28^{th} Satellite Design Contest　Mission Overview

Application category

Idea Section

1. Work information/Applicants information

Work title (less than 20 words)	**ARETHUSA**	
Subtitle	**A**djustable **R**opeway for t**ETH**ered **U**nderground **S**urvey and **A**nalysis	
	Name	Affiliation including faculty, department (Lab) and year of study
Group representative	Dan Padilha	The University of Tokyo, Department of Aeronautics and Astronautics (Kawaguchi Lab), Master Course (1st Year)
Member 1	Atsuhiro Gomi	The University of Tokyo, Faculty of Engineering, Department of Aeronautics and Astronautics, Bachelor Course (3rd Year)
Member 2	Takaya Nakamura	Tokyo University of Science, Graduate School of Science and Technology, Department of Mechanical Engineering (Mizoguchi Lab), Master Course (2nd Year)
Member 3	Daigo Takasaki	The University of Tokyo, Department of Aeronautics and Astronautics (Koizumi Lab), Master Course (1st Year)
Member 4	Woo Chung Yu	The University of Hong Kong, Faculty of Engineering, Department of Computer Science, Bachelor Course (3rd Year)

2. Outline of the satellite (approx. 200 words)

ARETHUSA - Adjustable Ropeway for tETHered Underground Survey and Analysis - is a lunar mission that exploits a novel tethered ropeway concept to explore the Marius Hills (MH) pit, the first lunar skylight discovered by the Japanese *Kaguya* satellite. Consisting of two rovers and a tether, ARETHUSA introduces the **Tethered Underground Survey System (TrUSS)**, that would demonstrate a safer, more economical way to access these lava tubes than conventional ways that involve locomotion across rough terrains. The mission would help us understand the Moon's geological history by precise measurement of the lunar volcanic strata exposed in the skylight walls, as well as to prototype a system for loading large payloads in and out of the skylight. After landing on the Moon, the Lunar Platform will be separated into two **"Base Station Rovers" (BSR)** positioned on opposing sides of the skylight, with a mutual tether attached to both BSRs. Helical anchors will be deployed to assure the stability of the system. After that, the scientific payload containing the **"Vertical Analysis Sensor" (VAS)** and two **"Mobile Micro Rovers" (MMR)** will be released and horizontally move along the tether. This payload will then vertically descend via the tether into the skylight like an elevator and map the skylight's inner walls. Once the payload reaches the bottom, the two MMRs would be released into the lava tube and commence in-situ assessment of the environment.

3. Aims and significance (Purpose, importance, technical or social significance etc)

(a) Aims

The primary objectives of ARETHUSA are (1) to scientifically analyse the lunar lava tubes and (2) to demonstrate the controlled access of extra-terrestrial skylights. The inner walls of the skylight provide natural access to the Moon's palaeo-regolith, which is key to understanding the Moon's volcanic history. The VAS would map and analyse these geological features, using optical, thermal, and spectroscopic imaging instruments during the tethered descent. The MMR conducting in-situ exploration inside the tube will also reveal the environmental characteristics of lava tubes and evaluate its habitability. Technically, the TrUSS will serve as a proof of concept for a system which enables safe, reliable access to the tubes. It can be further developed, enhanced and transformed into a system for the transport of cargo, materials and ideally humans across and into lava tubes and other difficult-to-access environments in future.

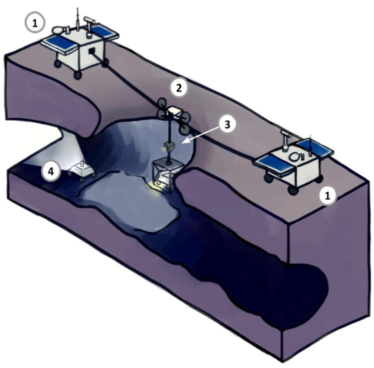
(b) Importance, technical or social significance

The scientific findings from our mission are crucial in verifying the hypothesis that these lava tubes are ideal candidates for utilisation through the construction of lunar bases. Precise mapping of the Moon's ancient layers of basaltic lava flows will also provide insights to understanding its subsurface mineralogy and geology. ARETHUSA aims to demonstrate that a ropeway-like structural design is feasible for the controlled exploration of lava tubes, and inspire new engineering designs based on this proof of concept.

4. Specific content of the Mission

(a) System (overall configuration, shape, mass, function, orbit, data acquisition etc, including ground station and satellite/mission device)

ARETHUSA Lunar Platform			
Dimensions	190 × 70 × 150 (cm)	**Wet mass**	650 kg
Launch & lunar rendezvous	- H-IIA Rocket (H2A02 dual PL) - Low-energy transfer and ballistic capture into lunar orbit	**ADCS + Landing operations**	- Sun Sensor - LIDAR - LRF
Landing & Propulsion	- BT-4 engine - 4 × 20 N-class RCS thrusters - Aluminum impact absorber	**Structure**	- Aluminium - ø 0.64 m two fuel tanks and ø 0.54 m oxidizer tank (spherical)



Referring to the left figure, the main components of the ARETHUSA Lunar Platform consist of:

(1) two Base Station Rovers (BSR), and the **(2)** Tethered Underground Survey System (TrUSS), which contains the **(3)** Vertical Analysis Sensor (VAS) and **(4)** two Mobile Micro Rovers (MMR).

	BSR *for one	**TrUSS**	**VAS**	**MMR** *for one
Dimensions	≥ 70 × 70 × 70 (cm)	158m tether (5mm M5 fiber)	30 × 30 × 30 (cm)	30 × 20 × 20 (cm)
Wet mass	70 kg	45 kg	10kg	Maximum 10 kg
Navigation	Teleoperated from ground station			Human-in-the-loop navigation system
Scientific payload	N/A	N/A	- Thermal Infrared Sensor (TIRF) - Radar (150~1200 MHz) - LIBS	- Energetic Particle Spectrometer - Sheath Thermocouple
Electrical power	- Li ion battery (50 kg) - Solar cell paddles × 2, (1 × 0.5m)	- Li ion battery (3 kg)	N/A	- Li ion battery (1 kg)
Communications	- Iris V2.1 X-band radio - Reflect-array antenna (29.2dB, 3.8W, X-band)	- S-band repeater	- PULSAR STX + SANT (S-band)	- PULSAR STX + SANT (S-band)
C&DH	Hyperion Technologies CP400.85 processing platform			
Environmental control	- Reversible Thermal Panel - Heat pipe - Radiation shielding	N/A	N/A	N/A

(b) Concrete achievement methods or necessary tasks and/or items to be developed

The key design philosophy of the main tethering system centers on reliability and stability. To achieve this, we referred to existing ropeway systems to analyse the forces acting on the underground survey system. We performed a quantitative evaluation of the BSR to be stabilized on the ground during survey from the mass of BSR and TrUSS, with safety factors of at least 2 considered due to the design's yet unproven use in the lunar environment. We anticipate that more rigorous finite element analysis and verification of the deployment and cargo transportation techniques will be required to assure that the entire system is stable and reliable. A preliminary analysis also showed that the use of helical anchors could provide additional stability and redundancy to the BSRs, albeit at the potential loss of an extra degree of freedom afforded by the BSRs' mobility.

