Conceptual Ideas for Radio Telescope on the Far Side of the Moon

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Abstract— **A radio telescope on the far-side of the Moon has tremendous advantages compared to Earth-based telescopes because it could observe the universe at wavelengths that are hitherto poorly explored by humans so far and the Moon acts as a physical shield that isolates the telescope from the radio interference and noises from Earth. This paper presents a novel concept for building a radio telescope on the far-side of the Moon.**

The main idea is to shape a suitable existing lunar crater ($1 - 50$km in diameter) on the far-side of the Moon into a spherical reflecting dish. The proposed Lunar Crater Radio Telescope (LCRT) would be able to observe the universe in the $5 - 100$m wavelength band (i.e., $3 - 60$MHz radio frequency band). The key innovations of this concept are: (1) LCRT would be the largest filled-aperture radio telescope in the Solar System. (2) LCRT could potentially make tremendous scientific discoveries in fields of cosmology and extrasolar planets by observing the universe in the $5 - 100$m λ band (i.e., $3 - 60$MHz ν band) that has been hitherto poorly explored. (3) It would require only a few robots from Earth and autonomously modify an existing lunar crater to build the LCRT; thereby significantly reducing launch weight and cost compared to all previous lunar-surface telescope mission concepts. (4) Furthermore, the Earth-based robots are not consumed during construction of LCRT. Therefore, they could create a network of LCRTs to (i) observe different regions of the universe, and (ii) enable lunar Very-Long-Baseline Interferometry (VLBI) astronomy. We envisage that this concept would unlock the potential for ground-breaking scientific discoveries in radio astronomy.

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1. INTRODUCTION

A radio telescope on the far-side of the Moon has tremendous advantages compared to Earth-based telescopes:

- Such a telescope can observe the universe at wavelengths (λ) greater than 10m (i.e., frequencies (ν) below 30 MHz) that are largely reflected by the Earth's ionosphere and are hitherto poorly explored by humans so far.
- The Moon acts as a physical shield that isolates the telescope from the radio interference and noises from Earth and Earth-orbiting satellites.

This paper presents a novel concept for building a radio telescope on the far-side of the Moon.

A number of historical lunar telescope mission concepts (e.g., Apollo-era concept [1], Very Low Frequency Array (VLFA) [2], Radio Observatory for Lunar Sortie Science (ROLSS) [3], Dark Ages Lunar Interferometer (DALI) [4], Arecibo-type telescope [5]) propose to bring the entire radio telescope from Earth. In contrast, our concept is to modify a suitable existing lunar crater on the far-side of the Moon into a spherical reflecting dish. Our proposed Lunar Crater Radio Telescope (LCRT) for the $5-100$m wavelength (λ) band (i.e., $3 - 60$MHz radio frequency (ν) band) with diameter greater than 1km would be significantly larger than the Arecibo telescope (300m diameter, 3cm$-$1m λ band, 300MHz$-$10GHz ν band) [6] and the Five-hundred-meter Aperture Spherical radio Telescope (FAST) (500m diameter, $0.1 - 4.3$m λ band, 60MHz$-$3GHz ν band) [7] on Earth.

