Lunar Meter-wave Telescope (TSUKUYOMI)

Satoru Iguchi（NAOJ)

NAOJ Future Planning Symposium 2024, 4, Dec., 2024

TSUKUYOMI – Current Team

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Lunar Meter-wave Telescope (TSUKUYOMI)

Current Members

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Related Research Community

Space Science Community including space engineering, astronomy, astrophysics, planetary science and so on.

Outline

2. Science Goals

宇宙創生の探究
Exploration of our Cosmic Origins

3. Science Objectives -Astrophysics-

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(Astrophysics)
月面からの電波天文観測により、人類未踏の暗黒時代の宇宙を探求する。
Exploring the Dark Ages of the Universe, an era unexplored by people, through radio astronomical observations from the lunar surface.

3. Science Objectives -Astrophysics-

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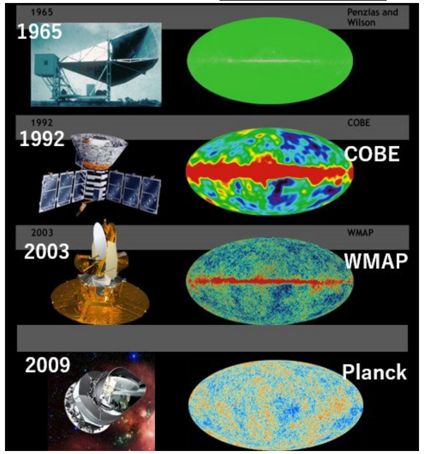
Fluctuations of space-time

Observational verification



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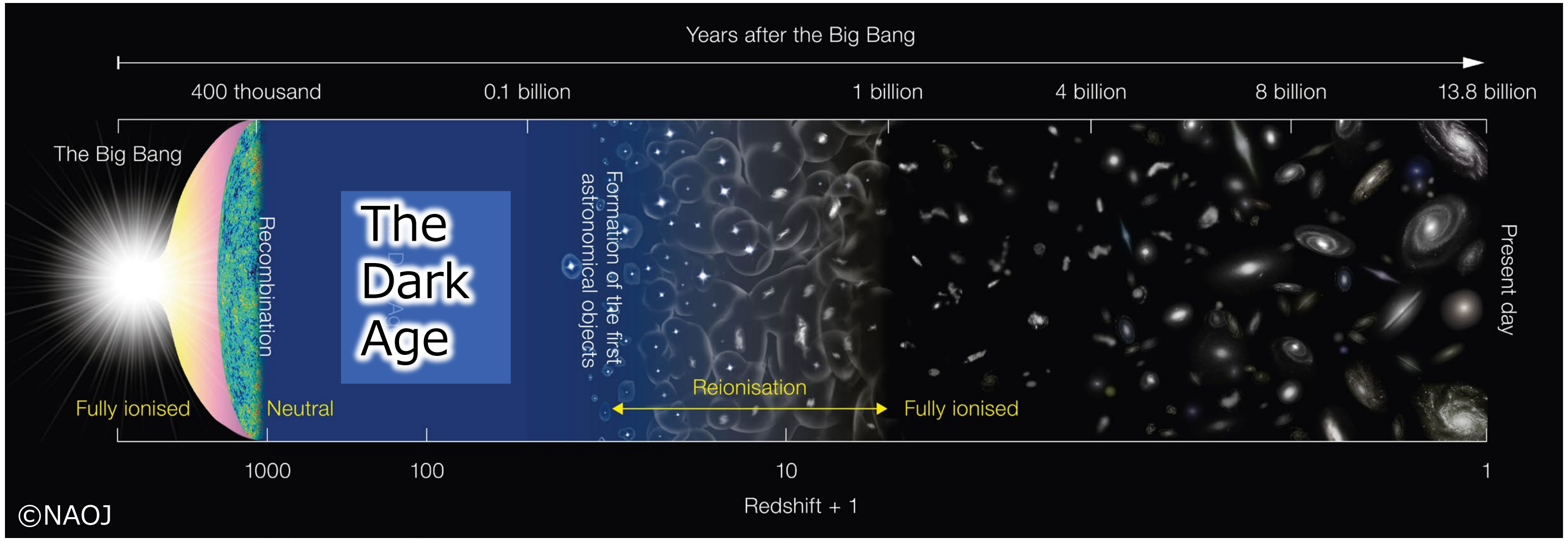
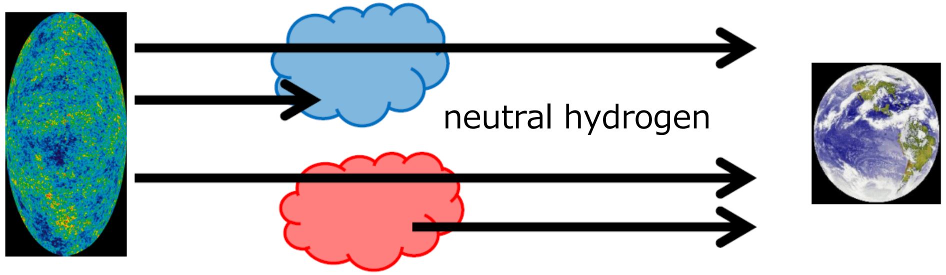
Nobel Prize in Physics 1978

Nobel Prize in Physics 2006

The fluctuations of the CMB were detected, which is consistent with "Inflation" in the big picture.



Neutral hydrogen interacts with radiation of wavelength 21.12 cm (frequency 1420.4 MHz) in the rest frame through the resonant transition between two hyperfine levels of ground state.



The 21-cm line of neutral hydrogen from the Dark Age of the Universe can be observed at frequencies of 1–50 MHz due to redshift.

Observe the 21cm line of neutral hydrogen from the Dark Age of the Universe on the lunar surface, where radio observations at 1–50 MHz are possible.