Concerning ancillary subsystems, the ideal is to adopt technologies that are or have been developed for other lunar mission proposals and that have tangible, verifiable published results. We proposed that the two BSRs will be teleoperated from the ground station, as is conventional practice. However, more development tasks are required to verify that the navigation of both BSRs in tandem is technically safe and stable.

Our selection of scientific equipment is based on the instruments that have been proved useful in past missions. The radar is based on the RIMFAX of the Mars2020 Perseverance rover and TIRF is based on Mini-TES of Mars Exploration Rover. The LIBS is based on the Mini-LIBS which is going to be loaded on the Exo-Mars rover. The design of the MMRs is tailored to meet principles of simplicity and controllability, as to assure that they may be operated on uneven terrains and conduct in-situ analysis. As the configuration and navigation system of MMRs are now based on previously proposed designs, we anticipate that more customisation could be made in future to enhance its functionality and mitigate risks.

The landing system has been proposed based on the SLIM project with custom changes, as it is expected to demonstrate the highest landing accuracy of any previous or existing mission. Aluminum fibers located on the landing legs will absorb the impact easily due to a design with similar mass as SLIM. Radars used for landing navigation have flight heritage in the successful Hayabusa project. The real-time image analysis is a key technology for landing accuracy that will need to be realized.

5. Originality and/or social effects

(a) Originality of the mission

Although there have been many proposals for lunar lava tubes exploration, ARETHUSA differs greatly in the way that it emphasises controlled access and reliability. Without the need for complicated robotic locomotion designs or flying craft requiring propulsive control, our unique ropeway-inspired design could overcome the challenge of sheer vertical walls with minimal risks. At the same time, as on Earth, a future system could be designed to handle significantly larger payloads, as will be important for providing access and transportation of construction materials, passengers, and cargo into these underground environments. Also, another unique point of ARETHUSA is the analysis of volcanic strata exposed in skylight walls, which is achieved via precise positioning of the VAS scientific instruments. The VAS could map the inner walls with high accuracy thanks to the stability provided by the tethered system and its horizontal and vertical position control. Additionally, the mobile BSRs could also move along the skylight edge, contributing an extra degree of freedom for 3-dimensional positioning within the skylight. Finally, with larger payload capacities, we could potentially send more scientific equipment and exploration rovers into the lava tube than other proposals, for extra redundancy and better mapping of the lunar subsurface environment.

(b) Anticipated results, effects, intended users

Scientific data obtained in this mission will provide crucial sources to study the moon's geological and structural characteristics. From an engineering perspective, we believe that ARETHUSA has the potential to be developed into an elevator system for repeatable access into and out of the lava tube and skylight. With further improvements to our tethering system design, TrUSS could be developed to handle even greater payloads. Amidst the widely expected "moon rush" of the 2020s, such transportation technology might even secure a strategic edge for the future utilisation of lunar underground shelters. With JAXA keen to play a leading role in lunar missions, a successful demonstration of controlled exploration of lava tubes would open up many opportunities to exploit these shielded environments and expand our frontiers in space.

ARETHUSA – Adjustable Ropeway for tETHered Underground Survey and Analysis

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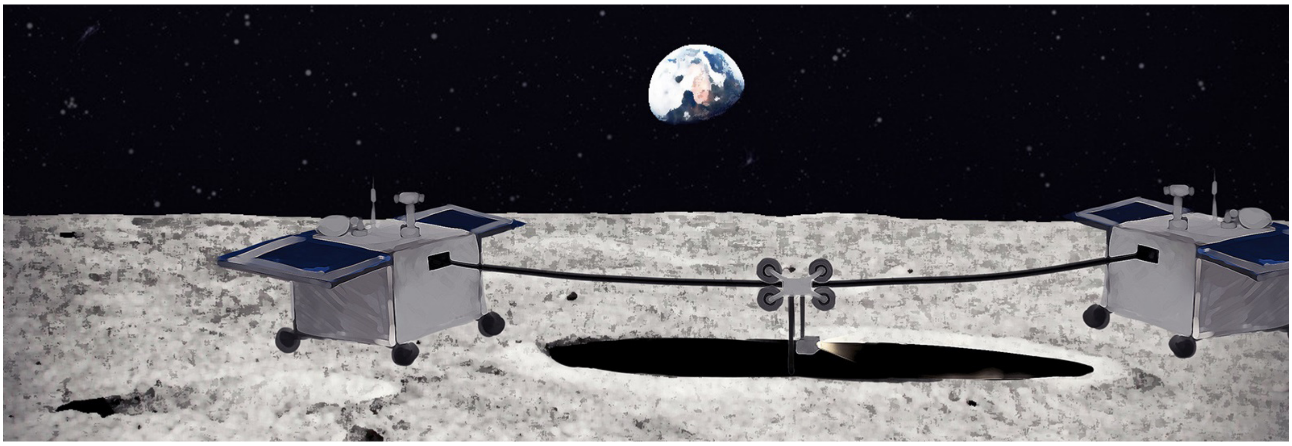
October 26, 2020 – As submitted to the 2020 Satellite Design Contest（衛星設計コンテスト）



THE exploration of lava tubes and caves on extra-terrestrial bodies is hailed as an important step towards the future establishment of off-world human habitats.[1] First postulated in the 1960s,[2] their existence was confirmed with the discovery of a "skylight" – a lava tube ceiling collapse[*] – on the Moon by the *Kaguya* lunar satellite.[3] Since then, several lunar and Martian skylights have been discovered, motivating research to understand their physical properties, including natural shielding against meteoroids and radiation and their stable thermal environment, to enable more permanent shelters for future utilisation and settlement of the Moon and Mars.[4]

The difficulty in accessing lunar lava tubes is a major challenge in their exploration, given skylight entrances with sheer vertical walls of unknown surface structure, and depths exceeding 50 m to 100 m. Existing proposals tend to rely on sophisticated robots for scaling down the rocky walls,[5] or flying craft needing propulsion and complex control.[6] These have yet to be demonstrated as safe, reliable methods for humans to descend into, and return from, the lunar subsurface.

We propose **ARETHUSA** – **A**djustable **R**opeway for t**ETH**ered **U**nderground **S**urvey and **A**nalysis, a lunar exploration and technology demonstration mission that features a tethered system providing both controlled ascent and descent of a payload of circa 20 kg into a lava tube skylight. The system is inspired by aerial ropeways, a reliable and historically-proven technology widely used in the transport of passengers and materials.[7,8] Named after a mythical nymph transformed into an underground spring by the goddess of the Moon, ARETHUSA is envisioned as a proof of concept for reliable access to and initial scientific investigation of lunar underground lava tube structures. In this way, ARETHUSA seeks to pave the way towards future inhabitation and utilisation of such environments.

[*] Also referred to in the literature as "sinkholes" or "pits".

1. Mission Objectives & Significance

ARETHUSA is designed to achieve several scientific and engineering objectives in support of selenological science and long-term plans for off-world human settlements. Two significant benefits of this mission, particularly in comparison with other lava tube exploration proposals, are: firstly, in measurements of the lunar volcanic strata exposed in the skylight walls, offering crucial insights into the volcanic processes behind the Moon's geological history; secondly, in a novel method of skylight and lava tube access with potential applications to the safe and reliable transport of astronauts and cargo, as required for future construction of underground habitats.

