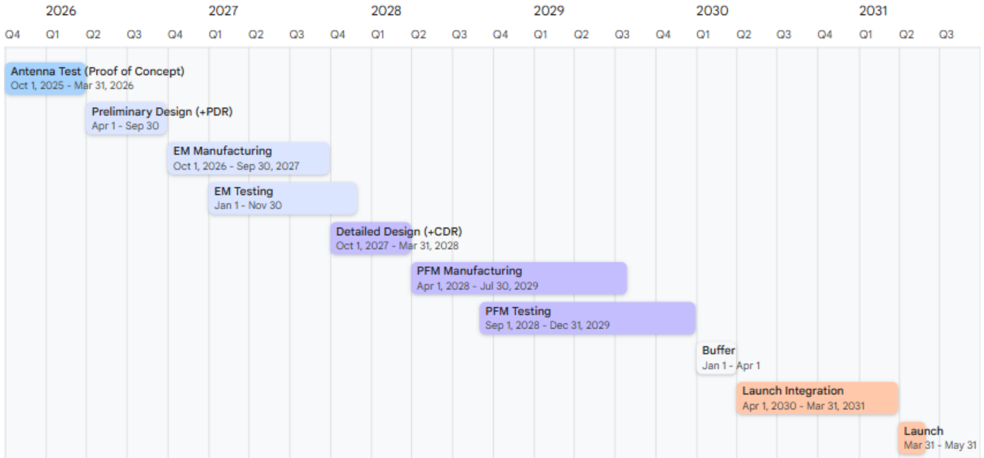
RCS nozzles capable of small orbital maneuvers



Implementation Plan

- **Project Responsibilities**
  - **ISSL :** Satellite bus design, integration, and testing.
  - **NAOJ and collaborators:** Scientific payload design and development.
- **Life Cycle Cost Estimate**
  - Total cost: **~3 million USD**.
  - Based on comparable university CubeSat projects and assumes:
    - Institutional support
    - Shared facilities
    - Student participation
    - Use of existing infrastructure

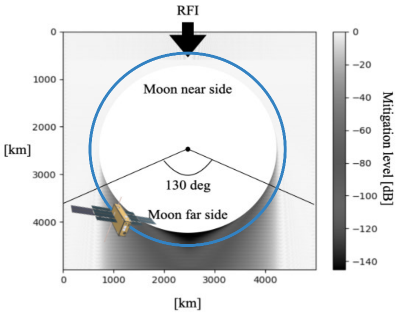
- **Schedule**
  - PoC → PDR → EM → CDR → PFM (4 years)
  - Relatively long schedule for a CubeSat to ensure effective EMC performance.



Conclusions

- TREED aims to detect the global 21-cm signal, a key probe of the early Universe, by observing at the radio-quiet lunar far side.
- The satellite will operate in a stable low lunar orbit for 1–4 years, enabling long-duration observations.
- Feasibility has been validated through subsystem analyses.

Low Lunar Orbit:



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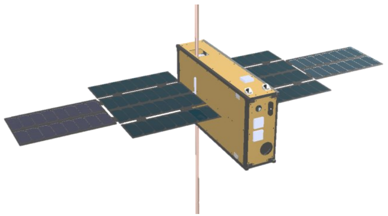

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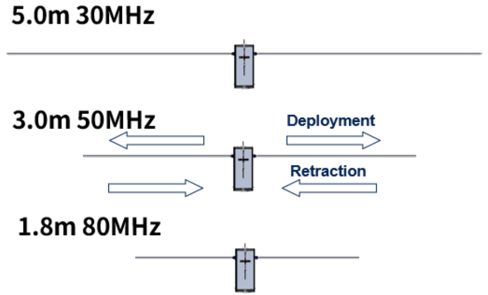

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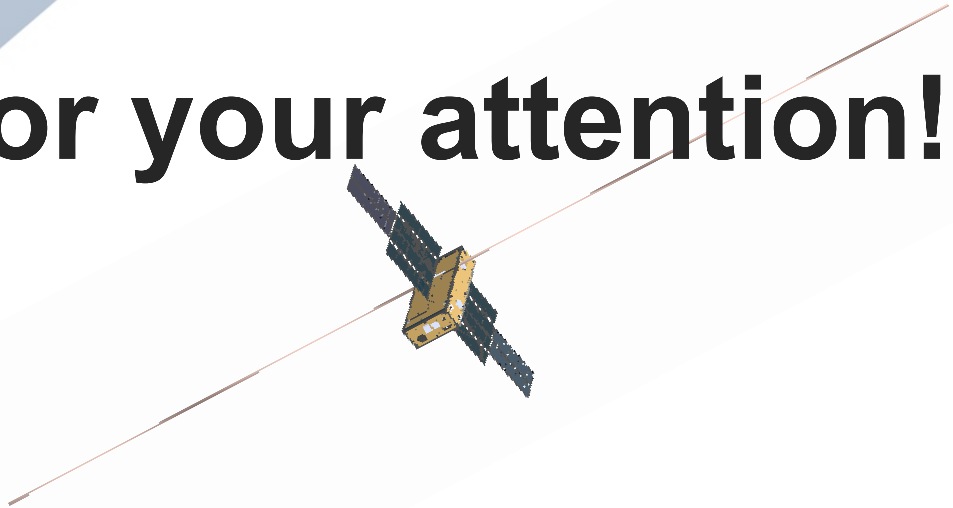

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Intelligent Space Systems Laboratory (ISSL), The University of Tokyo
Master’s Program (M1)