New Astronomy from the Moon:
A Lunar Based Very Low Frequency Radio Array

Yuki David Takahashi

Department of Physics and Astronomy,
University of Glasgow

Thesis submitted to the University of Glasgow
for the degree of Master of Science

July 2003

©Yuki David Takahashi, 2003
Acknowledgements

I would like to thank Dr. Graham Woan for welcoming me to work toward Moon-based astronomy as a master’s research project and for being a very approachable advisor. Whenever I went to his office, Graham always welcomed me to sit down and we discussed as long as we wanted to. I appreciated his openness to let me do anything I was motivated to do. I thank him for being a good listener, respecting my ideas and opinions. Whenever I asked him a question, he gave me new insights. Also, his inputs on the simulation studies were very valuable. I wished I had learned to take even more advantage of his expertise instead of trying too long to solve things by myself. Finally, I thank him for his patience. Thanks also to the rest of the friendly people of the Astronomy & Astrophysics Group at the University of Glasgow.

I would also like to thank Dr. Claudio Maccone for his encouragement. There is not enough space to express how much I appreciate helpful answers and support from Dr. Kurt Weiler, Dr. Wendell Mendell, Dr. David Schrunk, Burton Sharpe, Dave Doody, Phil Venturelli, Luis Armendariz, Chris Hirata, Josh Hale, Brad Zamft, and many others. Also, thanks to the US-UK Fulbright Commission for funding my valuable year in the UK.

I would like to dedicate this to all the people who have dreamed of doing astronomy (especially at the new very low frequencies) from the Moon: Stan Gorgolewski, James Douglas, late Harlan Smith, Jack Burns, John Basart, Stewart Johnson, Jeffrey Taylor, Wendell Mendell, Kurt Weiler, Namir Kassim, Dayton Jones, Tom Kuiper, Michael Mahoney, Robert Preston, Graham Woan, Jean-Louis Bougeret, Neb Duric, Brian Dennison, Michael Kaiser, Claudio Maccone, and to all the additional people who will help make this happen. My wish is that this work contributes in any way to inspire people toward the Moon to learn about the universe through the new, very low frequency window.

Finally, I dedicate this thesis to my Father and Mother who put their effort into raising me to be a hard worker.

Declaration of Originality

Except where specific reference is made to the work of others, this thesis has been composed by the author.
Abstract

This thesis aims to contribute toward a proposal to set up a very low frequency (VLF: ≲ 30 MHz) radio observatory on the lunar surface. The primary motivation for this proposal is to learn about our universe through a completely new spectral window in astronomy by taking advantage of the unique lunar environment. The secondary motivation is to take on a challenge of building and operating a facility on the Moon, especially through international cooperation, and to inspire everyone who looks at the Moon. After explaining these motivations and reviewing foregoing efforts toward this cause, the thesis examines unsolved questions about the advantages of the lunar environment, proposes a preliminary observatory to be set up at the lunar south pole, and identifies desirable measurements to be made at the earliest opportunities.

Chapter 1 describes the motivations for astronomy from the Moon, particularly at very low frequencies. The Moon offers a unique environment that enables astronomical observations that are otherwise impractical. In particular the Moon can be utilized as a shield against unwanted radiations and as a large stable platform. These advantages are crucial for VLF astronomy. Thus far the Earth’s ionosphere and interference have prevented any detailed observations at frequencies below ∼30 MHz, keeping this VLF window the only part of the electromagnetic spectrum yet to be explored in astronomy. Accordingly the potential for unexpected discoveries is significant. The lunar far side may well be the only accessible site that enables sensitive galactic and extragalactic VLF observations.

To realize this idea, Chapter 2 reviews the extensive foregoing efforts toward a Moon-based VLF observatory and identifies the next steps. The idea began in the mid-1960s and was advanced significantly during the 1980s, especially at a workshop dedicated to a lunar far side VLF array. In the 1990s, serious design studies were conducted by the Hughes Aircraft Company, the International Space University, and the European Space Agency. Referring to all these work, this chapter presents a background on observational considerations and the observatory design. The current consensus seems to be that although an array on the far side of the Moon is scientifically ideal and technologically feasible, funding is unlikely until the far side access becomes inexpensive. To accelerate the pace for this proposal, the key is probably to raise people’s interest in this project and its significant discovery potential. Also, the necessity of the Moon should be reaffirmed (Chapter 3), an affordable preliminary VLF array should be proposed for an initial sky survey (Chapter 4), and necessary measurements should be made utilizing every opportunity presented by the upcoming lunar missions (Chapter 5).
Chapter 3 examines questions that must be resolved to confirm the advantage of the lunar surface for a VLF observatory. We must verify that (1) the Moon can shield the interference sufficiently, (2) any lunar ionosphere does not limit the observations, and (3) the lunar surface and subsurface do not disturb the observations. To address various issues relevant to the VLF array project, a general tool was developed to simulate the propagation of radio waves in the lunar environment. This tool was used to investigate (1) how radio waves penetrate into the lunar surface for possible subsurface reflections back up to the antennas, and (2) how well the Moon shields long wavelength radio interference. On the far side locations over half way (45 degrees) from the limb, the simulations seem to show that radio waves would be attenuated by at least 10 orders of magnitude, even at a very low frequency of 50 kHz.

Prior to a full-scale observatory on the lunar far side, a crucial step now is to propose a realistic preliminary version at a more accessible site on the Moon, examined in Chapter 4. It will be for conducting an initial sky survey and testing an array on the lunar surface. The most economical method of deploying such lightweight antennas could be as a piggyback payload on some funded lander, most likely to the lunar south pole. This way, the project can utilize the same transportation, power, and communication systems required for further lunar development. A study was conducted to explore the possibility of using the 5-km tall Malapert Mountain near the lunar south pole as a shield against terrestrial radio interference. Simulations seem to indicate a several orders of magnitude attenuation over a region spanning ~50 km on the far side of Malapert Mountain. A preliminary concept is developed for the first lunar VLF array to be deployed in this shadowed region.

To be able to choose the site and design the observatory, Chapter 5 makes recommendations for specific measurements to be proposed for upcoming missions including SMART-1, LunarSat, and SELENE. It is especially critical to obtain detailed topology at candidate sites and to determine the electron density profile above the lunar surface at various times and locations.

The final chapter includes my vision for how an international effort can make this project happen. Suggestions are given for an orbiting precursor array by ~2010, a surface array near the lunar south pole by ~2015, and ultimately a far side array after 2020. Many nations share similar ambitions toward the Moon, including the United States, European Union, Japan, China, India, Canada, and Russia. Let us begin seriously exploring how to turn the individual objectives into a united proposal. I believe the Moon offers unique and significant opportunities for inspiring and uniting everyone on Earth.
# Contents

1 Motivation .................................................. 3
  1.1 Why Moon? .................................................. 3
  1.2 Why astronomy from the Moon? ............................. 4
  1.3 Why very low frequency astronomy from the Moon? ...... 6
    1.3.1 New view of the universe ............................. 6
    1.3.2 Need for the Moon ..................................... 9
    1.3.3 Feasible & urgent first step .......................... 15

2 Foregoing Effort and Next Step ............................... 17
  2.1 Historical overview ........................................ 17
  2.2 Observational considerations .............................. 20
  2.3 Observatory design ........................................ 22
  2.4 Precursor missions ........................................ 23
  2.5 Design studies ............................................ 24
  2.6 Current consensus ......................................... 24
  2.7 Next steps toward realization .............................. 25

3 Confirmation of Lunar Advantage ............................ 27
  3.1 Questions to resolve ....................................... 27
    3.1.1 Shielding of interference ............................ 28
    3.1.2 Lunar ionosphere ..................................... 28
    3.1.3 Lunar surface ......................................... 30
  3.2 Studies using radio wave simulation ....................... 33
    3.2.1 Radio wave simulation ................................ 33
    3.2.2 Lunar electrical properties .......................... 39
    3.2.3 Lunar ionosphere ..................................... 39
  3.3 Study I: Radio wave penetration into the lunar surface .. 41
  3.4 Study II: Interference shielding by the Moon ............. 42
    3.4.1 Setup ................................................ 42
    3.4.2 Results .............................................. 45
  3.5 Conclusions ................................................ 49
Chapter 1

Motivation

The primary motivation for setting up a very low frequency (VLF) observatory on the Moon is to learn about our universe through a completely new spectral window in astronomy. The secondary motivation is to take on a challenge of building and operating a facility on the Moon, especially through international cooperation, and to inspire everyone who looks at the Moon.