Scientific Objectives

The primary scientific objective is to reveal structural, environmental, and geological characteristics of lunar lava tubes. The inner walls of the skylight provide natural access to the Moon's palaeoregolith, exhibiting the ancient layers of basaltic lava flows key to understanding the Moon's volcanic history, and distribution and age of its subsurface mineralogy.[9] ARETHUSA will map and analyse these geological features using optical and thermal imaging and high precision radiometry during tethered descent into the skylight. Temperature and radiation dose

Summary of Significance & Originality

- First proposed demonstration of tethered technology for up to 3 degrees-of-freedom of controlled, reliable access of a lava tube skylight environment.
- Early exploration and assessment of an environment with significant applications to future human habitation.
- Scientific investigation of structural and geophysical properties of lunar lava tubes, towards a deeper understanding of the Moon's geological evolution.

measurements will also help to verify the potential habitability and suitability of the environment for future lunar base infrastructure.

Engineering Objectives

Lava tubes and underground spaces are ideal candidates for cheaper and more practical lunar infrastructure thanks to substantial protection from radiation and micro-meteorite impacts, and a lack of dust and temperature variations, and may therefore provide significant strategical advantages towards lunar utilisation.[9] ARETHUSA's primary engineering objective is to demonstrate a novel tethered ropeway concept for controlled access of extraterrestrial lava tubes, providing up to 3 degrees-of-freedom of access using economical and relatively lower-risk technology. The mission is to serve as a prototype for the future transport of cargo, materials, and even humans across and into lava tubes, avoiding more complicated or risky solutions that may need propulsion or locomotion across challenging rocky surfaces and terrains.

2. Mission Profile

The primary ARETHUSA mission is comprised of a Lunar Platform (LP), pictured in fig. 1. This consists of two Base Station Rovers (BSRs) positioned on opposing sides of a lunar lava tube skylight and attached by a mutual tether, forming a ropeway-like structure. Supported between them is the Tethered Underground Survey System (TrUSS), supporting a scientific payload and providing it with vertical access into the skylight. This payload includes a Vertical Analysis Sensor (VAS) used to measure and map the skylight itself, stabilised by a tethered station carrying a Mobile Micro Rover (MMR) to be released for exploration and structural assessment of the lava tubes below.

2.1. Mission Schedule

The mission is envisioned to operate in three phases: Launch & Lunar Rendezvous (section 2.3), Landing & Deployment (section 2.4), and Lunar Platform operations (section 3). Lunar Platform operations are expected to last at least one full day/night cycle ($\sim$ 28.5 days), providing sufficient time to: remotely assess and navigate the surface terrain for optimal positioning; deploy and operate the TrUSS by lowering the MMR into the lava tubes; perform scientific operations including environmental assessments of the lava tubes and skylight, under both lunar day and night conditions; and power up communications for full transmission of scientific data.

2.2. Spacecraft Structure

The bus of the ARETHUSA spacecraft (including the Lunar Platform and landing module) is made of aluminium, with a total spacecraft mass of approximately 650 kg (see table 1). The propellant tanks (section 2.4.3) are the largest and heaviest component. The Lunar Platform (section 3) is fixed atop of the tank during its spacecraft configuration until landing and deployment. Thruster nozzles and landing legs are located on the bottom of the spacecraft.

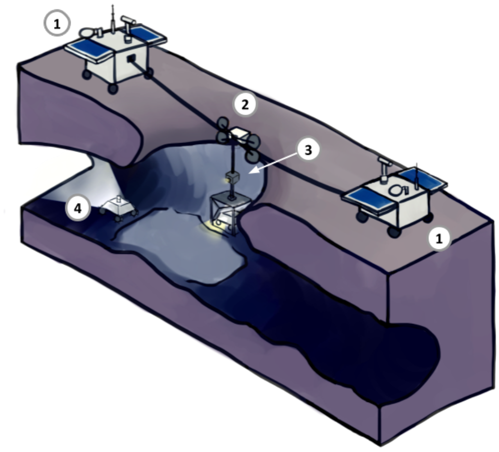


Fig. 1. Artistic impression of the ARETHUSA Lunar Platform (LP) exploring a lunar lava tube via its skylight. The LP consists of: ① Base Station Rovers (BSR, Section 3.2). ② Tethered Underground Survey System (TrUSS, Section 3.3), containing the ③ Vertical Analysis Sensor (VAS, Section 3.6) and ④ Mobile Micro Rovers (MMR, Section 3.6).

2.2.1. Attitude Determination & Control System. Attitude determination is provided primarily by a Sodern Hydra multiple-head star tracker (3.2 kg, 8 W)[10] and four NewSpace Systems NFSS-411 sun sensors (total 0.14 kg, 0.15 W) to provide redundant determination in each direction. Attitude control is sufficiently performed by 4 × RCS engines described in section 2.4.3.

2.3. Launch & Lunar Rendezvous

ARETHUSA is to be launched on an H-IIA launch vehicle from the Tanegashima Space Center (N 30°24′0″ latitude).[11] The launch payload is fixed to the lower fairing of a dual launch configuration, effectively piggy-backing on a larger lunar mission; this is assumed at this stage to allow for lower costs and risks. For injection into lunar transfer, ARETHUSA requires a characteristic energy of $C_3 \approx -2.1\,\mathrm{km^2/s^2}$, allowing either a short direct transfer (2∼6 days with $\Delta V \approx 820\,\mathrm{m\,s^{-1}}$) or an extended low-energy ballistic transfer and capture (70∼120 days with $\Delta V \approx 640\,\mathrm{m\,s^{-1}}$), the latter preferred for its launch window flexibility and much lower orbit insertion risk.[12] Under these requirements, the launch vehicle supports a maximum payload mass of ∼800kg within an approximately cylindrical ⌀3.7×5.3m volume.[†] The spacecraft is assumed to transfer into an elliptical orbit with 100 km perilune altitude that is gradually lowered to 15 km (using $\Delta V \approx 40\,\mathrm{m\,s^{-1}}$) until landing commences.

† Assuming a H2A202 dual payload fairing configuration.[11]

Table 1. Estimated mass budget for ARETHUSA.

Item	Value
Landing module (section 2.4.3)	455 kg
Propellant + oxidiser tanks	400 kg
Lunar Platform (section 3)	195 kg
BSRs (total of BSR-1 & -2, section 3.1)	140 kg
Tether + Power line (lateral only, section 3.2)	10 kg
TrUSS (excluding Scientific Payload, section 3.2)	18 kg
Scientific Payload (VAS + MMRs, section 3.3)	27 kg
Estimated Spacecraft Mass	650 kg

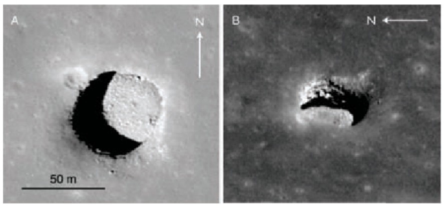


Fig. 2. Photos of the Marius Hills pit revealing presence of caves beneath the lunar surface, and the stratified layers of the skylight walls. Courtesy of [15].

2.4. Landing & Deployment

2.4.1. Landing Sequence. Landing operations begin from an altitude of 15 km and proceed according to the following sequence:

- 15 → 3.5 km **altitude:** The lander coasts in a ballistic trajectory, gradually lowering its altitude and reducing its horizontal velocity. From this initial height, the lander images the lunar surface to track and adjust its attitude and velocity appropriately.
- 3.5 → 0 km **altitude:** The lander begins vertical descent above the landing site, adjusting its horizontal position by using an Optical Navigation Camera to identify obstacles on the lunar surface.
- 0 km **altitude:** The lander lands on the lunar surface and deploys the Lunar Platform.