Frequency Wevelength	3-30 kHz 10-100 km	30 k-30 MHz 10 m-10 km	30 M- 3 GHz 0.1-10 m	3-100 GHz 0.3-10 cm	100 G-1 THz 0.3-3 mm	1-10 THz 30-30 μm	10-100 THz 3-30 μm	100 T-1 PHz 0.3-3 μm	1-3 PHz 0.1-0.3 μm
Class	Myriameter wave	Short wave Medium wave Long wave	Meter wave	Centimeter wave	Mm wave Submm wave	Far inflared ray	Mid inflared ray	Near inflared ray Visible light	Ultraviolet ray
Moon	×	○	○	○	○	○	○	○	○
Geocentric orbit	×	×	▲	○	○	○	○	○	○
Terrestrial Maunakea Atacama etc.	×	×	▲	○	○	×	▲	○	×

Lunar Ionosphere
Lunar dust
Earth's Aurora Borealis
High atmospheric absorption
Earth's RFI
Atmospheric absorption
Atmospheric thermal radiation
Earth's Ionosphere
Atmospheric absorption
Earth's RFI
Massive Satellite Communication Network
Atmospheric fluctuations

4. Science Investigations –Astrophysics-

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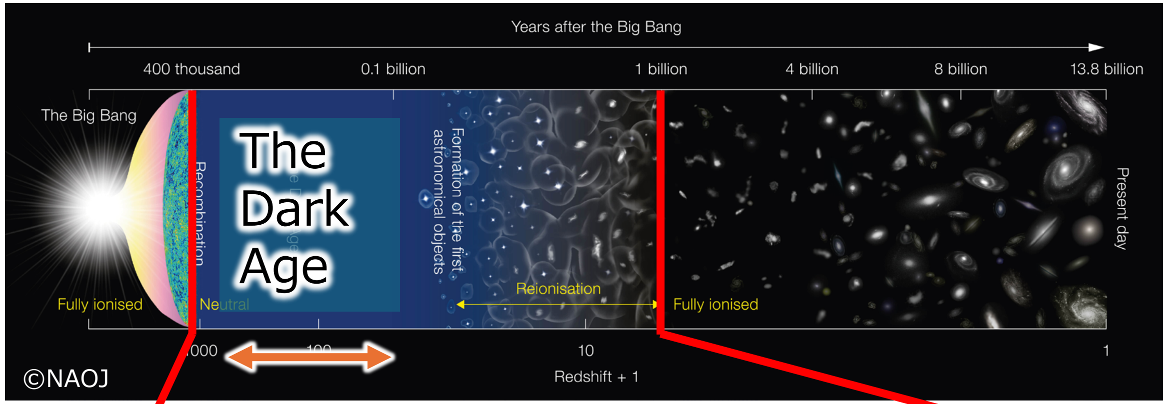
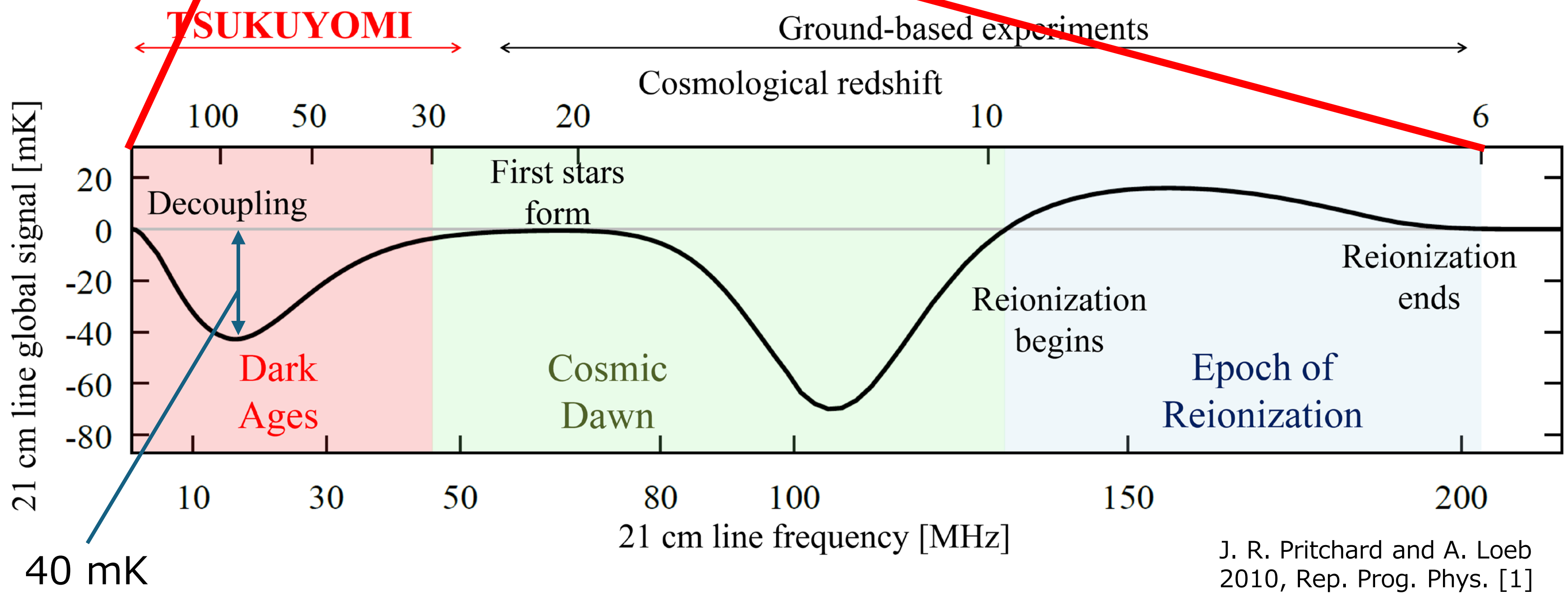
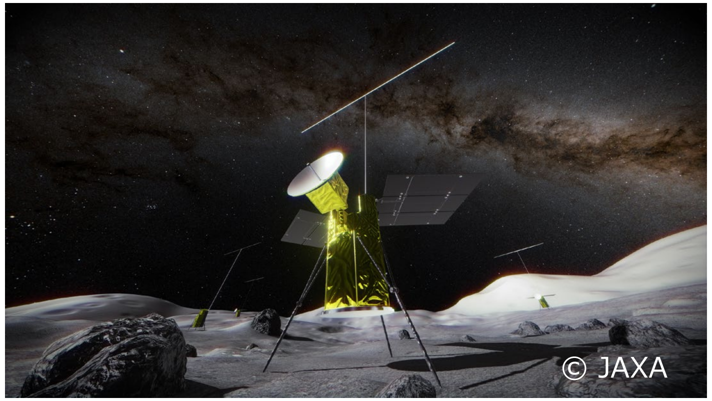
Cosmology: 21 cm line global (sky-averaged) signal of neutral hydrogen from the Dark Ages



- The cosmic evolution at this time was not yet significantly affected by astrophysical processes. -> **The Dark Ages offer a clean probe of fundamental cosmology.**
- The absorption with an amplitude of ~40 mK is expected to be detected in 15 MHz.



J. R. Pritchard and A. Loeb 2010, Rep. Prog. Phys. [1]



The prototype main goal is to develop the decameter-wave astronomy first, through system verification tests on lunar surface.