The Moon is $\approx$ 384300 km from the Earth, and the the

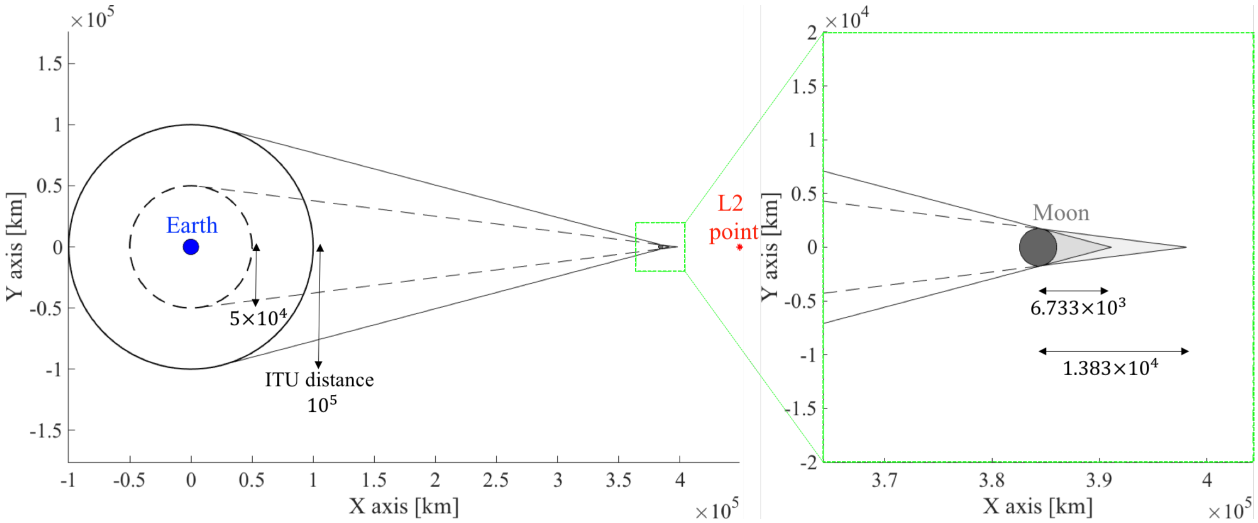


Figure 1. The Earth–Moon system

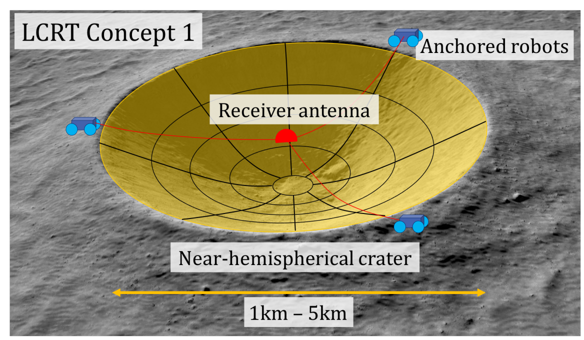
Lagrangian L2 point is further $\approx$ 64700 km from the Moon as shown in Fig. 1. The lunar orbiter Radio-Astronomy-Explorer-2 (RAE-2) satellite mapped the non-thermal galactic emission in the frequency range of 25 kHz to 13 MHz using a 37 m dipole antenna in 1973 [8]. Other single-satellite lunar-orbiting satellites have been proposed like the Lunar Observer Radio Astronomy Experiment (LORAE) [9] and the Dark Ages Radio Explorer (DARE) [10]. A number of multi-satellite missions have been proposed for deployment in the L2 point like the Astronomical Low-Frequency Array (ALFA) [11], the Formation-flying sub-Ionospheric Radio astronomy Science and Technology (FIRST) [12], and the Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) [13], [14] missions. According to the International Telecommunication Union (ITU), most of the Earth-orbiting satellites are within 100000 km from Earth. Therefore, the actual radio-quiet zone where the Moon shields the radio noise from Earth and Earth-orbiting satellites is just 6733 km from the center of the Moon, where the radius of the Moon is 1737 km. Even if we consider the conservative distance of 50000 km from Earth, where most of the geostationary satellites and lower-altitude satellites are located, the conservative radio-quiet zone is just 13831 km from the center of the Moon. The analysis in Appendix clearly shows that the proposed lunar-satellite missions at the L2 point will not be shielded from the radio interference from Earth-orbiting satellites. Hence, these missions have orders-of-magnitude smaller collecting area than LCRT and also experience poorer signal-to-noise (SNR) due to partial or no lunar-shielding from Earths radio noise.

This paper is organized as follows. The main idea of LCRT and its science objectives are presented in Sections 2 and 3 respectively. The mission plan and technical challenges are discussed in Sections 4 and 5 respectively. The paper is concluded in Section 6.

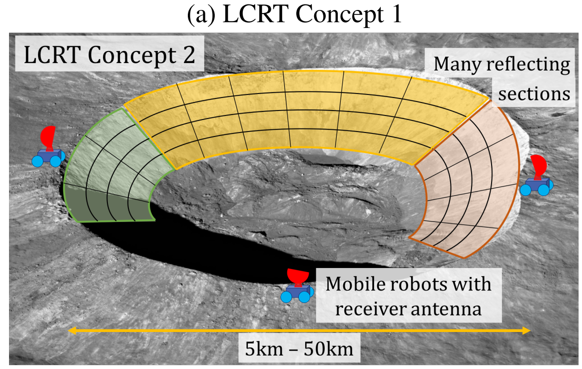
2. Lunar Crater Radio Telescope

Our objective is to explore the feasibility of building the LCRT on the far-side of the Moon that can observe the universe in the $5-100$m wavelength band (i.e., $3-60$MHz radio frequency band). A spherical shape allows signals from different directions to be observed by moving the receiver and enables long-duration tracking of a single astronomical target. The wavelengths place a precision accuracy of 1m ($\approx \frac{\min \lambda}{5}$) on the shape of the dish. We will evaluate the following two concepts for the LCRT design:

LCRT Concept 1: The hemispherical reflecting dish is built in a small crater of $1-5$km diameter. The receiver antenna is suspended above the dish by cables actuated by robots anchored to the crater rim. See Fig. 2(a).