The landing sequence is assumed to achieve a high landing accuracy close to the selected landing site through the use of state-of-the-art real-time image- and radar-based navigation, hazard detection, and line-of-sight guidance control technologies.[13,14]

2.4.2. Landing Site Selection. The preliminary selection for a landing site is the Marius Hills Pit (fig. 2), a lunar lava tube located at N 14°5′24″ E 303°18′36″ in the Marius Hills region, selected for its proximity to abundant volcanic structures and its smaller size compared to other known skylights.[4,9] The maximum and minimum skylight diameters are 57 m and 48 m respectively, and the maximum depth of the floor below the surrounding terrain is 45 m.

2.4.3. Landing Module. The landing module requires the use of an impact absorber and a landing radar. Aluminium fiber on the tips of each landing leg are used to absorb the impact.[16] Two types of landing radar with flight heritage from Hayabusa, LIght Detection And Ranging (LIDAR) and Laser Range Finder (LRF), are used as altimeters. LIDAR is a pulse radar that uses a laser as its transmitting light source,[17] whereas LRF uses 4 lasers, each at 30° relative to vertical, to identify its relative attitude to the landing plane. The measuring range differs between the two (see table 2).[18]

A main engine and four RCS engines are used for propulsion. The BT-4 main engine, with flight heritage on SELENE, uses a Hydrazine fuel and MON-3 oxidizer, and provides 547 N of thrust (specific impulse of $I_{sp} = 319.8$ s, weight ∼4 kg). The RCS engines are also based on the SELENE propulsion system, with each engine providing a thrust of 20 N. These RCS engines are monopropellant and share a common propellant tank with the main engine.[19] For orbit insertion and landing, a total of 400 kg of propellant is required, stored in three spherical tanks with a total volume of 0.36 m^3 (approximately ⌀ 0.64 m for two Hydrazine tanks and ⌀ 0.54 m for a MON-3 tank).

Table 2. Performance of altimeter radars for landing.

Radar	Measuring range	Accuracy
LIDAR	30 m - 25 km	1 m (at 30 m), 5.5 m (at 25 km)
LRF	7 m - 100 m	0.1 m (at 10 m), 3 m (at 100 m)

2.4.4. Post-Landing Deployment. Prior to landing, the Lunar Platform (LP) consists of a payload fixed above the propellant tanks of the landing module. Upon landing, two ramps are unfolded to allow the LP to deploy by driving down onto the lunar surface directly. A fold-type ramp design (total system weight ∼ 15 kg) is selected for its high reliability and redundancy.[20]

3. Lunar Platform (LP)

The LP provides the basis for achieving the scientific and engineering objectives (as per section 1) of the ARETHUSA mission. The LP is deployed from the landing module as a pair of Base Station Rovers (BSRs), which are then navigated towards opposing edges of the lava tube skylight. From there, TrUSS deployment commences so as to provide vertical access into the skylight for scientific operations.

3.1. Base Station Rovers (BSRs)

The **Base Station Rovers (BSRs)** are designed as two separate rovers that act as bases for the TrUSS lateral tether system used to lower the scientific payload into the skylight, and also provide the processing, communications, and power subsystems for the mission.

3.1.1. Structure & Dimensions. Each BSR is a small wheeled rover estimated to weigh approximately 70 kg, including electrical power (section 3.4), communications (section 3.5), command and data handling (section 3.6), and environmental control (section 3.7) systems. Most importantly, the two BSRs together act as the base supports for a tethered payload delivery system: the TrUSS (section 3.2).

Each BSR is assumed to provide a working volume of at least 0.35 m^3 with dimensions of at least 0.7 × 0.7 × 0.7m. This provides space for spools and motors for the tethers and power lines, support structures for the rover and wheels, and all other necessary equipment for each system. Solar electric paddles are deployed on hinges from either side of the BSR. A boom extends out from the top surface of the BSR, with a swivelling head mounted atop it, containing the Navigational Camera (NavCam), and a feed for the reflect-array antenna covering the top surface of the BSR.

3.1.2. Navigation. At first, the BSRs are connected by a short tether and navigated in tandem towards an appropriate initial location near the edge of the skylight. This is done primarily via tele-operation with near real-time feedback from each BSR's stereoscopic NavCam to ensure appropriate hazard avoidance and assessment of the environment around the skylight edge.

Having reached the skylight, **BSR-1**, containing the TrUSS with its scientific payload, remains in place while **(BSR-2)** navigates separately around the edge towards the opposing side of the skylight, travelling a maximum distance of approximately 150 m. A spool installed within BSR-2 continuously unspools the tether.

Once both BSRs are approximately in place, their positioning is refined such that each BSR is about 1 m away from the edge of the hole.[‡] Once BSR-2 reaches its final position, approximately 52 m on the opposite side from BSR-1, the tether is spooled up until it reaches its initial sag position (section 3.2.3).

Although each BSR has its own C&DH and navigation system, prior to separation the whole structure is treated as a single rover for control. The sensors (including the NavCam) of the front BSR are used for primary tele-operated navigation. Relative positioning of the BSRs is computed by mission control given imagery and odometer telemetry received. Loss of driving force or traction on either BSR could be compensated by further design allowing the other BSR to tow it using the tether.

3.2. Tethered Underground Survey System (TrUSS)

The **TrUSS** is a ropeway system for payload delivery[8] into the lunar lava tube, designed to be mounted on a tether supported by the BSRs and provide vertical access into the skylight.

The TrUSS has a drive motor for moving horizontally along the tether and an elevator motor and tether spool for lowering a payload vertically into the skylight. The payload consists of a VAS (section 3.3.1) to map the skylight structure, and a tethered station carrying MMRs (section 3.3.2) to analyse the subsurface environment. The TrUSS also provides power lines between the BSRs and VAS and tethered station; these are not exposed to tension loading from the forces acting on the TrUSS. Communication between them and BSRs is via wireless connection (section 3.5.2).

3.2.1. Operational Sequence. The TrUSS is operated according to the following sequence, as shown in Fig. 3:

① Once both BSRs have reached opposing sides of the skylight, the TrUSS is released from BSR-1 and tele-operated towards the center of the tether, positioned above the skylight. Its lateral position is measured by an odometer on the drive motor and calibrated against images from the BSR NavCams.

② When the TrUSS reaches its target position, the VAS and tethered station descend together.

③ From the bottom, the VAS is commanded to move along the vertical tether to commence scientific measurements of the inner walls of the skylight.

3.2.2. Tether. The tether is composed of M5 fiber, a high-strength (stress limit 5.7 GPa) synthetic fiber material.[21] The tether design is based on the *Tether Physics and Survivability (TiPS)* mission,[22] with ARETHUSA's proposed tether having a 5 mm diameter (assuming a safety factor of 2.5).

[‡]Or until an appropriate distance depending on the local slope of the skylight edge, which determines the ground clearance of the TrUSS.