4. Science Investigations

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Science Investigations until 2030

Sciences that can be performed from one antenna (Prototype)
(**Isotropic beam** is available)

- RFI from the Earth
- Solar radio burst
- Jupiter radio burst
- Spectrum of the Milky Way
- Underground structure of the Moon
- Dust condition of the Moon

Sciences that can be performed from 2 antennas (interferometer)

- Ionosphere of the Moon

**(Planetary Science)
Understanding
Rocky Planets**

**(Astronomy)
Milky Way in
Low Frequency**

Science Investigations beyond 2030

All data obtained from all these scientific observations will be used entirely as calibration data for the 21 cm line global signal detection.

used as calibration data

used as calibration data

used as calibration data

Interferometer

From 3 antennas

- Map of the Milky Way
- Stellar Radio Burst

From dozens of antennas

- Exoplanet planetary aurora emission (Jupiter type)

Sciences that can be performed from 10 antennas (single-dish mode)

21 cm line global (sky-averaged) signal of neutral hydrogen

**(Astrophysics)
Cosmology & Observation of the Dark Ages
→ Verification of standard cosmology**

**(Planetary Science)
Habitable Environments of Exoplanets
→ Investigation of environment for human living**

4. Science Investigations

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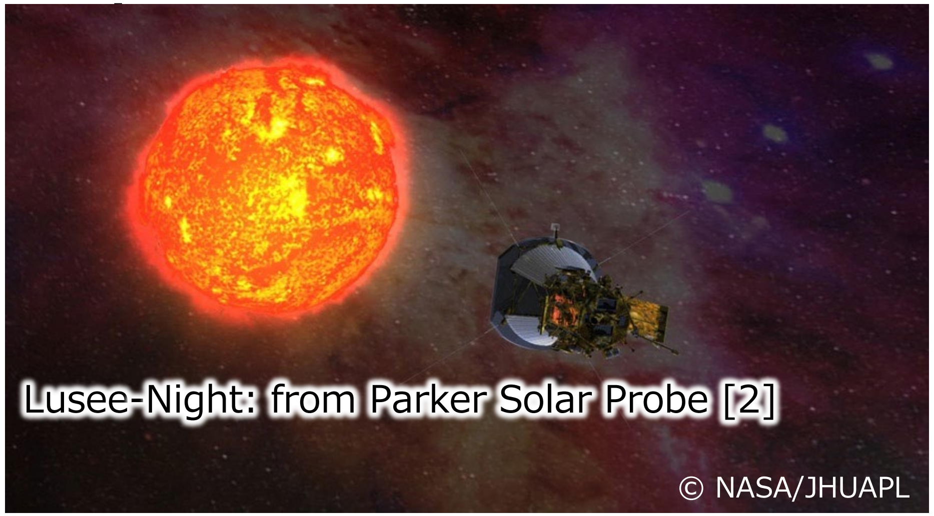
One or more antenna (single-dish mode)
2 or more antennas (interferometer)
3 or more antennas (interferometer)
10 or more antennas (single-dish mode)
Dozens of antennas (interferometer)

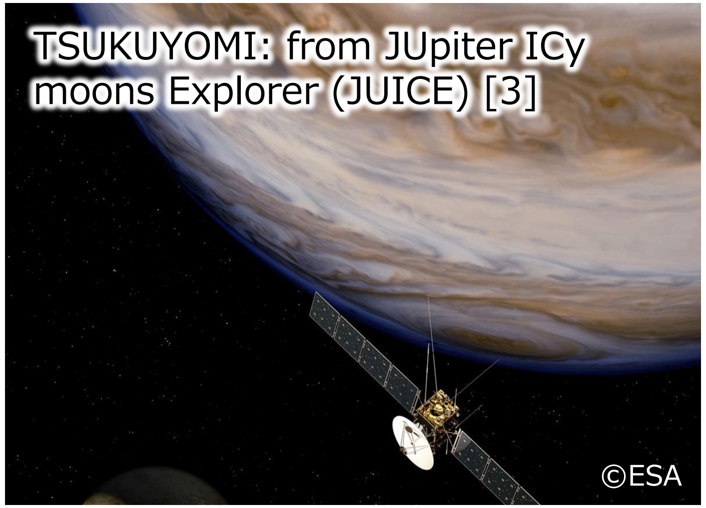
Science Goals		Science Objectives	Science Investigations	Observations useful for Calibration
Exploration of our Cosmic Origins	(Astrophysics) How the Universe began and evolved	Cosmology・Observation of the Dark Ages	**21 cm line global (sky-averaged) signal of neutral hydrogen**	**Radio Frequency Interference (FRI) from the Earth**
				Solar radio burst
				Jupiter radio burst
				Spectrum of the Milky Way
				Map of the Mily Way
	(Planetary Science) Identification and Characterization of Habitable Exoplanets	Exoplanet Planetary Aurora Emission	**Existence of magnetosphere**	
			Inner structure of planet	
		Stellar Radio Burst	**Space weather of Exoplanets : Stellar radio bursts (Type-I) and radio bursts associated with stellar flares and coronal mass ejections (Type-II, III, IV, V)**	
		Surface and Underground of Rocky Planets	**Underground structure of the Moon**	Dielectric measurement→helpful for beam measurement
			Dust condition of the Moon	Possibly affect on beam measurement
			Ionosphere of the Moon	Possibly need to calibrate SED

The first target would be the Astrophysics. Planetary Science is under consideration.

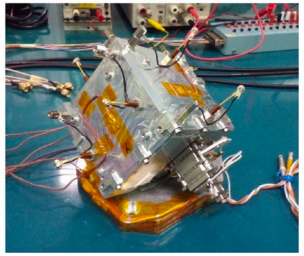
5. Instruments and Data to be returned

The Heritages of Low-Frequency Instruments from the fields of Solar and Planetary





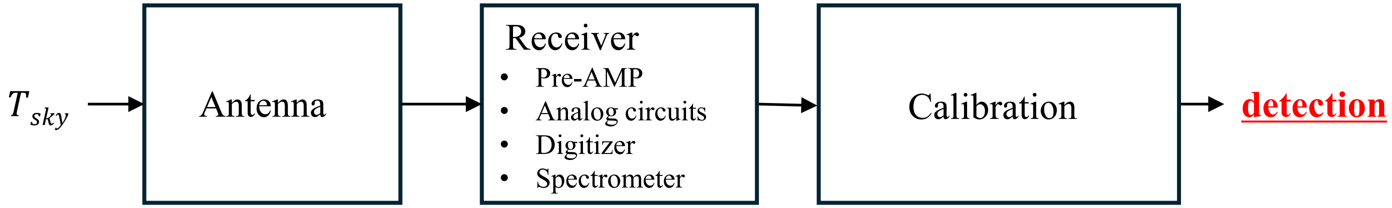
Radio & Plasma Wave Investigation [4]



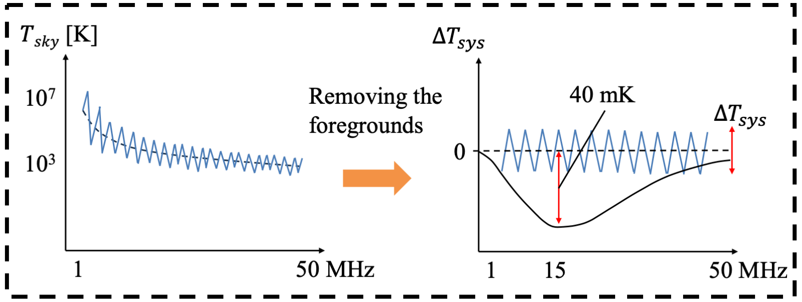
Freq. Range: 80 kHz–45 MHz
The unit including amplifier and FPGA was made in Japan (https://juice.stp.isas.jaxa.jp/).