1.1 Why Moon?

The Moon has a unique potential for inspiring and uniting everyone on Earth because it is the one common object, save the Sun, that virtually everyone sees regularly. Human presence on the Moon would provide everyone with something permanent to look up to in the heavens for inspiration. The astronauts’ visits between 1969 and 1972 must have impacted billions of people around the world, but they were temporary and with primarily nationalistic motivation. Going there again and doing something fascinating on such a universally familiar and visible heavenly body could inspire a new generation of people.

Many may say “we’ve been there” or “the Moon is boring – there’s nothing there”, but such remarks must be based on no actual experience. While the potential for life on Mars is exciting, robotic exploration may be initially sufficient. More people, including children, can better relate to the Moon simply because it is so much more visible and familiar.

We have additional reasons to go to the Moon, including science [1], further exploration, and resource utilization. Studies of the Moon can teach us much about how the Solar System and the Earth formed. The Moon also provides unique environment for science and astronomy, including high vacuum, small but finite gravity, and a stable surface. Being the closest and the most accessible body in outer space, it is the perfect first step for validating technology for further space exploration. Even for humans to go to Mars, gaining experience on the Moon will be valuable in minimizing the risk. In
addition, the presence of water ice at the lunar south pole is promising for production of propellant for further exploration from the Moon. Finally, the Moon has resources like $^3$He that may be brought back to Earth to potentially serve the world’s energy needs [2].

Out of the various possible activities on the Moon, astronomy is probably the most sensitive to the unique lunar environment.

### 1.2 Why astronomy from the Moon?

The ability to place telescopes above the Earth’s obscuring atmosphere has revolutionized the human view and understanding of the universe (for example, the Cosmic Background Explorer and the Hubble Space Telescope). Placing telescopes on the Moon presents additional advantages in many cases. Certain astronomical observations are likely to become possible only from the lunar surface.

In 1986, nearly 100 scientists and engineers gathered for a workshop on *Future Astronomical Observatories on the Moon*, sponsored by the National Aeronautics and Space Administration (NASA) and the American Astronomical Society [3]. There the participants identified many advantages of the lunar surface over both earth-based and space-based locations for astronomy. The lunar surface presents unique advantages in mainly three respects: shielding of unwanted radiation, large stable platform, and accessibility.

**Moon as a shield**

In free space, telescopes are constantly bombarded with radiation from the Sun and other relevant noise sources. The Moon, being a large body unlike anything else in the nearby space, can shield unwanted radiation from intense sources like the Sun and Earth.

The Sun is the strongest source, emitting all types of radiation and particles by means of solar wind, solar flares, and coronal mass ejections. In free space, the Sun interferes with astronomical observations almost continuously, while telescopes in orbit go in and out of the solar influence frequently. Telescopes on the lunar surface can avoid all the radiation from the Sun during the two weeks of night. The nighttime temperature on the Moon falls from $\sim 100$ K at “midnight” to $\sim 90$ K just before the sunrise, according to the Lunar Sourcebook [4]. Also, at a depth of $\sim 30$ cm, the temperature is expected to be very stable at $\sim 250$ K with only $\pm 3$ K variation [4]. Equipment can be buried in the regolith for protection against thermal stress from temperature extremes on the surface. Perhaps the coldest and the most thermally stable locations known are the permanently dark interiors of craters in the polar region: the temperature is expected
to be \(\sim 40\) K and very stable [4]. This allows passive cooling of thermal detectors with minimal noise for infrared observations.

For cases in which the Earth is a large noise source, the far side of the Moon is the only accessible location that can avoid all the radiation from Earth, including scattered light, thermal flux, and radio interference.

**Moon as a large stable platform**

In free space, high stability is difficult to achieve because orbits are not static. This makes formation flights with long baselines for interferometry very difficult. On the Moon, a very large and very stable platform is available for maintaining astronomical facilities in permanently stable configurations. No thrusters or propellants are necessary for positioning or station keeping. This stability level may be feasible only on the Moon due to difficulty in formation flying and vibration control in free space.

Also, in free space, destabilizing or corrective forces induce motions. For example, coolers for detectors produce vibrations that can take a long time to damp out in free space [5]. The Moon is a large fixed platform to push against and to damp out vibration.

**Moon for lower risk**

Telescope deployment or any necessary construction is much less risky on a solid platform with gravity than in free space where everything needs to be kept track of (for example by tethering). Facilities on the Moon are accessible by humans for maintenance, especially with a lunar base established nearby. Accessibility from a nearby lunar base allows service and upgrades for never-ending contributions to astronomy. If there is a surface presence, maintenance and commissioning, as well as upgrades and expansion, are easier, resulting in longer lifetimes. Anything constructed on the Moon stays on the surface permanently, as opposed to in free space where the spacecraft lifetime is limited in various ways. Nearly real-time communication is possible between the Earth and the Moon (3 seconds round trip).

**Applications**

Astronomy from the Moon has been advocated since at least the mid-1960s as soon as the Moon became accessible. At least four major meetings have been dedicated to advance this idea:

- 1986 Future Astronomical Observatories on the Moon (NASA Workshop) [3]
- 1990 Astrophysics from the Moon (NASA/AIP Workshop) [7]
- 1997 Astronomy from the Moon (IAU Joint Discussion) [8]
The lunar observatory concepts that have attracted the greatest interest are the lunar far side very low frequency radio array and optical/infrared interferometer. For example, in 2002, NASA funded a study to investigate the human-aided construction of large lunar telescopes, in which Duke et al [5] considered an infrared telescope to be in a permanently shadowed floor of a crater near the lunar south pole.

1.3 Why very low frequency astronomy from the Moon?

Each time a new part of the electromagnetic spectrum was used to observe the universe, humans made significant discoveries, many of them unexpected. Thanks to the space programs, the universe has been studied at all parts of the spectrum from gamma rays to radio waves, except the very low frequencies below \( \sim 30 \text{ MHz} \). The VLF radio waves are scattered and reflected by the Earth’s ionosphere, making astronomical observations practically impossible from the ground. Even from outer space, noise from the Earth and the Sun turned out to be too overwhelming for any observations outside the Solar System. The only way to avoid this radio interference seems to be to use the Moon as a shield. For this reason, the lunar far side VLF array has been the most seriously investigated concept for a Moon-based observatory, with the greatest number of papers written for it.