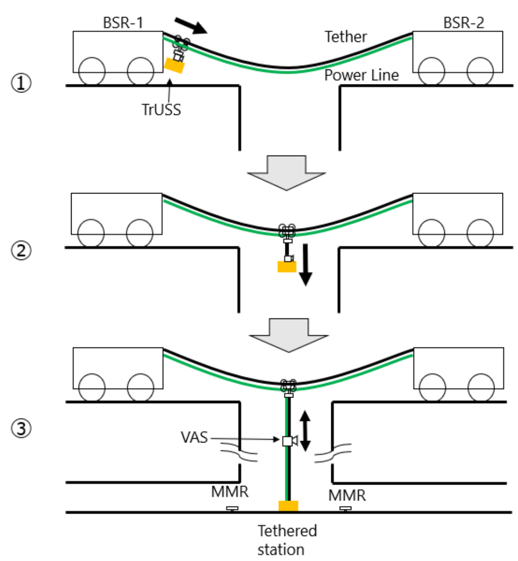


Fig. 3. The TrUSS provides tethered (black lines) horizontal and vertical positioning and power (green) for the scientific payloads (VAS+MMRs).

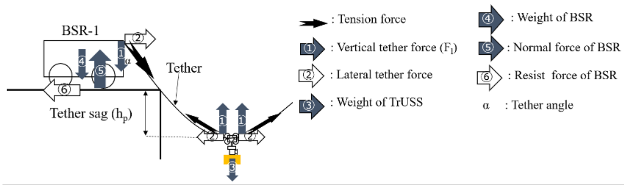


Fig. 4. Equilibrium of forces acting upon BSR and TrUSS.

The maximum diameter and depth of the target skylight necessitate a minimum length for the vertical descent tether of $\geq$ 100 m, and for the lateral tether connecting the BSRs of 158 m.[§] With these assumptions, the mass of the horizontal and vertical tethers are estimated to be 5.3 kg and 3.0 kg respectively (given material density 1700 kg/m^3).

A power line gauge of AWG 12 is selected for an assumed maximum current, weighing approximately 4.7 kg and 3.0 kg for the horizontal and vertical power lines respectively. In addition, the VAS may also require its own power line (3.0 kg) as it is expected to move separately. The vertical tether and vertical power lines are carried on spools within the TrUSS.

3.2.3. Lateral Forces & Stability. During the underground survey, the BSRs must be able to support the TrUSS and scientific payload appropriately with a stable and reliable method. The lateral forces acting on the BSRs from the tethers must be less than the static friction acting on the BSR wheels.

From Fig. 4, a loaded lateral tether force (F_l) acting on a BSR can be computed as:

$$F_l = (g_m * m_T)/2 * \tan\alpha * SF \qquad [1]$$

where m_T[kg] = mass of TrUSS, g_m[m/s^2] = lunar gravity, $\alpha[deg]$ = tether angle, and SF = safety factor of 2.5. Each wheel resistant force (F_x) is given by:[23]

$$F_x = rb\int_0^{\theta_e} -\sigma(\theta)\sin\theta\, d\theta \qquad [2]$$

where r[m] = wheel radius, b[m] = wheel width, θ_e[rad] = wheel entry angle, and $\sigma(\theta)$ = distribution of normal stress under a wheel.

[§]BSR-2 is required to move along the semi-circular edge of the selected skylight with radius $r \approx 25$ m, and assuming a safety factor of 2.

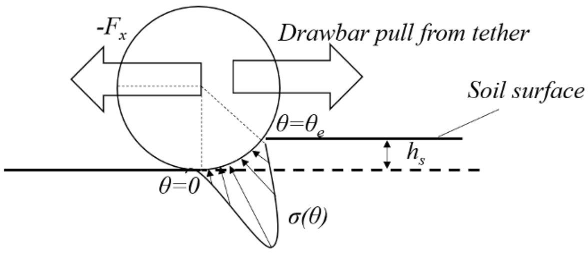


Fig. 5. Distribution of the normal stress under wheels on soil surface.

Using Bekker's empirical equations,[23] the distribution of normal stress is computed using linear approximations and a wheel exit angle of zero (as it is generally small).[24] Considering the total wheel contact patch, the wheel entry angle (θ_e, shown in Fig. 5) is found when the vertical force acting on each wheel (F_z) and the weight of the wheel are equal:

$$F_z = r^{n+1} * (k_c + bk_\varphi) * \int_0^{\theta_e} (\cos\theta - \cos\theta_e)^n \cos\theta \, d\theta$$
$$= g_m(m_T/2 + m_B)/4$$
$$\Leftrightarrow \quad (0.15)^{1+1} * (2.29 * 10^2 + 0.15 * 1.35 * 10^5)$$
$$* \int_0^{\theta_e} (\cos\theta - \cos\theta_e)\cos\theta \, d\theta = 1.62 * ((55/2 + 70)/4)$$

where n = sinkage exponent, m_B[kg] = mass of one BSR and number of wheels = 4. Lunar soil values for k_c (soil deformation from cohesion), k_φ (soil deformation from internal friction angle), r, and b are referenced from prior research.[25,26] Substituting θ_e into Eq. (2) finds a wheel resistant force of $(F_x) \cong 7.75\,\mathrm{N}$.

From Eqs. (1) and (2), the tether angle (α) when BSR is static is computed. When $\alpha < 15.6°$, the BSRs can stably support the tethered payload. Also, this angle provides the tether sag (h_p [m] shown in Fig. 4) as $h_p = (d_s/2)/\tan\alpha - h_B \cong 98.2\mathrm{m}$, where $d_s = 55\,\mathrm{m}$ is given by the average diameter of the target skylight plus a margin on both sides to each BSR, and h_B[m] = height of BSR. This tether sag is too deep for the initial position of TrUSS; therefore, the resistant force of BSR wheels alone may not be sufficient for stable support.

Thus, we recommend the use of helical anchors to support the BSRs. A single-helix anchor with a plate diameter of 27 cm, a shaft diameter of 4 cm and an installation depth into the lunar soil of 30 cm could be expected to resist a lateral load of about 300 N on the lunar surface.[27] For ARETHUSA, this lateral load is more than would be expected, and an even smaller helical anchor could possibly be used for BSR support.

The lateral tether force F_l also causes a destabilising torque acting on the BSR, with a restoring torque provided by gravity acting on its center of mass. The BSR remains in simple stable equilibrium so long as the torque forces satisfy the inequality:

$$h_B F_l \le m_B g_m d_B/2$$

where ${}^{d_B}/_2$[m] = distance from the center of mass to the wheel contact patch, assuming a center of mass halfway between the two sets of wheels (distanced d_B[meter] apart), and the front wheels acting as a fulcrum directly beneath the vertical force of the tether, and m_B here is replaced with a minimum (worst-case) weight for a BSR, giving a minimum base distance of $d_B = 0.62\,\mathrm{m}$.

3.3. Scientific Payload

3.3.1. Vertical Analysis Sensor (VAS). The VAS aims to analyse the geological and environmental features of the inner walls of the skylight and lava tube. It is supported by a rotating mechanism enabling it to investigate 360° of the inner wall and point the instruments towards the directions in which the lava tube extends. Furthermore, it contains its own drive motors, allowing it to independently climb the tether as necessary for scientific operations.