(a) LCRT Concept 1



(b) LCRT Concept 2

Figure 2. Two LCRT concepts

LCRT Concept 2: In a large crater of $5-50$km diameter, an array of reflecting spherical-sections are built on the crater wall, where different sections observe different parts of the sky. Another alternative to the suspended receiver antenna design is to mount the receiver antennae on mobile robots which move along the crater rim. See Fig. 2(b).

Description	***LCRT Concept 1***	***LCRT Concept 2***
Range of diameters	$1 - 5$km	$5 - 50$km
Number of craters	$\approx$ 3000 craters [15]	$\approx$ 2000 craters [15]
Angular resolution $\lambda = 5$m $\lambda = 100$m	For 2km diameter $\left(\theta \approx \frac{1.22\lambda}{\text{Diameter}}\right)$ $\theta = 10'$ $\theta = 3.5°$	For 20km diameter, 2km rim height $\theta = 1' - 10'$ $\theta = 0.35° - 3.5°$

Table 1. Summary of the two LCRT concepts

The key innovations of this concept are:

• LCRT would be the largest filled-aperture radio telescope in the Solar System.
• LCRT could potentially make tremendous scientific discoveries in fields of cosmology and extrasolar planets by observing the universe in the $5 - 100$m λ band (i.e., $3 - 60$MHz ν band) that has been hitherto poorly explored.
• It would require only a few robots from Earth and autonomously modify an existing lunar crater to build the LCRT; thereby significantly reducing launch weight and cost compared to all previous lunar-surface telescope mission concepts.
• Furthermore, the Earth-based robots are not consumed during construction of LCRT. Therefore, they could create a network of LCRTs to (i) observe different regions of the universe, and (ii) enable lunar Very-Long-Baseline Interferometry (VLBI) astronomy.

3. Science Objectives of LCRT

A radio telescope on the far-side of the Moon would observe the universe in wavelengths (frequencies) hitherto poorly explored and has the potential for tremendous scientific discoveries. Its science objectives include tracking the evolution of the neutral intergalactic medium before and during the formation of the first stars and probing the interior and habitability of extrasolar planets via their magnetic fields. These objectives are consistent with priorities identified in the Astronomy and Astrophysics Decadal Survey [16], and these observations are difficult, if not impossible, to conduct from Earth due to ionospheric absorption and reflection.

First Stars and the "Cosmic Dawn"

The Decadal Survey [16] identified "Cosmic Dawn" as one of three key science objectives, and a Cosmic Dawn Mapper aimed at exploring these epochs was identified in the recent Astrophysics roadmap [19]. Following recombination (redshift $z \approx 1100$), the universe entered a largely neutral state in which neutral hydrogen (HI) was the dominant baryonic component of the intergalactic medium (IGM). The highly redshifted hyperfine transition of HI ($\lambda = 21$ cm, $\nu = 1420$ MHz) provides unique information about the state of the IGM and large-scale structures during the formation of the first stars and potentially can probe the IGM prior to their formation. Multiple epochs can be identified [20], [21], associated with the true "Dark Ages," the epoch of the formation of the first stars, the epoch of first heating (likely from accreting black holes), and the Epoch of Reionization. A crucial feature of this HI spectral feature is that it allows the evolution of the Universe to be tracked, in contrast to the cosmic microwave background, which is a continuum measurement at essentially a single redshift. There are emerging constraints on the evolution of the IGM during First Heating and the Epochs of Reionization [22], [23], [24], but the Dark Ages ($z \approx 70$; $\nu \approx 20$ MHz) and the First Stars ($z \approx 40$; $\nu \approx 35$ MHz) epochs remain both exciting and unlikely to be constrained significantly from the ground.