1.3.1 New view of the universe

The part of the electromagnetic spectrum below \( \sim 30 \text{ MHz} \) remains the only unexplored window in astronomy. VLF astronomy therefore has a significant potential for even unexpected discoveries.

Outside the ionosphere

The Earth’s ionosphere has largely prevented ground-based astronomy at frequencies below the plasma cutoff of \( \sim 10 \text{ MHz} \). Even at 10 MHz or above, the ionosphere scatters the low frequency radio waves, worsening the angular resolution. For example, the best map of the radio sky to date at 10 MHz has a poor resolution of \( \sim 5^\circ \) (Figure 1.1). The upcoming ground-based Low Frequency Array (LOFAR) is proposed to observe at frequencies down to 10 MHz, but no lower [9].

At other parts of the electromagnetic spectrum inaccessible from the Earth, observatories were placed in outer space and have revolutionized the human view of the universe. At very low frequencies below 10 MHz, the only view of the universe we have is from the Radio Astronomy Explorer 2 (RAE-2) satellite in 1973 (Figure 1.2). This satellite carried only a pair of dipole antennas, so it had almost no angular resolving power. Without an appreciable angular resolution, this image provides almost no information.
about what individual objects may constitute the intensity.

Figure 1.1: A 10 MHz map of the southern sky at $\sim 5^\circ$ resolution, by Cane & Erickson in 2001 [10].

Figure 1.2: All-sky image at $\sim 2$ MHz from the Radio Astronomy Explorer 2 satellite in 1970s [11].

**Discovery potentials**

Outside the Earth’s ionosphere, the plasma cutoff for the local interplanetary medium is $\sim 30$ kHz; thus, nearly three new decades in frequencies can become available for astronomy. While this VLF range is conventionally included in the “radio” window of the electromagnetic spectrum, it is as wide as any other window in astronomy (Figure 1.3).

Figure 1.3: A new window for astronomy at very long wavelengths / very low frequencies. (All-sky maps credits: NASA)

Observations at VLF will likely uncover new objects and new phenomena never seen before at higher frequencies. For example, new candidates for dark matter could be discovered. We can also look forward to totally unexpected discoveries. Opening up this new window may be compared to becoming able to see infrared radiation with our eyes: we can hardly imagine what we might discover about the world.

We will be able to study phenomena not manifested in any other spectral band, including “low energy cosmic ray particles, thermal environments of discrete radio sources, and coherent radiation arising from collective plasma processes”, according to Neb Duric [12].

As James Douglas [13] stated, phenomena that can best be studied at low frequencies include galactic synchrotron emission, absorption by HII regions, and interstellar/interplanetary scattering; phenomena that can only be studied at low frequencies
are planetary/solar non-thermal emission (plasma instabilities in configurations impos-
sible to produce in lab). He stressed that “the appearance of radio sky at one degree
resolution below 10 MHz is still unknown”, and that “quite strong but very steep spec-
trum sources could exist at 1 MHz, unsuspected from any work done to date.”

John Basart et al (1997) stressed that “cosmic rays represent the most energetic
form of matter and trace the highest energy phenomena,” and their origin is “perhaps
the most fundamental question still remaining from the era of classical physics” [14].

Motivations  Concrete scientific motivations for VLF astronomy are well described in
reports by Weiler & Jones (1999) [15], the European Space Agency (1997) [16], Bougeret
(1996) [17], ESA (1992) [1], Weiler (1990) [18] and are simply outlined here:

- New phenomena, new objects, and new physics
  - Discover unusual phenomena, new classes of objects and processes.
  - Discover new coherent radio emitters, millisecond pulsars, and extrasolar
    planets.
  - Identify mechanisms of relativistic electron emission, injection, acceleration,
    diffusion, absorption, and evolution.
  - Study pulsars’ coherent emission regions.
  - Study plasma effects (free-free absorption, suppression of radiation by a cold
    plasma, synchrotron self-absorption, physics of electrically charged dusty
    plasmas).
  - Study diffusive shock acceleration processes.

- Galaxy formation and evolution
  - Detect fossil radio galaxies, very high redshift radio galaxies and clusters.
  - Study cosmic ray diffusion times away from galactic disks (galaxy halo emis-
    sion).
  - Study magnetic field distributions in galaxies (galactic cluster halos and in-
    tergalactic magnetic fields).
  - Measure intergalactic medium.
  - Map disks and halos of normal galaxies, radio galaxies, and quasars.

- Interstellar medium
  - Map the distribution of diffuse ionized hydrogen (HII), “the only major com-
    ponent of the interstellar medium that has not yet been surveyed” [19].
– Study composition and distribution of thermal and non-thermal (relativistic) gases in the interstellar medium.
– Study the origin of interstellar plasma turbulence and the energy transport.

• Origin of cosmic rays

– Detect and image old galactic supernova and γ-ray burst remnants to find possible cosmic ray acceleration sites.
– Map distributions of galactic low-energy cosmic ray electrons to understand cosmic ray acceleration and transport.

• Our solar system

– Study the planetary/solar non-thermal radiation from plasma instabilities in conditions impossible to produce in laboratory (only possible at VLF [13]).
– Observe interplanetary medium (solar wind turbulence).
– Sun: map the propagation of electron streams through the corona (Type III bursts) and propagation of coronal shock waves (Type II bursts); forecast the arrival of coronal mass ejection.
– Jupiter: Determine the location of non-thermal emission in the magnetosphere to understand the emission process.
– Earth: Globally image terrestrial magnetosphere to study its interaction with the Sun.
– Moon: Study its ionosphere and exosphere, response to varying solar wind conditions, and the ionized environment above the surface.

The first detailed observation at very low frequencies will mark history in astronomy. It could create a revolution in human view of the universe. Venturing to open the window into the unknown could return an unimaginable reward.

1.3.2 Need for the Moon

To make all these discoveries, VLF astronomy will need to be based on the Moon for two main reasons: (1) the necessity to use the Moon as a shield against overwhelming radio interference from the Earth and the Sun, and (2) the requirement for keeping the interferometric array elements in a stable configuration on a rigid structure like the lunar surface.

Need for interference shielding

In 1968, to make the first VLF measurements (in a frequency range of 0.2 - 9.2 MHz), the Radio Astronomy Explorer 1 (RAE-1) satellite was launched into an orbit 6000
km high [20]. This and other satellites like the Interplanetary Monitoring Platform (IMP) series [21] discovered that the Earth itself had often very intense emissions at very low frequencies. Such terrestrial emissions, both natural (auroral) and man-made, seriously interfered with attempts at astronomical observations. RAE-1 also detected many Solar bursts and emissions from Jovian planets [22]. Based on evidence collected from a number of spacecraft, Figures 1.4 and 1.5 show the sources encountered outside the Earth’s ionosphere.

Figure 1.4: Flux densities of active radio sources in the 10 kHz - 100 MHz range, from a 1997 ESA report [16], adapted from Zarka et al [23]. This shows the significance of interference compared to the background. $A_e$ is the effective area of the antenna.

All the galactic and extragalactic objects to be discovered are hidden in the sky/galactic background. The Earth’s auroral kilometric radiation (AKR) and Solar type III storms dominate the middle of the VLF spectral window. The AKR is in a very low frequency range of 50∼750 kHz, but very intense. Even emissions from Jupiter and Saturn can be comparable to the galactic background, depending on the antenna’s effective area and beam pattern. Unless the Sun, Earth, and the planets are the observation
Figure 1.5: Overview flux spectra of the principal sources of noise in the terrestrial environment below 10 MHz, from Desch 1990 [24]. The flux densities of the Earth-based sources are as seen from almost half way to the Moon. While the spectral estimates may be relatively outdated, this plot shows the “Spheric”, including both man-made and lightning emissions, dominant above $\sim 1$ MHz.