A visible and thermal infrared (VIS+TIRF) compound sensor will measure the temperature distribution of the inner wall of the skylight during tethered descent and the wall of the lava tube after descent. The TIRF sensor is able to measure the temperature precisely with a resolution of 0.3 K, but its spatial resolution is low. On the other hand, the VIS sensor has high spatial resolution but cannot measure the temperature. By overlaying data from these two instruments, the advantages of both are realised.[28] The external dimensions of the compound sensor are 260 × 150 × 150mm, its mass is 3.4 kg, and the data collection frame rate is 30 frames/s.

A radar is used to reveal the structure of lunar skylight's inner wall and the underground layers of the lava tube. Its frequency can be adjusted from 150 MHz to 1200 MHz; lower-frequency waves are used to penetrate and reveal the structure of underground layers, and higher-frequency waves to map the surface structure. The radar's power consumption is 5 W to 10 W, mass is 3 kg, and the size is 196 × 120 × 66mm.[29]

A Laser-Induced Breakdown Spectrometer (LIBS) is capable of determining the elemental composition of the inner wall with tens of µm spatial resolution from a distance of more than 1 m. The total mass of this instrument is 1 kg.[30] An extensible probe may be desired so that the LIBS can reach closer to the wall.

3.3.2. Tethered station - Mobile Micro Rovers (MMR). The tethered station is designed to carry and deploy two MMRs, to provide them with power charging capabilities (from the BSRs' electrical power system, section 3.4), and to act as a stabilising counter-weight or anchor for the VAS during its scientific operations.

Once the tethered station reaches the floor of the skylight pit, the two MMRs are deployed. These are used for the in-situ lava tube exploration, providing redundancy and exploration of both sides of the tube simultaneously. Each of the MMRs aims to at least: (1) measure ambient temperature, (2) analyse radiation dosage, and (3) capture panoramic images for scientific and public outreach.

Structure Each MMR weighs 10 kg at maximum, has dimensions of ~ 30 × 20 × 20cm, and are proposed to be made of carbon fibre reinforced plastics.[31] Each MMR contains: a rotating turret with a laser range finder and two CMOS cameras; a high-power strobe light installed on the front side; grouser wheels for extreme terrain mobility; and an on-board controller.

Science instruments A Sheath thermocouple and an energetic particle spectrometer are available on each

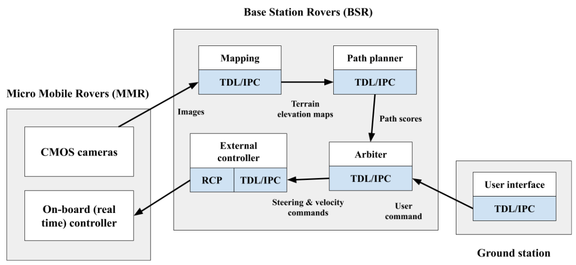


Fig. 6. Each component in an MMR's navigation system communicates via message passing protocols listed below its block.

MMR. The Sheath thermocouple measures spatial temperature inside the lava tube through the Seebeck effect. The energetic particle spectrometer measures the absorbed radiation dose – that is, the intensity of radiation and radiation quality factor that defines the type of radiation present.

While navigating, each MMR's strobe light and CMOS cameras capture panoramic images of the environment. At each observation point, it switches off its light and waits to cool down to avoid interfering with temperature and radiation measurements.

Navigation Each MMR's 2D laser range finder is mounted on a servo to enable 3D range scanning. The navigation system (fig. 6) constructs a 25 cm resolution terrain elevation map given input from the two CMOS cameras along with the MMR's orientation.[32] The system is designed to evaluate paths (fig. 7) and explore semi-autonomously, improving the system's robustness to communications issues while retaining human-in-the-loop safety for unexpected circumstances.

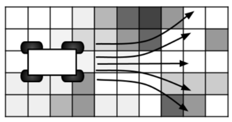


Fig. 7. The MMR Path Planner evaluates a discrete number of exploration paths.

3.4. Electrical Power System

The electrical power system for ARETHUSA needs to supply power to distributed components and survive the long and cold lunar night. Solar panels are used to generate electricity which is stored in Li-ion batteries. A total of $2\,\mathrm{m}^2$ of solar panels generate 500 W, with each BSR having two solar paddles of $0.5\,\mathrm{m}^2$. The specific energy of each battery is $213\,\mathrm{W\,h\,kg}^{-1}$ and energy density is $395\,\mathrm{kWh/m}^3$.[33] Total electric energy needed overnight is 15 kW h, so the total weight of batteries is 100 kg including a safety margin. A 50 kg ($\sim$0.054m^3) battery is installed on each BSR, a 3 kg battery is loaded on the Tethered Station to distribute power to the MMRs, and a 1.0 kg battery is loaded on each MMR, as per table 3. Using this, an MMR can operate remotely for 3 hours in succession. The VAS is powered directly by the TrUSS, which receives power from a BSR via a power line cable unspooled with the tether.

Table 3. Specification of batteries on ARETHUSA.

Item	2× BSRs	Tethered station	2× MMRs
Mass [kg]	100	3	2
Energy stored [kW h]	21.3	0.64	0.43

Table 4. Link budget for ARETHUSA communications.

Item	Value
Noise ($T \approx 200\,\mathrm{K}$, $B_N = 10\,\mathrm{MHz}$)	$-249.6\,\mathrm{dB}$
Path Losses (X-band, $\downarrow$ 7167.5 $\uparrow$ 8425 MHz)	222.3 dB
EIRP (3.8 W, $G_{Tx} = 29.2\,\mathrm{dB}$)	28.0 dB
SNR ($G_{Rx} = 67.7\,\mathrm{dB}$, $L_A \approx 0\,\mathrm{dB}$)	123.0 dB
Link Margin ($C = 3.5\,\mathrm{Mbit/s}$, $B = 130\,\mathrm{kHz}$)	3.4 dB

3.5. Communications

ARETHUSA must support communication across a distance of $(3.84 \pm 0.5)\times10^5$km, manual rover operations via stereoscopic images, and near real-time control to minimise navigation and deployment time. These requirements necessitate a high-gain ground receiver, a relatively high data rate, and frequent or continuous contact respectively. Mission telemetry, scientific, and operations data are to be transmitted via the NASA Deep Space Network (DSN) 34 m BWG antennas, which can provide a maximum possible 87% time coverage for ARETHUSA,[34] and a very high 67.7 dB receive gain with minimal system noise.[35]

3.5.1. Transponder & Antennas. The Iris V2.1 (NASA JPL) transponder fulfils the above requirements with X-band communications,[¶] and supports the data capacity required for near real-time rover navigation. It has flight heritage spanning communication distances from LEO to Mars, and is considered a reliable, low-cost option for micro-satellite mission,[36] requiring a maximum of 35 W for simultaneous TX/RX.[37]

A 3.8 W reflect-array transmission antenna with dimensions of $\sim$40 × 40cm is to be installed on the top surface of each BSR. A small feed antenna located on the backside of the BSR's NavCam head bounces a signal off the reflect-array. Such a design is mechanically simple and low-cost, provides beam steering and shaping via phase control of the array components,[38] and supports a high transmitting gain ($\sim$29.2dB, based on an existing design demonstrated with the Iris V2.1[39]). As per Table 4, this is sufficient to support a channel capacity of 3.5 Mbit/s for ARETHUSA. In terms of pointing, the Earth is expected to subtend an angle of 2°, remaining relatively high in the lunar sky from the proposed landing site with up to 7.5° deviation over a lunar day/night cycle.[40]

3.5.2. Internal Communications. Internal communications between the BSRs, VAS, and MMRs need to support distances of 50 m to 100 m, with complications arising from signal bouncing, multi-path interference, and attenuation due to the lava tube and skylight walls. To mitigate these effects and ensure the highest possible reliability, internal communications will utilise disruption-tolerant networking protocols[41] on a standard S-band ($\sim$2.25 GHz) system[42] (PULSAR STX radio + SANT antenna) with a repeater on TrUSS.