Magnetic Extrasolar Planets

Detection of radio emission at 22 MHz from Jupiter was identified quickly as being due to its planetary-scale magnetic field [25], [26]. Subsequent spacecraft investigations have revealed that many of the planets, and even some moons, either have or have had a planetary-scale magnetic field. Generated by dynamo processes within the planet, planetary-scale magnetic field are a remote-sensing method to constrain the properties of a planet's interior, and it may be possible to measure the magnetic fields of extrasolar planets. If this proves possible, it will offer one of the few means of understanding the potential diversity of planetary interiors. In the case of the Earth, its magnetic field has also been speculated to be partially responsible for its habitability. Thus, knowledge of the magnetic field of an extrasolar planet may be a necessary component of assessing its habitability, or understanding an absence of life on an otherwise potentially habitable planet. All of the giant planets in the solar system and the Earth generate radio emission via the electron cyclotron maser instability, which results from an interaction between the solar wind and the planetary magnetosphere. There is a long history of both predictions of and searches for extrasolar magnetospheric radio emissions [27], [17]. The emission process is due to accelerated electrons streaming down the planet's magnetic field toward its magnetic poles. All "magnetic" planets show a sharp truncation in their radiated powers at an upper frequency determined by where the local cyclotron frequency (determined by the strength of the planet's magnetic field) drops below the local plasma frequency (determined by the atmospheric density). For Jupiter, this cutoff frequency is near 40 MHz, while for all of the other planets in the solar system, it is below 1 MHz. Current efforts to detect magnetospheric radio emission from extrasolar planets have been unsuccessful, but almost all efforts have been at frequencies of 74 MHz and higher, potentially above the cutoff frequencies for most extrasolar planets.

Studies of the Dark Ages and the magnetospheric radio emissions offer potential observational synergies given their frequency ranges. The redshifted HI spectral feature from the Dark Ages and First Stars occurs at radio frequencies 10 MHz $\leq \nu \leq 40$ MHz, while the magnetospheric radio emissions occur at frequencies $\nu < 40$ MHz, potentially down to 0.5 MHz.

4. Notional Mission Plan

First, the LCRT concept and a suitable lunar crater are selected. A spacecraft, carrying the equipment shown in Table 3, is launched using Space Launch System (SLS) rocket and lands near the selected crater. In 2 years, the robots shape the crater and lay a reflective wire-mesh so that it acts as a reflecting spherical dish. Then, the receiver antenna is deployed and the LCRT is calibrated. Finally, this LCRT starts exploring the universe! Then, the construction robots move on to another nearby crater and being the construction

Requirement	*Dark Ages*	*Extrasolar Planets*
Wavelength (Frequency) range	$7-30$m ($10-40$MHz)	$7-100$m ($3-40$MHz)
Estimated strength of signal	Surface brightness measurement of 25mK	$10^{-4}-10^{-7}$Jansky, estimated using Jupiter's emissions [17]
Number of targets in the sky	Potentially the entire sky. We will start with observing 2 particularly cold areas in the sky	$>$ 100, likely to increase after NASA's Transiting Exoplanet Survey Satellite (TESS) mission launches next year.
Desired angular resolution	$< 5°$ [18]	$<$ 10 arc min
Desired SNR	$>$ 5, assuming integration time of 3000hrs (i.e., 10 lunar nights) and rms uncertainty of 5mK	$>$ 7, assuming integration time of 1hr and rms sensitivity of 5×10^{-7}Jansky
Preferred observation time	Lunar night, because Suns normal radio emissions could cause interference	Both lunar day and night, but solar radio bursts could cause interference

Table 2. LCRT's estimated technical requirements for achieving science objectives

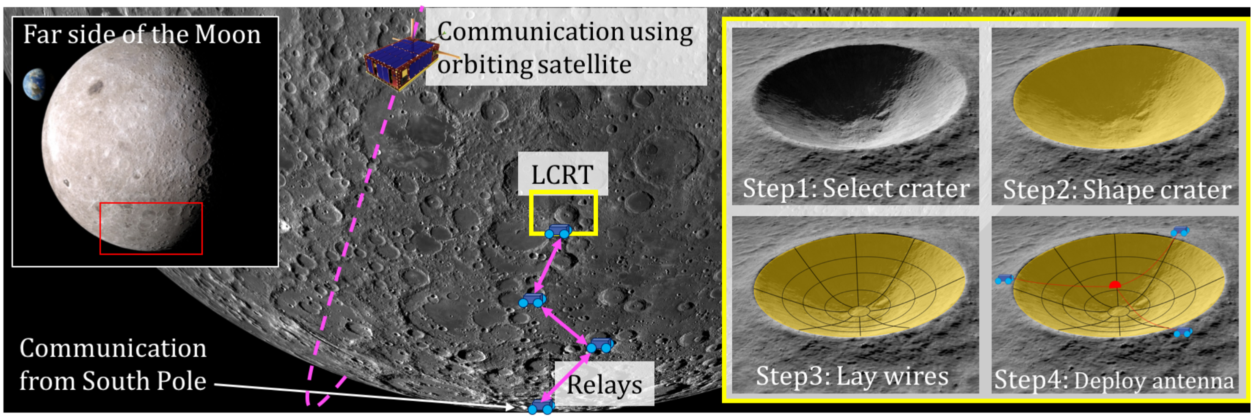


Figure 3. Overview of mission plan and construction of LCRT

of another LCRT, subject to availability of consumables. Note that the various steps in LCRTs construction process can be performed in parallel. In this concept, we will investigate the growth of mission requirements (launch mass, power, construction time) with LCRT size. See Fig. 3.