Dipole antenna on the Moon surface

Conceptual design and system overview were described in Iguchi et al. 2024, SPIE [5].



- Antenna receives a signal (T_{sky}) from CMB, neutral hydrogens, and foregrounds.
- The foreground radiation is mainly dominated by the Milky Way galaxy is 10^7–10^3 K at 1–50 MHz.
- The residuals after the calibration of the bandpass response and removing the foregrounds are required to be less than the 21-cm global signal.



5. Instruments and Data to be returned

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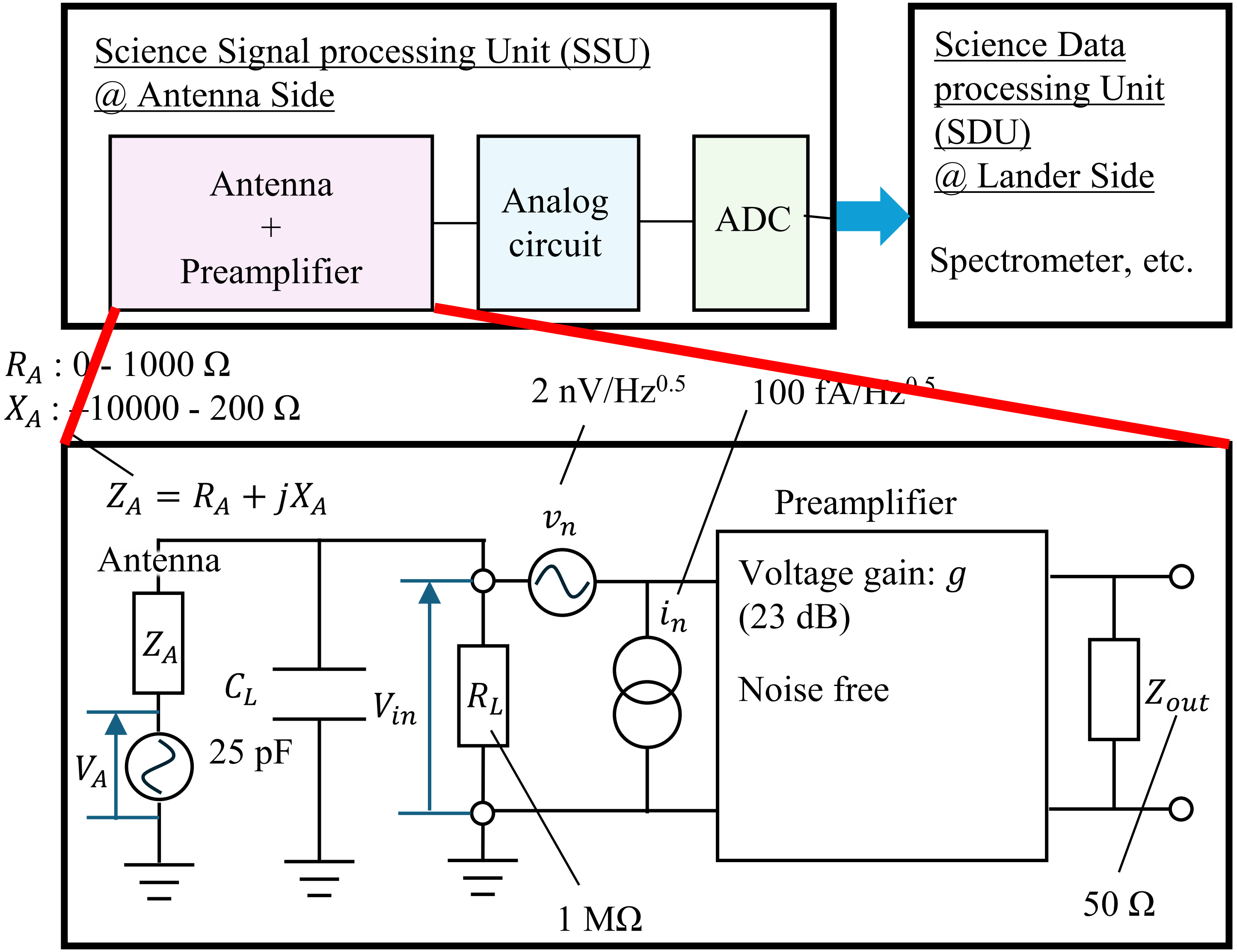
Analog circuit design (Matsumoto et al. 2024, SPIE [6])



$$T_{sys} = T_{sky} + \frac{1-\eta}{\eta} T_{amb} + \frac{|v_n|^2 + i_n^2 |Z_S|^2}{4|\alpha|^2 k_B R_A \eta}$$

$$\eta = \frac{\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} d\theta\, G(\theta,\phi)}{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta}$$

$$|\alpha|^2 = \left|\frac{V_{in}}{V_A}\right|^2 = \frac{1}{(1 - 2\pi f C_L X_A)^2 + (2\pi f C_L R_A)^2}$$

$G(\theta,\phi)$: Antenna gain
η: Antenna forward efficiency
R_A: Resistance of antenna, X_A: Reactance of antenna
C_L: Input capacitance of preamplifier
R_L: Input resistance of preamplifier
Z_{out}: Output impedance of preamplifier
g: Gain of preamplifier
v_n : Equivalent noise voltage density of preamplifier
i_n : Equivalent noise current density of preamplifier
Z_S: The combination impedance of the antenna and the preamplifier
T_{sky}: Sky temperature, T_{amb}: Ambient temperature
f: Frequency, Δf: Frequency resolution