3.6. Command & Data Handling (C&DH)

Each BSR has its own C&DH subsystem controlling all other subsystems, as does each MMR for storing data collected from science instruments prior to transmission.

[¶] Higher data capacity is also available on the Ka-band.

The Hyperion Technologies CP400.85 processing platform[43] is chosen as the C&DH subsystem in both cases, with radiation tolerant storage of up to 64 GB, sufficient for the scientific data to be collected.

3.7. Environmental Control

In operating on the lunar surface, the BSRs must withstand the harsh lunar environment. The mean lunar surface temperature ranges between 380 K during the day and 120 K at night. For this, a Reversible Thermal Panel (RTP)[44] is installed on the surface of each BSR. During the lunar night, the aluminium surface insulates the spacecraft and maintains internal temperature. During the day, the radiator is deployed and the surface of an Optical Solar Reflector (OSR) is exposed, reflecting sunlight and emitting heat by infrared radiation.[45] Thus, the heat is dissipated and the internal temperature is kept lower than 284 K without any active control. A heat pipe is also used for local thermal control;[46] a 30 W heater is sufficient to maintain the spacecraft at 273 K during the night.

The Moon's very weak magnetic field means high levels of radiation experienced on the surface, including solar wind, solar radiation and cosmic radiation. To withstand these hazards, the BSRs are shielded by aluminium; if needed, additional spot shielding, such as tantalum boxes or tungsten cylinders, is to be used for specific components.[47]

Lunar dust is considered to pose a low risk for the duration of the mission; moderate sealing of BSR components should prove to be sufficiently protective.

4. Conclusion & Anticipated Results

The ARETHUSA mission is expected to demonstrate the first controlled exploration of an extra-terrestrial underground lava tube, providing a novel method for simpler, more reliable access for future utilisation and potential habitation of such environments.

The mission will require the development of the TrUSS tethered payload delivery design, building on thousands of years of ropeway technology on Earth. Under the proposed design, micro exploration rovers and scientific equipment can be moved into and out of the lunar lava tube without relying on propulsive power or complex locomotion. In operating within the Moon's lower gravity and airless vacuum, we envision that TrUSS will build upon the benefits of aerial ropeways in the transportation and delivery of large payloads in construction, mining, and passenger applications, as used widely on Earth.[7,8] A detailed design including FEM analysis, tether spool and motor configuration, and validation of the deployment techniques will be necessary for the success of the mission.

The scientific results of the mission will lead to a greater understanding of the lunar subsurface and its advantages for human utilisation. Somewhat uniquely, ARETHUSA will focus particularly on the paleoregolith strata exposed by the skylight walls, providing crucial insights into the Moon's volcanic and geological history. Data collected from the selected site, lying in a Helium-3 rich region,[9] may support future industrial operations on the Moon. Development of ARETHUSA will require an appropriate set of scientific analysis equipment, which may additionally benefit from a third degree of freedom afforded by the mobile BSRs moving along the skylight edge, or from fixing the BSRs in place using helical anchors, providing potential applications in regolith sample analysis.

The ARETHUSA mission was designed to support the exploration and utilisation of lunar lava tubes. We hope that the technologies demonstrated may lead to advances in the exploration of such extreme off-world environments on the Moon, Mars, and perhaps beyond.

[1] G. Cushing, T. N. Titus, J. J. Wynne, et al. "THEMIS observes possible cave skylights on Mars". In: *Geophysical Research Letters* 34.17 (2007).

[2] W. R. Halliday. "Terrestrial pseudokarst and the lunar topography". In: *Bulletin of the National Speleological Society* 28.4 (1966), pp. 167–170.

[3] J. Haruyama, K. Hioki, M. Shirao, et al. "Possible lunar lava tube skylight observed by SELENE cameras". In: *Geophysical Research Letters* 36.21 (Nov. 2009). DOI: 10.1029/2009gl040635.

[4] M. von Ehrenfried. *From Cave Man to Cave Martian*. Springer, 2019. DOI: 10.1007/978-3-030-05408-3.

[5] S. Clark. *Spacewatch: UK's first moon rover poised for 2021 touchdown*. Oct. 2019. URL: https://www.theguardian.com/science/2019/oct/17/spacewatch-uks-first-moon-rover-poised-for-2021-touchdown.

[6] J. Thangavelautham, M. S. Robinson, A. Taits, et al. *Flying, Hopping Pit-Bots for Cave and Lava Tube Exploration on the Moon and Mars*. 2017. arXiv: 1701.07799 [cs.RO].

[7] K. Hoffmann and N. Zrni. "A Contribution on the History of Ropeways". In: *History of Mechanism and Machine Science*. Springer, 2012. DOI: 10.1007/978-94-007-4132-4_26.

[8] K. De Decker. *Aerial ropeways: automatic cargo transport for a bargain*. Jan. 2011. URL: https://www.lowtechmagazine.com/2011/01/aerial-ropeways-automatic-cargo-transport.html.

[9] S. W. Ximenes, J. O. Elliott, and O. Bannova. "Defining a Mission Architecture and Technologies for Lunar Lava Tube Reconnaissance". In: *Earth and Space*. ASCE, 2012. DOI: 10.1061/9780784412190.038.

[10] *HYDRA Multiple Heads Star Tracker with High Performance*. Tech. rep. Sodern Ariane Group. URL: https://www.sodern.com/website/docs_wsw/RUB_316/tile_689/_Hydra.pdf.

[11] *H-IIA User's Manual*. Ver. 4.0. MHI Launch Services, Feb. 2015.

[12] J. S. Parker and R. L. Anderson. *Low-energy lunar trajectory design*. JPL deep-space communications and navigation series. Hoboken: Wiley, 2014. ISBN: 9781118853870.

[13] 樋口丈浩 , 上野誠也 , 植田聡史 , et al. " 小型月着陸実証機 SLIM の着陸誘導制御技術 ". In: *Proceedings of the 17th Space Science Symposium*. Institute of Space and Astronautical Science (ISAS). Jan. 2017.

[14] S. Fukuda, S.-i. Sakai, E. Sato, et al. "SLIM: Small explorer for technology demonstration of lunar pinpoint landing". In: *The 24th Workshop on JAXA Astrodynamics and Flight Mechanics*. 2014, p. 109.

[15] J. Ashley, M. Robinson, B. Hawke, et al. "Lunar Caves in Mare Deposits Imaged by the LROC Narrow Angle Cameras". In: *First International Planetary Caves Workshop*. Oct. 2011.

[16] 北薗幸一 , 能見公博 , and 丸祐介 . "SLIM 探査機における着陸衝撃吸収システム ". In: *Proceedings of the 17th Space Science Symposium*. Institute of Space and Astronautical Science (ISAS). Jan. 2017.