Description	*Mass/item*	*No. items*	*Total Mass*
Construction robots	$1,000$kg	7	$7,000$kg
Wires for wire-mesh	2kg	$10,000$	$20,000$kg
Receiver antennae	500kg	1	500kg
Target tracking mechanism	$1,500$kg	1	$1,500$kg
Power, thermal equipment	$1,000$kg	4	$4,000$kg
Miscellaneous			$7,000$kg
Total Mass to be launched			$\mathbf{40,000}$**kg**

Table 3. Estimated Mass budget for constructing one LCRT (Concept 1 in a 2km diameter crater)

5. Technical Challenges

In order to prove the feasibility of the LCRT concept, we need to further explore these key technologies:

Generate LCRTs technical requirements

We will generate LCRTs technical requirements in terms of wavelength (frequency) coverage, angular resolution, signal-to-noise ratio (SNR), target tracking accuracy, mission lifetime, etc. for accomplishing the science objectives. Our estimates are shown in Table 2.

Select lunar craters for LCRT concepts

We will survey and select suitable craters on the far-side of the Moon for the two LCRT concepts using the Lunar Reconnaissance Orbiter Camera (LROC) database [15], although many potential craters have not yet been identified as shown in Fig. 4. We estimate there are ≈ 3000 and ≈ 2000 suitable craters for LCRT Concepts 1 and 2 respectively [15].

Mineability of the crater is another important constraint in the selection process. Mineability of lunar regolith is expected to be high, due to the predominance of fine-grained particles, and of lunar basaltic or anorthositic rock (e.g., bedrock or boulders) is expected to be low. It is possible to estimate the ratio of bedrock or boulders to finer-grained materials in a crater from orbital data. In general, we expect the mineability to be higher for smaller, older craters in mature terrain [28].

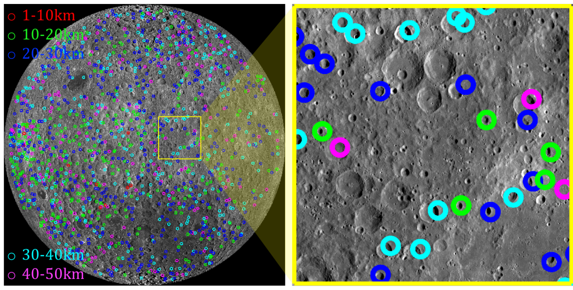


Figure 4. Candidate craters for LCRT concepts. Many craters have not yet been identified in LROC database.

Autonomously shape the lunar crater

A number of excavation and construction robots can be used for coarsely shaping the lunar crater (see Fig. 7): ATHLETE rover [29] is equipped with a percussive bucket for efficient excavation [30] and can be used for rapid-prototyping-based construction [31]. Axel rover [32] can climb down steep terrain and can be used as a steamroller [33]. Chariot rover with bulldozer attachment can be used for excavation and construction [34]. The low mass RASSOR excavator can harvest large amounts of regolith in low gravity [35]. We will evaluate various excavation, mining [28], [36], [37], and construction techniques that will enable us to efficiently achieve the desired shape.

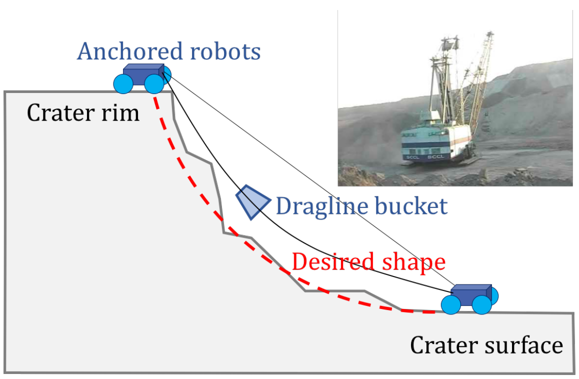


Figure 5. Dragline excavator concept

We will also investigate a dragline excavator concept shown in Fig. 5, which was first envisioned in [38], since our desired shape is amenable to this type of excavation. The excavated material can be dumped in the center of the crater as it will not reflect radio waves. Similarly, large boulders, difficult to reach/excavate regions, and other regions with large deviation from the desired shape can be safely ignored because they will not reflect radio waves. The two robots can drive in parallel along the crater circumference and shape sections of the crater. *Time and Power estimates:* On Earth, a Singareni OCP-I dragline with 24m^3 bucket, 96m boom has a projected annual output of $2.8 \times 10^6\text{m}^3$ [39]. Assuming we will shape $< 40\%$ of the surface, 5 of these draglines can shape a 2km-diameter, hemispherical crater in 2 years. We propose carrying 7 of these draglines, each weighing < 1000kg and requiring < 50KW power.