In addition to the AKR, terrestrial interference includes signals from communication transmitters both on the ground and in orbit. Above $\sim 2$ MHz, man-made transmissions leaks through the ionosphere and have been recorded by the WIND/WAVES experiment to be as much as 4 orders of magnitude stronger than the cosmic background even from a distance of half way to the Moon (Figure 1.7) [25].

As the wavelengths corresponding to very low frequencies are tens of metres to kilometres, astronomical observation requires an interferometric array of dipole antennas (as in Figure 2.2). Because each dipole antenna has very limited directivity, the noise from any visible source in the sky constitutes interference. In space, the Earth and Sun are always visible, producing interference beyond a manageable level for VLF astronomy.
Figure 1.6: Solar bursts, AKR, and Jupiter’s emissions seen by the Radio Receiver Band 1 (RAD1) of WAVES investigations on the WIND spacecraft [26].

Figure 1.7: Man-made radio transmissions seen by RAD2 of WIND/WAVES [26].
These interference sources are not only strong but also unpredictably variable in time; therefore, subtracting them is impractical. Basart et al. [14] demonstrated how the interference constrains sensitive imaging at low frequencies from space. They concluded that terrestrial interference would always be a problem unless (1) the array is far from the Earth in solar orbit, (2) the array is on the far side of the Moon, or (3) sophisticated bandwidth selection techniques are used to avoid interfering signals. Solar orbit will still be subject to the intense solar radiation. Bandwidth selection techniques will not help if the interference has a continuous spectrum, as produced by natural sources. Thus, the only practical shield against the very long wavelength interference is the Moon. A VLF array must be placed where the Moon blocks the Earth.

In outer space, the only physical way to avoid such interference is to shield the antennas with something much larger than the wavelength of the interfering radiation. Since the relevant wavelengths are up to kilometres, the only available shield large enough nearby the Earth is the Moon. Following the RAE-1 satellite, therefore, RAE-2 was launched in 1973 to an orbit around the Moon (Figure 1.8).

Figure 1.8: Radio Astronomy Explorer 2 satellite with its dipole antennas [20].

The terrestrial interference would be weaker in general from the distance of the Moon and completely eliminated while on the other side of the Moon. Figure 1.9 shows how significant the terrestrial interference is even at the Moon and how it is eliminated behind the Moon. While the satellite was in the geometrical shadow of the Earth behind the Moon, the antenna temperatures dropped by a few orders of magnitude. This was an encouraging result for the future of radio astronomy.
To take advantage of the shielding by the Moon, therefore, the observatory must be on the lunar far side, either on the surface or in the orbit. Since the lunar far side always faces away from the Earth, an observatory on the far side surface will be permanently free from the terrestrial noise. Indeed, it is the only location permanently free from the significant man-made and natural interference from the Earth. For this reason, the far side of the Moon has been considered the ultimate site for radio observations since the 1960s, whether for astronomy or for a search for extraterrestrial intelligence. However, many thought that placing an observatory on a lunar orbit would be a cheaper way of taking advantage of the shielding effect when on the far side of the Moon.

**Need for stable platform for interferometry**

As mentioned above, VLF astronomy requires interferometry involving many antennas because of the very long wavelengths involved. While lunar orbiting observatories have been proposed to observe while on the far side of the Moon, the lunar orbit is too unstable for maintaining many more than a few antennas in an array – gravity differentials
constantly alter the relative positions of the antennas. Basart et al [14] discusses the difficulty of calibrating an array with constantly changing baselines. Sensitive and detailed imaging at very low frequencies will require many dozens of antennas separated by tens of kilometres. Dayton Jones admitted that the proposed lunar orbiting array of 4 or 5 antennas would unlikely be able to produce scientific results that can capture the public interest [27].

An alternative way of avoiding the terrestrial interference may be to place an observatory on a more stable orbit far from the Earth. Even in a more stable orbit, however, the position of every element of an array needs to be monitored and controlled continuously. In contrast, the lunar surface is a stable platform for interferometry with no such continuous calibration requirement. It can maintain any number of antennas in fixed positions with any desirable separations. Many more antenna elements are practical than in a space-based array. Only then can long enough observations be made to achieve the sensitivity required for discovering even faint sources.

**Advantages of lunar surface over free space**

In 1998 a distinguished team proposed to NASA a 16-element VLF array on a distant Earth orbit 2.6 times the distance to the Moon [28]. Being 2.6 times further would reduce the terrestrial noise by a mere 1 order of magnitude and the strong solar interference will still be present. Compared to any free-space locations, the lunar surface offers many advantages in addition to the stability.

The Sun’s dominating radiation can be avoided during the 2 weeks of lunar night (the Sun can be studied during the day). The location can avoid other strong variable sources like Jupiter, simplifying mapping significantly. Only half the sky needs to be mapped at a time, simplifying mapping and calibration. 3-dimensional imaging required for space-based array is extremely complicated [14].

Finally, antennas on the Moon will remain there without expensive maintenance. The observatory can therefore begin modestly and expand gradually over time. Maintenance and upgrade would be possible, especially with a lunar base established.

In summary, the lunar far side is recognized as the best site of all for VLF radio astronomy.

### 1.3.3 Feasible & urgent first step

During the 1990s, three teams conducted design studies for VLF arrays and all have concluded that technology already exists for deploying the array on the Moon robotically, even on the far side. Radio antennas are robust against environmental conditions like dust, temperature extremes, and micrometeorites. An initial array could be set up inexpensively with a lunar lander equipped with a rover.
Planners of lunar missions must choose the sequence of development carefully since human activities will change the lunar environment irreversibly. For example, a better regulation of radio transmissions may have eased the pursuit of VLF astronomy. This is especially important for searches for extraterrestrial intelligence. Compared to other potential lunar activities, astronomy will be relatively harmless, while often sensitive, to the lunar environment. The unique radio quiet environment on the Moon may not last long once active development begins. The Lunar Sourcebook notes that 10 MHz wave can propagate through the upper lunar regolith with minimum loss, making it the optimum band for communication [4].

To secure the last hope for the VLF astronomy, this radio observatory project deserves consideration in an early stage of lunar development. The criticality of VLF astronomy was expressed by the Astronomy and Astrophysics Survey Committee of the National Research Council in 1991 [29], which recommended “... that an orderly program begin during the 1990’s directed toward the development of low frequency radio astronomy techniques on the ground and in space, ultimately leading to the establishment of a low frequency, high resolution radio astronomy telescope on the Moon”.
Chapter 2

Foregoing Effort and Next Step

To make the VLF astronomy project happen, let us first review the extensive foregoing effort toward the Moon-based VLF observatory and identify the next steps to take.

2.1 Historical overview

Initial ideas

1964: Gorgolewski  The advantage of the Moon for low-frequency astronomy was first brought up at the Lunar International Laboratory Discussion Panel in 1964. Stanislaw Gorgolewski [30] pointed out that the lunar far side would be the best for a radio astronomy observatory to avoid natural and man-made terrestrial interference. He also pointed out that the lunar night will open to view frequencies down to tens of kHz, but that further study is required to find the lowest usable frequency during the day. At the First Lunar International Laboratory Symposium in 1965, he proposed an aperture synthesis system using one antenna on the surface and two on orbit [31].