[17] T. Mizuno, T. Kase, T. Shiina, et al. "Development of the Laser Altimeter (LIDAR) for Hayabusa2". In: *Space Science Reviews* 208.1-4 (Feb. 2016), pp. 33–47. DOI: 10.1007/s11214-015-0231-2.

[18] 松尾芳郎 . ***LiDAR* の開発と応用 (第 *2* 回)**. http://tokyoexpress.info/2020/04/11/lidar の開発と応用第 2 回 /. Apr. 2020.

[19] 高橋衛 , 田村昌之 , and 岸野義宏 . " かぐや推進系の開発および運用結果 ". In: *IHI* **技報** 49.3 (2009). URL: https://www.ihi.co.jp/var/ezwebin_site/storage/original/application/e402bd27dceecb981641a0323e972a66.pdf.

[20] M. Sutoh, T. Hoshino, and S. Wakabayashi. "Rover deployment system for lunar landing mission". In: *Acta Astronautica* 138 (Sept. 2017), pp. 454–461. DOI: 10.1016/j.actaastro.2017.06.019.

[21] J. Pearson, E. Levin, J. Oldson, et al. "Lunar space elevators for cislunar space development". In: *Retrieved from NASA Institute for Advanced Concepts* (2005).

[22] V. Husson. *TiPS*. 2007. URL: http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/tipn_general.html.

[23] G. Ishigmai. "Locomotion mechanics for planetary exploration rovers based on steering characteristics". In: *Master's Thesis (Sendai, Miyagi, Japan: Dept. of Aerospace Engineering, Tohoku University* (2005).

[24] K. Iagnemma and S. Dubowsky. "Mobile robot rough-terrain control (RTC) for planetary exploration". In: *Proceedings of the 26th ASME Biennial Mechanisms and Robotics Conference, DETC*. Vol. 2000. 2000.

[25] M. Deans, G. Fries, K. Lay, et al. *Icebreaker: A Lunar South Pole Exploring Robot*. Tech. rep. Carnegie Mellon Tech. Rept., CMU-RI-TR-97-22, 1997.

[26] A. Basilevsky, A. Abdrakhimov, J. Head, et al. "Geologic characteristics of the Luna 17/Lunokhod 1 and Chang'E-3/Yutu landing sites, Northwest Mare Imbrium of the Moon". In: *Planetary and Space Science* 117 (2015), pp. 385–400.

[27] J. Crabtree, J. L. Klosky, R. Gash, et al. "Helical anchors: Lateral resistance for shaping the lunar surface". In: *Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments*. 2008, pp. 1–10.

[28] K. Machida, S.-i. Tsuri, and A. Iwasaki. "Visible/Thermal-Infrared Hybrid Sensor System for On-Orbit Service Robot". In: *Journal of the Robotics Society of Japan* 23.7 (2005). DOI: 10.7210/jrsj.23.864.

[29] *RIMFAX*. Tech. rep. NASA Mars 2020 Mission Perseverance Rover. URL: https://mars.nasa.gov/mars2020/spacecraft/instruments/rimfax/.

[30] 石橋高 , 亀田真吾 , 荒井朋子 , et al. " 月・惑星着陸探査用元素分析装置 : レーザ誘起絶縁破壊分光装置 (LIBS)". In: **日本惑星科学会誌遊星人** 21.3 (2012), pp. 260–266.

[31] J. Walker, N. Britton, K. Yoshida, et al. "Update on the qualification of the Hakuto micro-rover for the Google Lunar X-Prize". In: *Field and Service Robotics*. Springer. 2016, pp. 313–330.

[32] F. Cozman. "Experience with Rover Navigation for Lunar-like Terrains". In: *Proceedings of the International Conference on Intelligent Robots and Systems*. IROS. IEEE Computer Society, 1995. ISBN: 0818671084.

[33] Tech. rep. GS Yuasa. URL: https://www.gs-yuasa.com/jp/technic/vol13_2/pdf/13_02_001.pdf.

[34] C. H. Lee and K.-M. Cheung. "Lunar Network Coverage Analysis". In: *57th International Astronautical Congress*. AIAA, Oct. 2006. DOI: 10.2514/6.iac-06-b3.4.01.

[35] *34-m BWG Stations Telecommunications Interfaces*. Tech. rep. 810-005, 104, Rev. L. NASA JPL, 2019.

[36] *State of the Art Small Spacecraft Technology*. Tech. rep. NASA/TP — 2018 – 220027. NASA Ames, 2018. URL: https://www.nasa.gov/sites/default/files/atoms/files/soa2018_final_doc.pdf.

[37] M. M. Kobayashi, S. Holmes, A. Yarlagadda, et al. "The Iris Deep-Space Transponder for the SLS EM-1 Secondary Payloads". In: *IEEE Aerospace and Electronic Systems Magazine* 34.9 (2019).

[38] P. Nayeri, F. Yang, and A. Elsherbeni. *Reflectarray antennas: theory, designs and applications*. Hoboken, NJ, USA: John Wiley & Sons, 2018. ISBN: 9781118846766.

[39] R. E. Hodges, N. Chahat, D. J. Hoppe, et al. "A Deployable High-Gain Antenna Bound for Mars: Developing a new folded-panel reflectarray for the first CubeSat mission to Mars." In: *IEEE Antennas and Propagation Magazine* 59.2 (Apr. 2017), pp. 39–49. DOI: 10.1109/map.2017.2655561.

[40] B. King. *Observing Earth from the Moon*. Oct. 2018. URL: https://skyandtelescope.org/astronomy-blogs/explore-night-bob-king/observing-earth-from-the-moon/.

[41] E. J. Wyatt, K. Belov, J. Castillo-Rogez, et al. "Autonomous networking for robotic deep space exploration". In: *International Symposium on Artificial Intelligence, Robotics, and Automation for Space (ISAIRAS)*. 2018.

[42] R. Radhakrishnan, W. W. Edmonson, F. Afghah, et al. "Survey of Inter-Satellite Communication for Small Satellite Systems: Physical Layer to Network Layer View". In: *IEEE Communications Surveys & Tutorials* 18.4 (2016), pp. 2442–2473. DOI: 10.1109/comst.2016.2564990.

[43] *CP400.85*. Tech. rep. Hyperion Technologies. URL: https://hyperiontechnologies.nl/products/cp400-85-processing-platform/.

[44] 宮田喜久子 and 長野方星 . "Research and Development on the Flexible Thermal Management Device for Expanding the Feasibility of Space Probes". In: *Transactions of the Society of Instrument and Control Engineers* 54.5 (2018), pp. 508–517. DOI: 10.9746/sicetr.54.508.

[45] 小林明秀 . " 宇宙機の熱制御における表面処理 ". In: **表面技術** 66.6 (2015). DOI: 10.4139/sfj.66.256.

[46] 岡本篤 , 畠中龍太 , 安藤麻紀子 , et al. " 宇宙用ヒートパイプの開発状況報告および宇宙機への適用形態の提案 ". In: *Proceedings of the 14th Space Science Symposium*. Institute of Space and Astronautical Science (ISAS). Jan. 2014. URL: http://www.isas.jaxa.jp/j/researchers/symp/sss14/paper/P2-212.pdf.

[47] P. Fieseler, S. Ardalan, and A. Frederickson. "The radiation effects on galileo spacecraft systems at jupiter". In: *IEEE Transactions on Nuclear Science* 49.6 (Dec. 2002). DOI: 10.1109/tns.2002.805386.