Moreover, lunar excavation will be comparatively easier than Earth due to lower gravity. If we select mature craters near the lunar equator, with highlands geology, then the samples from the Apollo landing sites can be used for testing/validation of our excavation techniques. The fine-grained regolith sampled at the Apollo sites are similar to wet sand on Earth [28]. Translating these parameters into force requirements, estimating their wear-and-tear, and service lifetimes of mining equipment is possible.

Cover the dish with wire mesh

In order to transform the shaped crater into a reflective dish, we will investigate techniques to lay a reflective (conductive), micro-meteorite strike resistant [40] (See Fig. 6), wire-mesh on the crater, with specifications in Table 4.

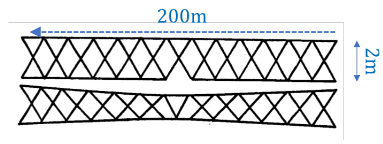


Figure 6. Micro-meteorite strike resistant wire design

The wire mesh would be laid on the coarsely shaped crater using intermediate anchors, which allow for thermal expansion-contraction, in order to achieve the desired shape with 1m ($\approx \frac{\min\lambda}{5}$) accuracy. We will perform a tradeoff study between bringing wire reels from Earth (e.g., 2km diameter LCRT needs 10^4 AWG21 copper wire reels, where each 200m reel weighs 2kg) and ISRU-based manufacturing of wires from the metal-rich lunar soil [41], [42]. Note that the lunar surface acts as an insulator due to the very-low humidity, hence laying the conducting wires on the lunar surface will not ground them.

Specification	***Value***	***Reason***
Wire length	200m	$\approx 2 \times \max\lambda$
Wire diameter	Copper: 0.72mm (AWG21) Aluminum: 0.91mm (AWG19)	resistance less than 10Ω across the wire [17]
Wire spacing	5m	$\approx \min\lambda$

Table 4. Specification of Wire Mesh

Design the receiver antenna

We will design the receiver antenna for the $5 - 100$m wavelength band, based on current designs in Arecibo and FAST. We propose using an array of dipoles (line feeds) and digitally correcting for the delays due to spherical aberrations. Other designs like the Gregorian system and thermal effects on the receiver antennas performance will also be investigated.

Design the target tracking mechanism for the receiver antenna

Angular motion of an astronomical target on the Moon is much slower than Earth (rotation period is 27.3 days). We propose two architectures, shown in Fig. 2, to track an astronomical target moving at $0.55°$/hr. The proposed Arecibo-based architecture involves three stationary (anchored) robots maneuvering the receiver antenna. The second architecture involves a mobile robot carrying the receiver antenna along the crater rim. We will evaluate these target tracking architectures for the two LCRT concepts.

Figure 7. Excavation and construction robots: (a) ATHLETE, (b) Axel, (c) Chariot, (d) RASSOR

Select the best LCRT concept

Finally, we will select the best LCRT concept by evaluating the concepts in terms of technical requirements, mission requirements (launch mass, power, construction time), etc.

Calibrate the LCRT

We will determine a strategy to calibrate the LCRT in the poorly explored $5-100$m wavelength band. We propose using known radio sources [43], their black-body approximations, and dark patches in the sky. We will also determine a strategy to evaluate the LCRTs performance by observing selected science targets.

Explore the feasibility of lunar Very-Long-Baseline Interferometry (VLBI)

To create multiple LCRTs and enable VLBI, we will investigate the additional consumables that need to be brought from Earth (e.g., receiver antenna system, wires) or manufactured in-situ on the Moon (e.g., wires).

Other Technical Challenges

Although we use a number of technologies that are currently not mature, we will not be addressing them in this concept because we envisage maturity of these technologies in the future, of which some are already being pursued under studies:

Communication with Earth from the far-side of the Moon:—We have identified two potential approaches for communication: (i) Setup relay stations to the South Pole of the Moon using Transformer robots [44], (ii) Communicate using an orbiting lunar satellite or a satellite at the Earth–Moon L2 Lagrange point [45].