1985: Douglas & Smith  After the RAE observations (Section 1.3.2), more serious considerations began when James Douglas and Harlan Smith [32] presented a very low frequency radio astronomy observatory on the Moon at the Lunar Bases and Space Activities of the 21st Century conference. In addition to the advantages of the Moon over free space, they considered the limiting factors, design, and the establishment of the observatory.

1988: First workshop on lunar VLF array

After Douglas and Smith presented their ideas at the 1986 workshop Future Astronomical Observatories on the Moon [3], the VLF array became clearly one of the most interesting and important observatory concepts [33]. In 1988, a workshop was held specifically to
consider this concept: *A Lunar Far-Side Very Low Frequency Array* [34]. This meeting of 16 participants laid most of the foundations of this subject [12, 35, 36, 37, 38, 39, 13].

Jack Burns [33] pointed out that the far-side VLF array would likely be a project for the second phase of NASA’s lunar base scenario (around 2007), but that planning for such large projects takes a long time. As an example, he mentioned that it took almost 30 years, from the first NASA-sponsored meetings on space telescopes in 1962, until the Hubble Space Telescope would finally be a reality.

The meeting concluded with a general consensus that the scientific motivation for low frequency astronomy is potentially very strong, but James Douglas emphasized the need to strengthen the case much further. They also agreed that the lunar far side is the only viable location within the inner solar system for sensitive VLF astronomical observations and that a lunar array is technically feasible. For further investigations, the consensus was that a design study should be conducted and precursor missions planned.

**1990-1992: Observatory concepts in evolutionary sequence**

After the workshop on the far side array, the effort was focused on more near-term precursor missions. These ideas were presented at the international workshops on *Low Frequency Astrophysics from Space* [40] and *Astrophysics from the Moon* [7]. The investigated concepts included a lunar orbiting observatory by Burns and Basart [41, 42], a lunar near side array by a Jet Propulsion Laboratory team [43, 44, 45], and a lunar far side array by Basart and Burns [46, 47]. Dayton Jones [48] outlined an evolutionary sequence for low frequency astronomy analogous to the progression of infrared and X-ray astronomy missions. Smith [49] also envisioned similar development stages of lunar VLF observatory program, stressing that it can and should begin with the first lunar lander. He also imagined the possibility of accessing the back side observatory site by rovers from a lunar base near the limb.

**1990s: Design studies**

The prospect for astronomy from the Moon was becoming increasingly promising. During the 1990s, at least three groups conducted major design studies for the lunar far side VLF array concept. Equally relevant and perhaps the most detailed was the space-based Astronomical Low Frequency Array (ALFA) proposal to NASA.

**1992: Astronomical Lunar Low Frequency Array (Hughes)** The first serious design study of a lunar far side array was conducted by the Hughes Aircraft Company [50]. This study included a detailed engineering design and an 8-year schedule leading to a launch by the year 2000 [51].
1993: International Lunar Farside Observatory and Science Station (ISU)  
The next comprehensive design study was conducted by the International Space University in a design project directed by Wendell Mendell [52]. They proposed a phased approach including a precursor orbiter, preliminary 5-element array, and a final 300-element array. In addition, this study considered the political and legal aspects, organization, management, cost, funding, marketing, and cost-benefit trades.

1997: Very Low Frequency Array on the Lunar Far Side (ESA)  
Based heavily on work by Jean-Louis Bougeret [17] and Graham Woan [53], ESA sponsored a one-year design study by a team of nine experts [16]. This was probably the most recent and scientifically comprehensive study to date. “This study... showed the feasibility of the project within the framework of Phase III of the ESA Moon program: ‘science from the moon’. Before the mission can be started, however, a number of in-situ measurements need to be performed to confirm certain environmental conditions.”

1998: Astronomical Low Frequency Array (JPL, NRL, GSFC)  
In 1998, an array in a distant orbit of the Earth was proposed to NASA for the Medium Explorer mission ($150M) [28]. The proposal included useful details about data analysis and archiving, including the array configuration, cross-correlation, side-lobe / interference suppression, calibration, sensitivity, dynamic range, and imaging. Although very close, the proposal was not selected because the science was rated as only “very good” but not “excellent” and because NASA estimated the cost to be too high [27].

Continuing effort and challenges  
Even while working on the free-flying ALFA, member of the proposal team continued promoting the Moon-based concepts. Jones and Weiler [54] reiterated the advantages of the Moon and suggested “semi-hard” landings as inexpensive means of the antenna deployment. Basart et al examined important issues of sensitivity, interference constraints on imaging, baseline calibration, and mapping difficulties associated with wide-field imaging [14], and suggested how these issues could be resolved as the VLF observation evolves toward the lunar surface arrays [55]. At the conference on Space Based Radio Observations at Long Wavelengths in 1998, Weiler [56] addressed some technical challenges of space- based and moon-based radio array while Kuiper and Jones [57] brought up some engineering challenges of lunar surface arrays. Woan [58, 59] reviewed the capabilities and limitations of space- based and moon-based observations at long wavelengths and stressed the need to resolve the questions about lunar electrical environment. Investigations into VLF observatories on the Moon have also been conducted in Japan [60].
2.2 Observational considerations

Figure 2.1 shows constraints imposed in radio astronomy.

![Angular Resolution in Radioastronomy](image)

Figure 2.1: Angular resolution as a function of radio frequency, including dependence on interplanetary/interstellar scattering and interferometer baselines. From Bougeret (1996) [17]

**Low frequency limits** The interplanetary plasma around the Earth due to the solar wind has a cut-off frequency of $\sim 30$ kHz, which will limit the lowest observable frequency [16]. Another limiting factor may be the lunar ionosphere if it exists with enough concentration. The plasma cut-off frequency $\nu_p$ depends on the electron number density
\( n_e: \nu_p(\text{MHz}) \approx \sqrt{n_e(\text{cm}^{-3})}/100. \) As long as the electron number density in the lunar ionosphere is \(< 100e^-/\text{cm}^3\), the corresponding cut-off frequency would be lower than 100 kHz.

**Baseline length**  Figure 2.1 shows how interplanetary and interstellar scattering and the observatory baseline determine the achievable angular resolution at various radio frequencies. For example, interstellar scattering broadens an extragalactic point source to \(1/3^\circ\) at 1 MHz. More serious is the interplanetary scattering that broadens an extrasolar point about 5 times more. Angular broadening due to the interplanetary medium (IPM) and the interstellar medium (ISM), respectively, as a function of radio wave frequency \(\nu\) (in MHz) are, according to Woan [53]:

\[
\theta_{\text{IPM}} \sim \frac{100}{\nu_{\text{MHz}}^2} \text{arcmin}
\]
\[
\theta_{\text{ISM}} \sim \frac{22}{\nu_{\text{MHz}}^2} \text{arcmin}
\]

The IPM scattering-limited resolution of a VLF array determines the maximum useful baseline \(D\) (at least for targets directly overhead):

\[
D \sim \frac{1000}{\theta_{\text{arcmin}} \nu_{\text{MHz}}} \text{km} \sim 10\nu_{\text{MHz}} \text{km}.
\]

Ironically, the maximum useful baseline depends on the highest frequency to be observed at. To achieve the highest possible resolution at the ionospheric cut-off of about 20 MHz, the array should span a few 100 km, but no more. Since the galaxy is at least partially opaque below 1 MHz (due to free-free absorption), 1 MHz is about the lower limit for extragalactic and many galactic observations. Achieving the scattering-limited resolution of \(1\sim2^\circ\) at 1 MHz is desirable for significant advances in science.