6. Originality and International Competitiveness

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- **<u>Japanese participation in the Artemis project</u>**
  - In Octorber 2019, Japan announced its participation in the Artemis program then signed the Artemis in 2020.
  - Japan encourages to expand lunar exploration opportunities and promote world-leading science achievements.
- **JAXA launched a call for proposals for <u>Feasibility Studies</u> on lunar scientific research and technology demonstration in 2021.**

  1. Astronomy from the lunar surface
  2. Selection, collection, and return of important scientific lunar-surface samples
  3. Understanding lunar interior structure through a lunar seismic network

  ✓ **We formulated a research group to cover these <u>Three</u> sciences.**

- **This presentation is based on this feasibility study work and also '<u>Front-Loading for Lunar Science</u>' program organized by JAXA Space Exploration Center.**

6. Originality and International Competitiveness

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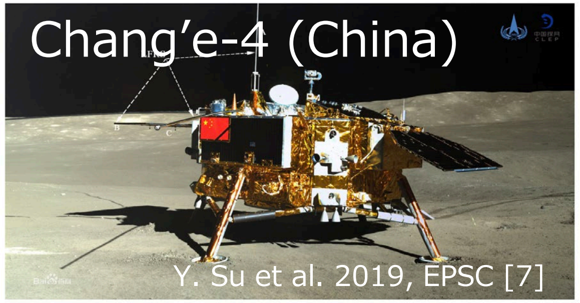
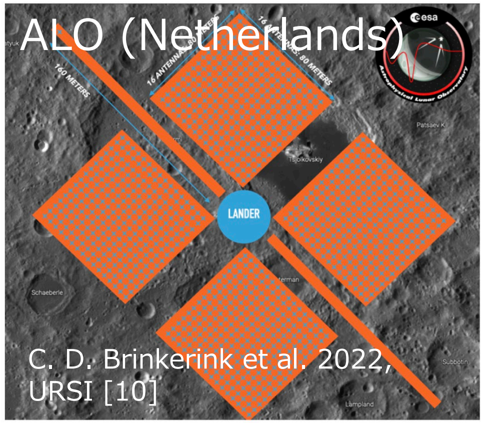
On the Moon



100kHz-40MHz
Landed on Jan. 2019. Scientific observations were performed. But, it seems to have interference issues from instruments.

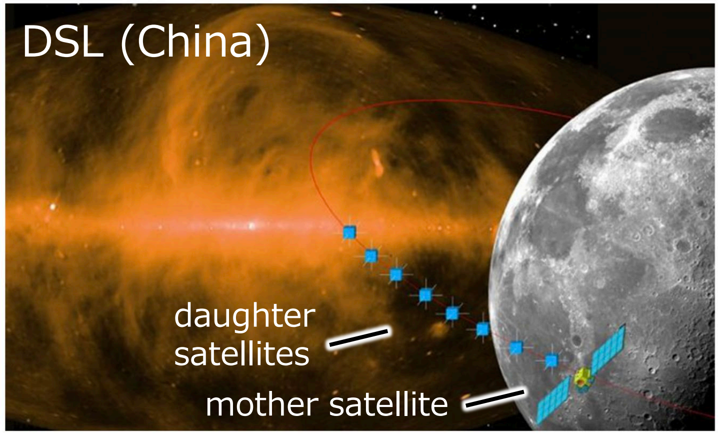
1-40MHz
Plan to launch in 2026 [8].

100kHz-40 MHz
A 10 km interferometer with 128 antennas (report [9]).



The ESA has a plan to construct a low-frequency radio telescope on the lunar surface (pole/far-side (future plan).

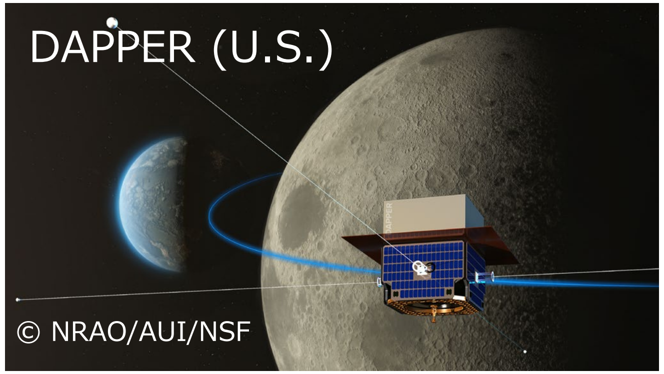
On the orbit



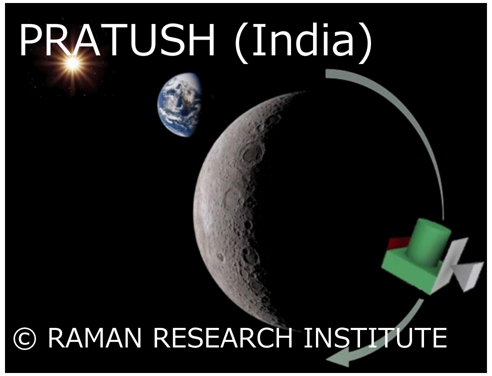
X. Chen et al. 2021, Phil. Trans. R. Soc. [11]

One daughter satellite has a 40-120 MHz radiometer, and others for an interferometer covering 30 MHz or less.

Plan to launch in 2027



17-38MHz
(future plan)



40-200MHz
(future plan)

6. Originality and International Competitiveness

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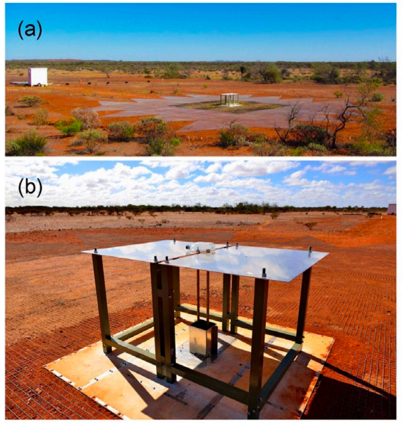
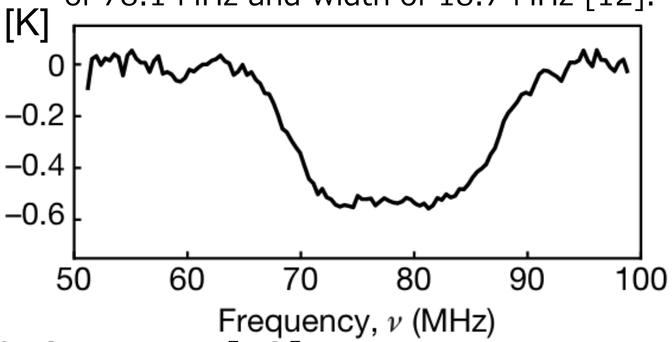
The signals from 50-130 MHz correspond to the Cosmic Dawn.

EDGES (U.S.)