Power and heat for mobile robots:—In order to meet the maximum power requirement of 400KW and provide warmth during the extremely cold lunar nights (with temperatures reaching -150^0C), we propose having 3 large, stationary solar panels (each generating > 150KW, weighing < 1000kg) and adequate battery packs and heating equipment [46]. Other researchers have proposed storing the thermal energy using thermal capacitors [47] or a modified Magaldi system [48].

Surviving the super-fine lunar dust:— The lunar dust is a potential hazard for any robotic mission on the Moon as it can contaminate equipment and clog moving parts. Addressing this issue is a focus of all space agencies that are planning to send robotic missions to the Moon [49]. We do not expect this dust to affect the LCRTs performance because it is transparent in the $5-100$m wavelength band.

Autonomy of robotic systems:—Autonomy in robots is developing at a fast rate and currently autonomous robots are being designed to explore the Solar System (e.g., Mars, Europa, Titan). Hence, we assume our robots will be able to perform their tasks autonomously, with minimal oversight from Earth.

Risks and mitigation

The risks and their mitigation strategies associated with the LCRT concept are:

- The desired LCRT size and mission requirements (launch mass, power, time of construction) might be too large for a single SLS rocket launch. Although initial estimates in Table 3 help ameliorate this risk, we will determine the best science goals that can be achieved for this case.
- Consumables for additional LCRTs for lunar VLBI might not fit in a single SLS rocket launch. We will investigate if additional launches by lower-power rockets can supply these consumables.
- Excavation of lunar crater might be too difficult (due to force, power constraints). We will select craters that need almost no excavation and make the reflecting dish using only the wire mesh.

6. CONCLUSIONS

In this paper, we described a novel concept for building a radio telescope on the far-side of the Moon. The proposed Lunar Crater Radio Telescope (LCRT) concept involves shaping a suitable existing lunar crater ($1-50$km in diameter) on the far-side of the Moon into a spherical reflecting dish that would be able to observe the universe in the $5-100$ m wavelength band (i.e., $3-60$ MHz radio frequency band).

This concept directly contributes to multiple Technical Areas (TA) of the NASA Space Technology Roadmaps [50]:

- TA 8.2 Observatories, as we are exploring the feasibility of building an observatory on the Moon
- TA 4: Robotics and Autonomous Systems, as we are developing a number of autonomous robotics solutions.

In addition, this concept will look into what is necessary to open-up these poorly explored wavelengths (> 10m) for scientific exploration of the universe. Furthermore, the excavation, construction, and mining tasks would pave the way for humans to return to the Moon (a priority of the current administration) and possibly lead to a permanent outpost on the Moon.

Building the largest filled-aperture radio telescope in the Solar System on the far-side of the Moon is bound to create lot of public excitement! We will engage the public by disseminating the concept and results through a dedicated website. We envisage that this concept would unlock the potential for ground-breaking scientific discoveries in radio astronomy in wavelengths that are hitherto poorly explored by humans so far.

APPENDIX

In Fig. 8, we show the different orbits around Moon from altitude 500 km to 4000 km. It is seen in Table 5 that the closest orbit at 500 km altitude only enjoys $\approx 20\%$ time in the actual radio quiet zone. The time period T of a satellite at an altitude a is given by $T = 2\pi\sqrt{\frac{(r_M+a)^3}{G m_M}}$, where the radius of the Moon $r_M = 1737$ km, the mass of the Moon $m_M = 7.35 \times 10^{22}$ kg, and the Gravitational constant $G = 6.67 \times 10^{-11}\text{m}^3\text{kg}^{-1}\text{s}^{-2}$. Therefore, these multi-satellite missions should be launched in low-altitude orbits. Note that these orbits allow the satellites to directly communicate with Earth for at least 50% of their orbital period. This analysis clearly shows that the proposed lunar-satellite missions at the L2 point will not be shielded from the radio interference from Earth-orbiting satellites [11], [12], [13], [14] (see Fig. 1).

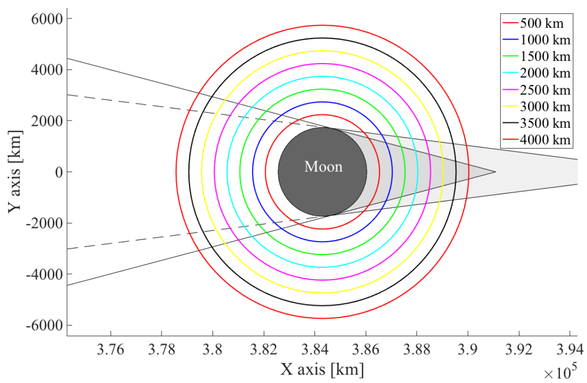


Figure 8. The orbits around Moon

Altitude	*Time Period*	*Time inside actual RQZ*	*Time inside conserv. RQZ*
500 km	2.64 hrs	20.0%	24.0%
1000 km	3.57 hrs	13.7%	17.7%
1500 km	4.59 hrs	9.8%	13.9%
2000 km	5.69 hrs	7.2%	11.3%
2500 km	6.87 hrs	5.2%	9.4%
3000 km	8.13 hrs	3.7%	7.9%
3500 km	9.45 hrs	2.5%	6.7%
4000 km	10.83 hrs	1.6%	5.7%