**Scientific observation goals**  In relation to the observational limitations, practical science goals of the VLF array can be defined. The strong non-thermal galactic background makes the signal-to-noise ratio (S/N) independent of receiver noise. Also, the inhomogeneous interstellar medium prevents linear polarization studies (except for the closest sources). A precursor all-sky survey at very low frequencies will guide us significantly in defining the scientific goals for the future.

Possible research effort may be categorized as follows [12]:

- 1-30 MHz: High-resolution all-sky survey
- 10-30 MHz: Discrete sources (galactic, extragalactic)
- \(\sim 1\) MHz: Interstellar medium studies (absorption, scintillation)
- \(\lesssim 1\) MHz: Solar / planetary studies
Woan in the ESA study [16] specified the baseline requirements for all sky survey at 0.5-16 MHz. Mapping will take \(\sim\)2 weeks. Left and right hand circular polarizations shall be separately recorded.

2.3 Observatory design

The first array Douglas and Smith [32] proposed was merely short wires laid on the lunar surface. They envisioned that an early array may be a 15 km \(\times\) 30 km T-array with 300 elements. This could then evolve into a filled array of 100\(\times\)100 elements. A denser array can be used for short wavelength operation.

An aperture synthesis array seems to be preferred over a scanning phased array because, although imaging takes longer with aperture synthesis, it offers better beams with lower sidelobes, more flexibility in the array configuration with less number of elements, much simpler phasing, and more reliable operation [37].

Electrically short dipole antennas would be sufficient because the system temperature will be limited by the sky brightness. Dipoles antennas should be short compared to the observing wavelength to keep the antenna pattern generally similar with no sidelobes throughout the entire frequency range [37]. For example, a 1-metre dipole would be only 1/10 the wavelength even at 30 MHz. To improve the directivity, Basart and Burns [37] suggested that dipole antennas could be grouped into 2\(\times\)2 mini-arrays in phase. Since polarization measurements are unnecessary for extrasolar observations, dipoles may be single or crossed. Figure 2.2 shows an example of a crossed dipole antenna unit.

According to Woan in the ESA study [16], S/N of about 200 is achievable at 1 MHz with 300 elements after integrating over half the lunar day (\(\sim\)2 weeks). S/N of 200 is sufficient and possibly the upper limit because of uncertainty in side-lobe levels. Woan [53] proposed a spiral Y array for sampling the transform plane uniformly while keeping the filling factor high for shorter baselines for higher frequencies.

Douglas and Smith [32] expected that establishing such an array of many short dipoles would be extremely simple and economic with low power requirement. Each antenna (short wire) could weigh only 50 grams, with a total being only <50 kg. Relative positions of antennas need to be known to only a metre precision.

**Site** Jeffrey Taylor [38] identified several site selection criteria for the Moon-based observatory:

- Lunar librations and diffraction of radio waves limits the minimum distance from the lunar limb.

- For line-of-sight communications among the array elements and for deployment vehicles, smooth surface is required.
Figure 2.2: A crossed-dipole antenna in ESA’s design [16]. Each element can be packaged in a $25 \text{ cm} \times 25 \text{ cm} \times 25 \text{ cm}$ box.

- The observatory site should be at least $10\sim100$ km from active mining sites to avoid artificial atmosphere.
- For viewing planets, polar sites are inappropriate because all the planets will be near the horizon.
- The large crater Tsiolkovsky ($20^\circ\text{S}, 130^\circ\text{E}$) is an excellent candidate, with over $100$ km of relatively smooth floor.

2.4 Precursor missions

Taylor and Burns [39] suggested preliminary studies for precursor missions to:

- Measure the lunar ionosphere (with short tunable dipole antennas),
- Survey the low-frequency sky (0.5 - 30 MHz),
- Study signal propagation effects through the interstellar medium.

**Lunar Observer Radio Astronomy Experiment (LORAE)**  In 1990, Burns [41] proposed to put simple lightweight, low power crossed-dipole antenna on board the then-planned Lunar Observer orbiter around the Moon. Such experiment would be valuable for conducting lunar occultation studies of the brightest sources and a low-resolution all-sky survey while on the far side.

**Lunar near side array**  A team at the Jet Propulsion Laboratory [43] proposed a compact array to be placed on the near side during the early lunar expeditions. Such
project would be able to verify deployment and data handing, study the auroral kilometric radiation and solar bursts during the day, and map the sky during the night.

Deployment stages  Douglas [13] suggested a possible sequence of missions:

- Lunar orbiter receiver
- Early landers with several elements
- 10 elements over 5 - 10 km (robotic deployment tests)
- 100 elements over $\sim$20 km
- 1000 elements hard-landed

2.5 Design studies

Table 2.1 summarizes the major design studies described above. All the lunar array designs chose the Earth-Moon Lagrange point L2 for relay satellite. L2 relay satellite would provide a continuous link with minimum tracking requirement [16].

2.6 Current consensus

These design studies and workshops, as well as other studies at JPL and NRL, have resulted in the following general consensus:

- The scientific case for VLF astronomy is established, but astronomers must advocate interest.
- The best approach is to map the sky by aperture synthesis using an array of short dipole antennas.
- Certain lunar environmental factors must be verified, including the absence of significant ionosphere.
- Tsiolkovsky Crater seems to be the best candidate site for the far side array.
- A lunar far side array is feasible with current technology, but it is unlikely to be funded until access to the lunar far side becomes easier through other programs.
- The VLF astronomy program should take a phased approach, beginning with less expensive missions.
Table 2.1: Summary of very low frequency array designs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hughes</td>
<td></td>
<td>ISU</td>
<td>ESA</td>
<td>JPL,NRL,GSFC</td>
</tr>
<tr>
<td>Site</td>
<td>Chaplygin</td>
<td>Tsiolkovsky</td>
<td>Tsiolkovky</td>
<td>10^6 km orbit</td>
</tr>
<tr>
<td></td>
<td>(137 km crater,</td>
<td>(100 km crater,</td>
<td>(100 km crater,</td>
<td>(2.6× further</td>
</tr>
<tr>
<td></td>
<td>5°S, 150°E)</td>
<td>20°S, 129°E)</td>
<td>20°S, 129°E)</td>
<td>than Moon)</td>
</tr>
<tr>
<td># elements</td>
<td>40</td>
<td>5 → 300</td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>Aperture</td>
<td>25 km</td>
<td>100 m → 17 km</td>
<td>40 km</td>
<td>100 km</td>
</tr>
<tr>
<td>Layout</td>
<td>Ellipse</td>
<td>Circular area</td>
<td>Spiral Y</td>
<td>Spherical</td>
</tr>
<tr>
<td>Antenna</td>
<td>0.3-m crossed dipoles</td>
<td>1-m single dipoles</td>
<td>4-m crossed dipoles</td>
<td>5-m crossed dipoles</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.1 - 30 MHz</td>
<td>1, 3, 10, 30 MHz</td>
<td>0.5 - 16 MHz</td>
<td>0.3 - 30 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>100 - 1000 kHz</td>
<td>50 kHz</td>
<td>100 kHz</td>
<td>~ 125 kHz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>10 Jy (1 day)</td>
<td>-13 dB</td>
<td>S/N = 50 ~ 200</td>
<td>50 Jy (1 hour) @ 10 MHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>2 ortho linear</td>
<td>-</td>
<td>2 circular</td>
<td>-</td>
</tr>
<tr>
<td>Lifetime</td>
<td>12 years</td>
<td>10 years</td>
<td>5 years</td>
<td>2 years</td>
</tr>
<tr>
<td>Array</td>
<td>1600 kg</td>
<td>400 kg</td>
<td>1320 kg</td>
<td></td>
</tr>
<tr>
<td>Launch</td>
<td>8200 kg (Titan IV)</td>
<td>$2500 kg (Titan IV)</td>
<td>2720 kg (Ariane 5)</td>
<td>Delta 7425</td>
</tr>
<tr>
<td>Lander</td>
<td>4900 kg</td>
<td></td>
<td>1400 kg</td>
<td></td>
</tr>
<tr>
<td>Rover</td>
<td>750 kg</td>
<td>2600 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relay sat.</td>
<td>950 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.7 Next steps toward realization