- The EDGES adopted a wideband dipole-like antenna covering the frequency range to detect the 21-cm global signals from the cosmic dawn, that is located in Western Australia in which is a radio-quiet site.
- The EDGES group reported an absorption profile with an amplitude of ∼600 mK centered at 78 MHz.



Recovered model profile of the 21-cm absorption, with a signal-to-noise ratio of 37, amplitude of 0.53 K, centre frequency of 78.1 MHz and width of 18.7 MHz [12].



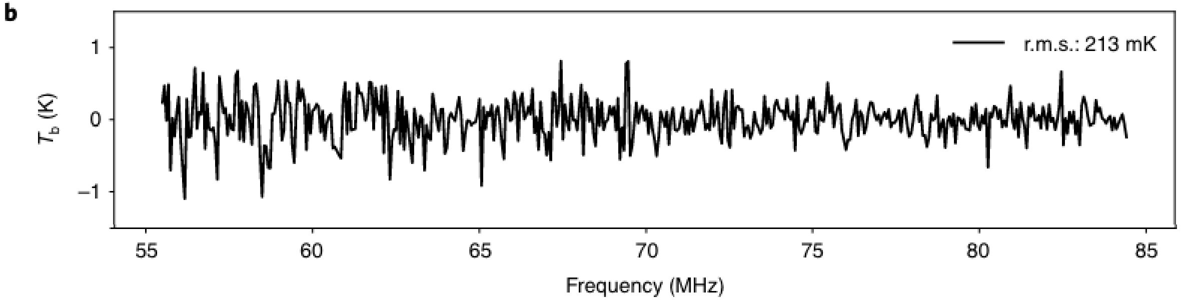
J. D. Bowman et al. 2018, Nature [12]

- It is also reported that the EDGES's measurements have some concerns regarding the unphysical foreground model and not unique solution [13].

SARAS3 (India)

- Shaped Antenna measurement of the background RAdio Spectrum (SARAS) also aims to detect the cosmic-dawn global signals from 87.5–175 MHz
- SARAS3 presented non-detection of the cosmic dawn sky-averaged 21-cm signal.

Residuals on subtracting a best-fit sixth-order polynomial model [14].



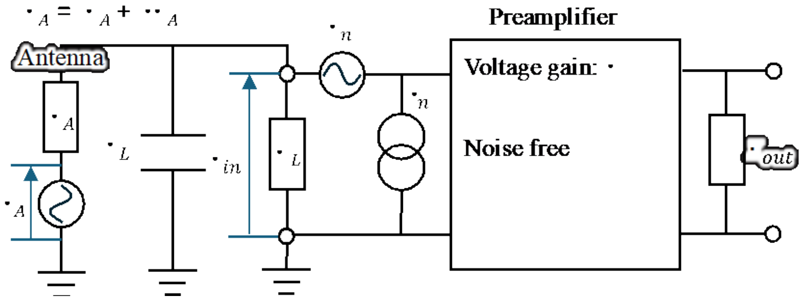
S. Singh et al. 2022, Nature Astronomy [14]

Observation system by using a dipole antenna

- Simple structure enables us to easily model its beam pattern and account for coupling with the lunar regolith.
- **Bandpass flatness** is managed by carefully designing the output power of a preamplifier P_{out}. (Iguchi et al. 2024, SPIE [5])

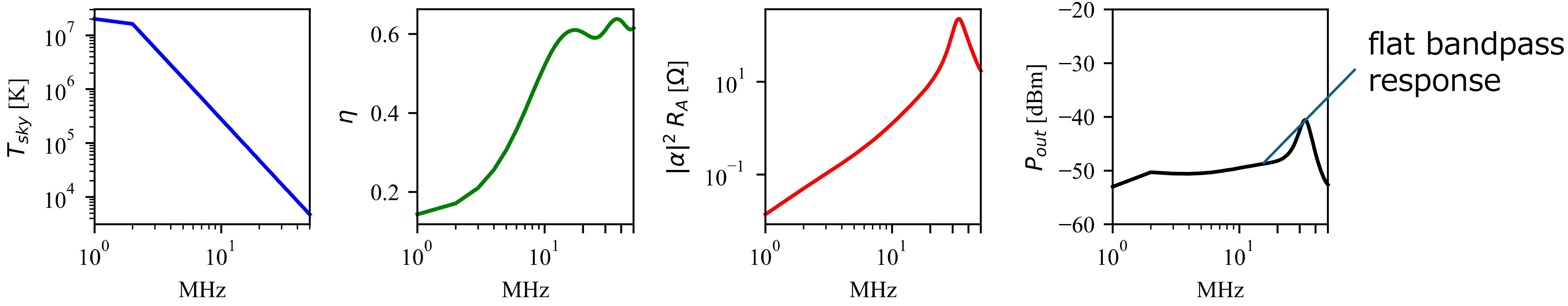
$$P_{out} = 4k_B|\alpha|^2 R_A \eta \left[T_{sky} + \frac{(1-\eta)T_{amb}}{\eta} + \frac{|v_n|^2 + i_n^2 |Z_S|^2}{4|\alpha|^2 k_B R_A \eta} \right] \frac{g^2 \Delta f}{Z_{out}}$$

$$|\alpha|^2 = \left| \frac{V_{in}}{V_A} \right|^2 = \frac{1}{(1 - 2\pi f C_L X_A)^2 + (2\pi f C_L R_A)^2}$$



R_A: Resistance of antenna, X_A: Reactance of antenna
C_L: Input capacitance of preamplifier, R_L: Input resistance of preamplifier
Z_{out}: Output impedance of preamplifier (50 Ω), g: Gain of preamplifier
v_n : Equivalent noise voltage density of preamplifier
i_n : Equivalent noise current density of preamplifier
Z_S: The combination impedance of the antenna and the preamplifier
T_{sky}: Sky temperature, T_{amb}: Ambient temperature
f: Frequency, Δf: Frequency resolution

Foregrounds × Forward efficiency × Radiation factor → Output power



(a) (b) (c) (d)