Table 5. Percentage of time spent inside the actual and conservative Radio Quiet Zone (RQZ)

The relative dynamics of multi-satellite missions in Earth orbit are described by the linear Hill–Clohessy–Wiltshire (HCW) equations and similar higher-fidelity equations [51]. Similar linear equations can also be written for multi-satellite missions in Moon orbit. The orbits and baselines of four multi-satellite missions at 500 km altitude during the 31 mins period in the radio quiet zone are shown in Fig. 9.

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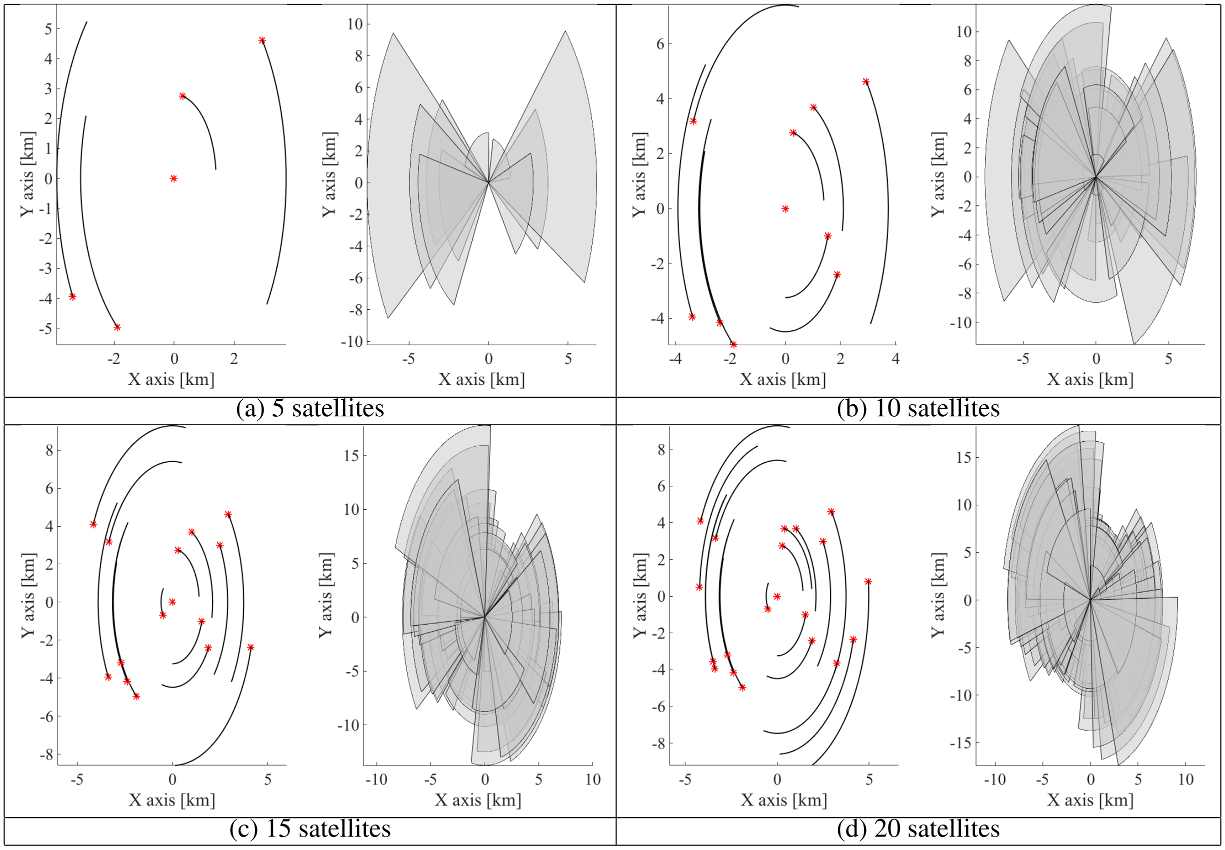

Figure 9. Orbits and Baselines of multi-satellite missions at 500 km altitude and inside the radio quiet zone

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