What can we do now to build upon the foregoing effort and make the VLF astronomy from the Moon a reality? We should reinforce the scientific motivation, reaffirm the need for the Moon (Chapter 3), propose an affordable VLF array for an initial sky survey (Chapter 4), and ensure that the necessary measurements will be made as early as possible to support the first lunar array proposal (Chapter 5).

Since the root motivation for the VLF array is science, we must arouse people’s interest in the significant discovery potential of a VLF study of the universe. Burns [33] suggested that we should develop stronger quantitative theoretical arguments for VLF observations by working with theoreticians to make predictions with specific observational signatures. It will be very instructive to model observations with a theoretical array. For this, an initial survey will be very valuable to find out what kinds of targets
exist at low frequencies. VLF astronomy is at a stage similar to where x-ray and infrared astronomy was back in the 1970s.

Currently the low frequency radio astronomy community seems to be waiting for the ground based Low Frequency Array (LOFAR) to revive the general interest in this field. LOFAR [9] will attempt to observe at frequencies as low as 10 MHz, and is planned to begin operating around 2006.
Chapter 3

Confirmation of Lunar Advantage

As stated above, the case for a lunar VLF array can be strengthened by confirming the advantages of the Moon, namely its effectiveness as a shield and a platform. To verify the shielding of radio interference by the Moon, we must find out how much the VLF interference is attenuated at various locations on the Moon. To validate the lunar surface as an acceptable platform for the VLF array, we must ensure that the lunar surface environment does not present any major disadvantages to VLF observations. The only way to definitely verify these is by placing antennas on the lunar surface to make direct measurements. A more economical alternative is to simulate these measurements with a computer using known or estimated properties of the Moon.

To address various issues relevant to the VLF astronomy project, a general finite-difference time-domain tool was developed to simulate electromagnetic wave propagation in the lunar environment. In addition to helping verify the advantages, the estimates from this simulation should be very informative and helpful in selecting the site for the VLF array. The shielding effect is expected to depend on the location on the Moon. Thus, this study will help choose a suitable site. It will also help specify required measurements for validating potential sites. This study aims to help choose a site where the observatory can definitely take advantage of both the interference shielding and the lunar platform.

The simulation seemed to show that, even for a very low frequency of 50 kHz, radio waves are attenuated by at least 12 orders of magnitude on the lunar surface further than \(\sim 30^\circ\) behind the limb. Similar simulations at higher frequencies confirmed that the attenuation improves at shorter wavelengths.

3.1 Questions to resolve

To verify definite advantage over free-flyer before developing a Moon-based array, the 1997 ESA report [16] listed several questions to be resolved about the lunar environment, especially at candidate sites:
• Verification of the Earth noise attenuation
• Ionosphere (electron density, scale height)
• Magnetic field (its containing effects due to interaction with local plasma)
• Surface electrical properties (permittivity & conductivity → antenna beam shape)
• Subsurface reflections (sounding)
• Topology (0.5 m altitude resolution over 10-m grid size)

3.1.1 Shielding of interference

The most important motivation for the Moon as a site for radio astronomy is its ability to shield interference, as explained in Section 1.3.2. It is therefore critical to verify this effect with a rigor in relation to the desired performance of VLF observations. We shall evaluate how radio observatory on the far side of the Moon will perform in terms of the interference from the terrestrial kilometric radiation and man-made signals. Although the Radio Astronomy Explorer 2 roughly verified the disappearance of terrestrial noise behind the Moon, some waves with very long wavelengths could diffract around the lunar limb. For example, in the occultation experiments of both the Earth (Figure 1.9) and the Sun (Figure 3.1), some interference is observed near the beginning and the end of the geometrical occultation, especially at lower frequencies. This may be not only because of the larger source size but also because of diffraction at longer wavelengths.

For high sensitivity observations, the interference should be attenuated by much more than a few orders of magnitude. Even if the flux of diffracted waves is below the background noise level, an interferometer could pick up the noise if coherent. To ensure that required performance is feasible, it is crucial to find out quantitatively how much the radio interference is attenuated at various locations on the Moon and depending on the radio frequency.

We may then very roughly constrain the allowable location for the observatory by comparing the attenuated noise to the galactic background level. Such information will help constrain the location of sufficient shielding, that is, how far into the far side to situate the observatory. The attenuation levels shall be examined at candidate sites, including craters Tsiolkovsky, Aitken, and Daedalus.

3.1.2 Lunar ionosphere

The reason astronomers have not been able to explore the VLF range is the ionosphere of the Earth with a plasma cut-off frequency of \( \sim 10 \text{ MHz} \). This cut-off corresponds to an electron number density of \( \sim 10^6 / \text{cm}^3 \). If the Moon also has an “ionosphere”, it could prevent radio observations below a certain cut-off frequency and limit the resolution
even at higher frequencies because of scattering. The plasma cut-off frequency in MHz depends on the electron number density roughly by:

$$\nu_p(\text{MHz}) \approx \sqrt{\frac{n_e(\text{cm}^{-3})}{100}}.$$ 

In 1971, measurements by the Apollo 14 Charged Particle Lunar Environment Experiment (CPLEE) detected an electron concentration as high as $10^4/\text{cm}^3$ over several hundred metres in altitude during the lunar day [61]. This corresponds to a cut-off frequency as high as 1 MHz. During the lunar night, the surface potential was observed to become negative, as shown in Figure 3.2, reducing the plasma density.

During the mid-1970s, dual-frequency radio occultation experiments by the Luna 19 and the Luna 22 orbiters were conducted to infer the electron concentrations on the sunlit side (Figure 3.3) [63, 64]. Their preliminary analysis showed peak electron concentrations above the sunlit surface of 500~1000 cm$^3$. This could limit astronomical observations to only above $\sim$0.3 MHz.

Investigation of the ionosphere near the lunar surface is critical and the most urgent in determining the lowest observable frequency at various times of the lunar day and
The negative surface potential in the night side would likely keep electrons away. It could be possible using lunar orbiter missions, if not ground-based observations.

### 3.1.3 Lunar surface

So long as we take advantage of the lunar surface as an observatory platform, we must verify that the properties of the surface itself does not pose any significant disadvantages.

**Surface electrical properties**

Properties of the lunar surface that will directly influence radio wave propagation are electric permittivity and conductivity. Compared to free space, the lunar surface has relative permittivity $\varepsilon_r$ ranging 2~10 and very low but finite electrical conductivity $\sigma$ ranging $10^{-14} \sim 10^{-9}$ [4]. The difference in permittivity between the vacuum and the surface results in some reflection of the incident wave. This reflection should not be a problem for antennas laid directly on the surface. Unlike on the Earth, the lunar surface is a good insulator so that the antennas can lie on the ground and receive the electric field parallel to the surface.