6. Originality and International Competitiveness (incl. 7. Current Status)

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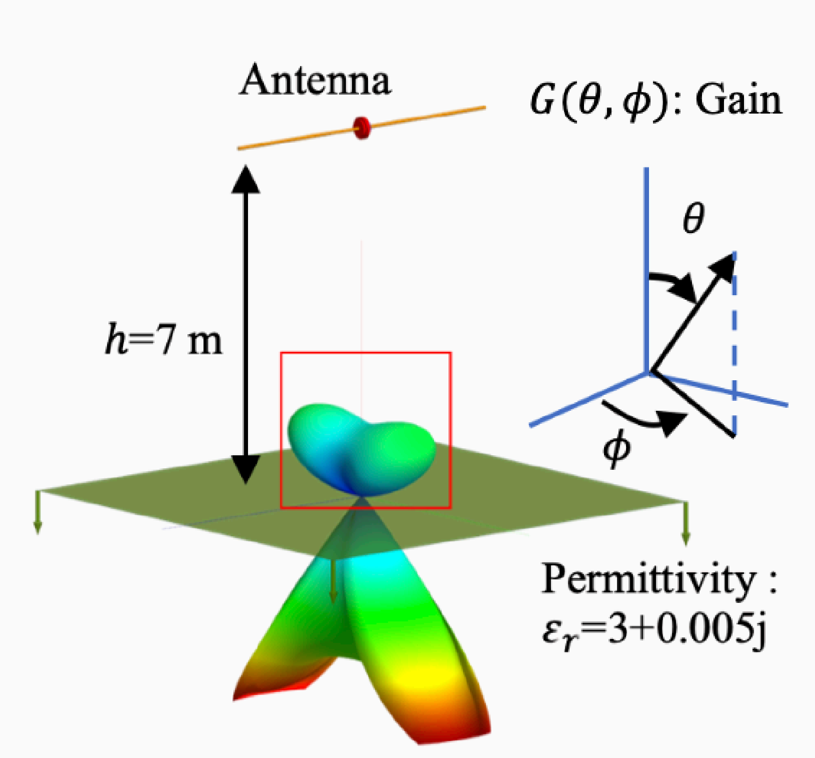
Requirements of antenna height from the ground (Yamasaki et al. 2024, SPIE [15])

- The larger height improves the antenna forward efficiencies at the lower frequency.
- The height of 7 m or more achieves the sensitivity requirement ($\Delta T_{sys} < 8$ mK) at 15 MHz.

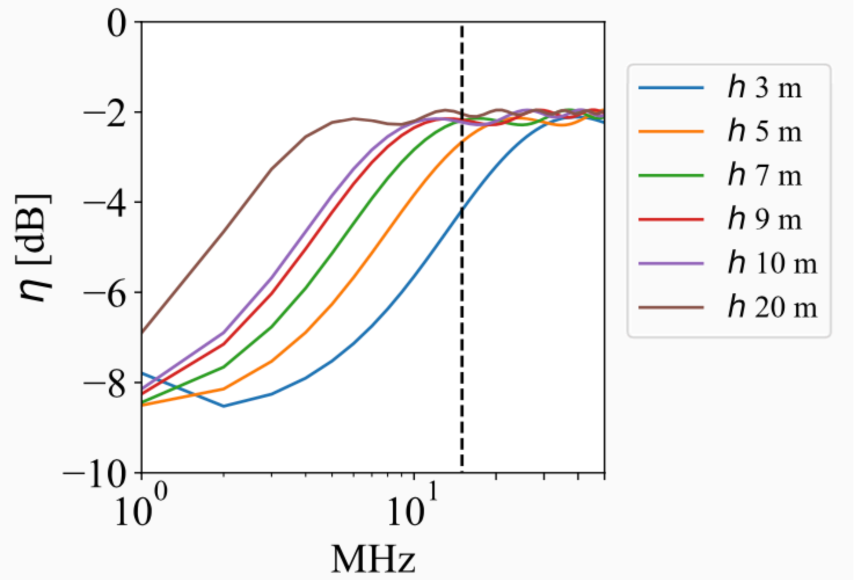


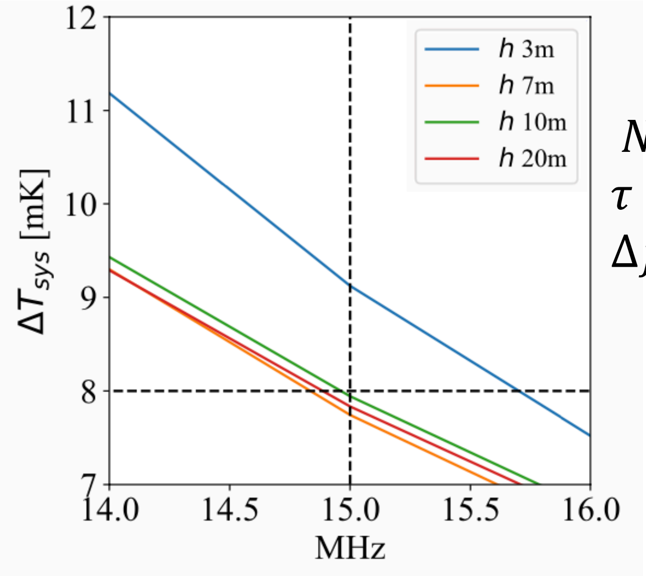
$$\eta = \frac{\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}} d\theta\, G(\theta,\phi)}{\int_0^{2\pi} d\phi \int_0^{\pi} d\theta}$$

$$T_{sys} = T_{sky} + \frac{1-\eta}{\eta} T_{amb} + \frac{|v_n|^2 + i_n^2 |Z_S|^2}{4|\alpha|^2 k_B R_A \eta}$$

$$\Delta T_{sys} = \frac{T_{sys}}{\sqrt{N_{ant} \Delta f \tau}}$$

N_{ant} : Number of antennas, τ : Integration time,
Δf : Frequency resolution,
h : Antenna height from the ground

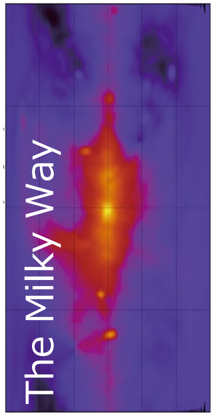


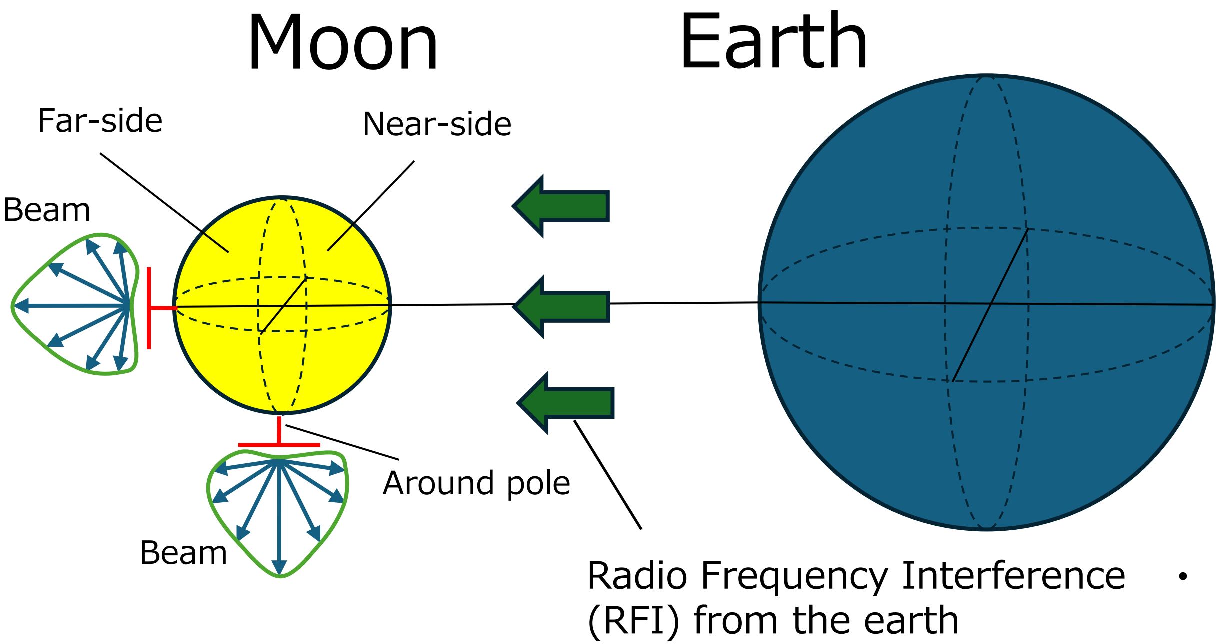


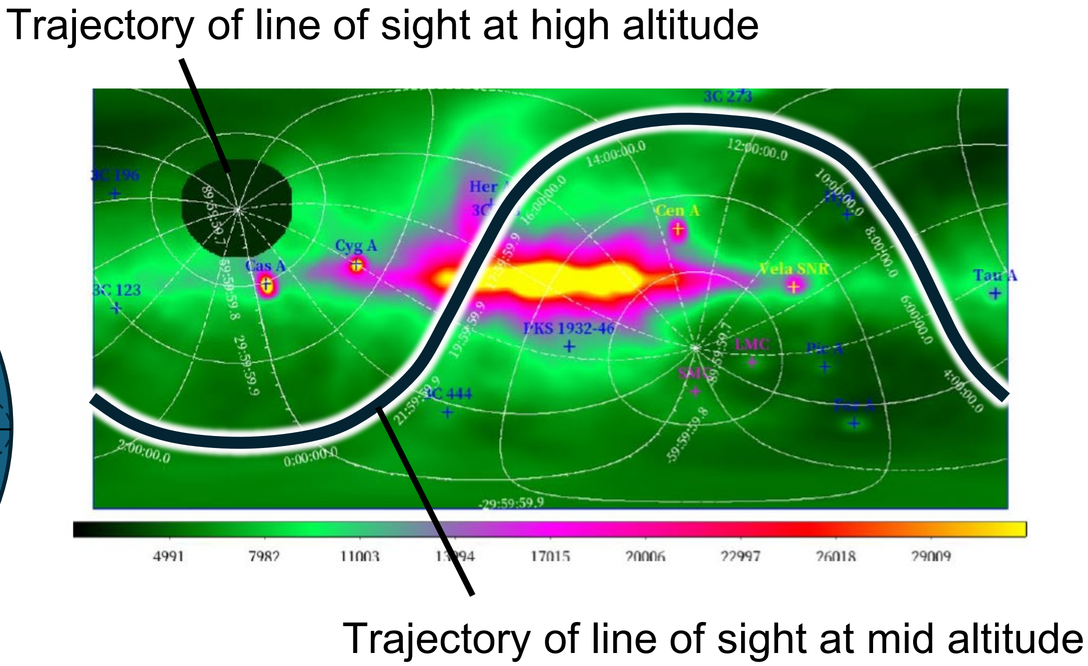
$N_{ant} = 10$,
$\tau = 8000$ h,
$\Delta f = 1$ MHz

6. Originality and International Competitiveness (incl. 7. Current Status)

Landing site (Iguchi et al. 2024, SPIE [5])



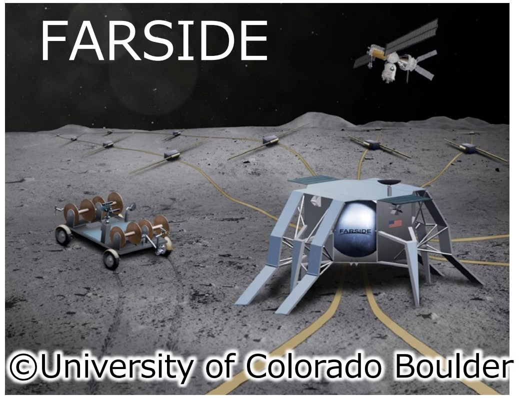




Landing site	Sensitivity	RFI condition	UV coverage
High altitude	○	×	×
Mid altitude	×	○	○

- The higher the latitude of the landing site, the lower the radiation from the Milky Way, which dominates the system noise (up to 1/2), due to the line-of-sight orbit shown in red line in the right figure. In other words, landing closer to the south pole will further improve the sensitivity calculated assuming a uniform distribution on p. 16.
- On the other hand, the influence of Radio Frequency Interference (RFI) from the earth will be stronger. From an interferometric point of view, the closer the landing site is to the south pole, due to the very slow rotational speed of the line of sight, the less the UV space is filled and the worse the interferometer image.

6. Originality and International Competitiveness (incl. 7. Current Status)



	FARSIDE [9]	LuSEE-Night [8]	TSUKUYOMI (prototype)	TSUKUYOMI [5]
Year of Launch	---	2026	2027-2028(9)	2030~
Landing site	Far-side of the Moon	Far-side of the Moon	(South pole of the Moon)	Under discussion
Observing Frequency Range	1–40 MHz	0.5–50 MHz	1–50 MHz	1–50 MHz
Number of Antennas	128	1	1	10
Number of Polarizations	1	2	1	1 or 2
Length of Antenna	5 m	6 m	5 m	5 m
Integration Time	1800 hours	(240 hours)	(240 hours)	8000 hours
Antenna Height from the Ground	~0 m	3 m	7 m	7 m
Sensitivity@15 MHz	29 mK*	43 mK*	63 mK*	7.7 or 5.5 mK*

It corresponds with an accuracy to detect the absorption of 40 mK.
Our goal is 8 mK, which is 1/5 of 40 mK.

(): Bracketed value is used for sensitivity comparison.
*: These estimations of telescope sensitivity are based on the formula reported in Iguchi et al. 2024, SPIE [5]. This calculation does not include the effect of landing site on the sensitivity.

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