The finite conductivity results in a slow loss of the transmitted wave with depth. This loss is characterized by the loss tangent $L$, defined as the ratio of the imaginary to the real part of the complex dielectric permittivity:

$$L = \frac{\sigma}{\omega\varepsilon_r\varepsilon_0}.$$
Figure 3.3: Day-side lunar ionosphere profile, as inferred from the Luna 19 and 22 measurements. The data point uncertainty is ±200/cm³. The apparent drop near the surface may not be statistically significant. From Vyshlov 1976 [63], adapted by Woan 2000 [59].

where \( \omega \) is the wave frequency and \( \varepsilon_0 \) is the permittivity of free space. For the lunar surface, the loss tangent is found to be typically 0.001~0.1 [4]. The rate of loss in the conductive medium is characterized by the skin depth \( \delta \), which is the depth at which the field amplitude has decayed by a factor of \( e \). For \( L << 1 \), the skin depth is [53]:

\[
\delta \approx \frac{\lambda}{\pi \sqrt{\varepsilon_r} L},
\]

where \( \lambda \) is the wavelength in vacuum.

**Subsurface reflections**

With \( \sqrt{\varepsilon_r} \approx 3 \) and \( L \) ranging 0.001~0.1 for the lunar regolith, the low frequency radio waves would be able to penetrate into the lunar regolith to depths of the order 1~100 times the wavelength before attenuating much. Woan in the ESA study [16] pointed out that dipole antennas on the lunar surface could pick up unwanted reflections off of
subsurface discontinuities. If there are any sharp discontinuities in electrical property below the surface, the penetrated waves could reflect off and be picked up by the antennas from beneath as noise [53]. Dipole antennas with almost no directivity would not be able to distinguish such subsurface reflections from the normal waves coming from above. We should therefore choose a site free of significant subsurface reflections by discontinuities such as the regolith-crust boundary and mass concentrations. Large craters are the primary candidates for VLF arrays, but careful sounding of subsurface structures is essential before selecting the exact site (see Figure 3.4).

![Figure 3.4: Typical upper lunar crust structures under a large crater [4].](image)

In summary, this study aims to address the following questions:

- How much would the radio interference be attenuated at various locations on the lunar far side (for various wavelengths)? In particular, how much would the terrestrial interference be attenuated at candidate sites?

- As observed from candidate sites, what direction does the terrestrial interference come from, and how coherent are they?

32
• Does the lunar “ionosphere” influence the observations?
• How might the subsurface structures reflect radio waves to affect the observation?
• How well would a tall mountain shield the terrestrial interference?

3.2 Studies using radio wave simulation

To investigate the above issues and other potential matters related to radio observations from the Moon, a numerical program was developed that can simulate wave propagation in any relevant media. This section describes the approach used to simulate the wave propagation, lunar electrical properties, lunar ionosphere, and interferometric observations.

3.2.1 Radio wave simulation

The simulation of electromagnetic waves was based on the following laws for induction of electric ($E$) and magnetic ($H$) fields in static, linear, isotropic media:

\[-\nabla \times E = \mu \dot{H}\]
\[\nabla \times H = \varepsilon \dot{E} + \sigma E\]

where $\mu \approx \mu_0$ is the magnetic permeability, $\varepsilon$ is the electric permittivity, and $\sigma$ is the electric conductivity of the medium.

Scalar wave simulation

Taking the curl of the first and the time derivative of the second and combining them, a wave equation is obtained:

\[\nabla^2 E - \nabla (\nabla \cdot E) = \frac{1}{c^2} \left( \frac{\sigma}{\varepsilon_0} \dot{E} + \varepsilon_r \ddot{E} \right),\]

where $1/c^2 = \mu_0\varepsilon_0$ ($\mu_0$ and $\varepsilon_0$ are respectively the magnetic permeability and electric permittivity of free space) and $\varepsilon_r$ is the relative permittivity (dielectric constant).

For simplicity, simulation with a scalar field could provide the roughest approximation for propagation of unpolarized electromagnetic waves. In this case, $\nabla \cdot E = 0$ and the scalar wave equation is:

\[\nabla^2 E = \frac{1}{c^2} \left( \frac{\sigma}{\varepsilon_0} \dot{E} + \varepsilon_r \ddot{E} \right).\]
**Finite-difference time-domain method** This wave equation was solved numerically with a finite-difference method. Using the 2nd-order finite difference in time (with step size $\Delta t$), the temporal derivatives are:

$$\dot{E} = \frac{E(t + \Delta t) - E(t - \Delta t)}{2\Delta t} + O[(\Delta t)^2].$$

$$\ddot{E} = \frac{E(t + \Delta t) - 2E(t) + E(t - \Delta t)}{(\Delta t)^2} + O[(\Delta t)^2].$$

Applying these to the wave equation,

$$\nabla^2 E \approx \frac{1}{c^2} \left( \frac{\sigma}{2\varepsilon_0 \Delta t} [E(t + \Delta t) - E(t - \Delta t)] + \frac{\varepsilon_r}{(\Delta t)^2} [E(t + \Delta t) - 2E(t) + E(t - \Delta t)] \right).$$

This can be solved to obtain an expression for updating the field value:

$$E(t + \Delta t) \approx \left( \frac{\sigma \Delta t - \varepsilon_r}{\frac{\sigma \Delta t}{\varepsilon_0} + \varepsilon_r} \right) E(t) + \left( \frac{\varepsilon_r (\Delta t)^2}{\frac{\sigma \Delta t}{\varepsilon_0} + \varepsilon_r} \right) \nabla^2 E,$$

where $\nabla^2 E$ can also be discretized by finite differencing the spatial derivatives to 2nd order under a suitable coordinate system.

With rectangular coordinate system in 2 dimensions, $\nabla^2 E = \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2}$. Taking equal spatial step sizes ($\Delta x = \Delta y = \Delta s$),

$$\nabla^2 E \approx \frac{1}{(\Delta s)^2} \left[ E(x + \Delta x, y) + E(x, y + \Delta y) - 4E(x, y) + E(x - \Delta x, y) + E(x, y - \Delta y) \right].$$

For investigation of the Moon’s shielding effects, the terrestrial interference was simulated as a plane wave incident on a spherical Moon with radially symmetric electrical properties. This problem has a cylindrical symmetry with respect to an axis parallel to the direction of the plane wave propagation. Thus, the cylindrical coordinate system $(\rho, \phi, z)$ was chosen, in which $\nabla^2 E = \frac{1}{\rho} \frac{\partial E}{\partial \rho} + \frac{\partial^2 E}{\partial \phi^2} + \frac{\partial^2 E}{\partial z^2}$ with azimuthal symmetry.

After the initial values of the field components were specified at every grid point, the fields can be evolved in time according to these equations. The spatial step size was chosen to sample the simulated wave sufficiently so that the intensity of the wave remains reasonably un-dispersed while it propagates in free space. With the present algorithm, at least 6 spatial intervals per wavelength were desired: $\Delta s \leq \lambda/6$. The temporal step size was limited by the stability condition for 2-dimensional finite difference algorithm [65]: $\Delta t \leq \frac{\Delta s}{c\sqrt{2}}$. It was chosen to be half of the spatial step size in units where $c = 1$: $\Delta s$ in [metre] and $\Delta t$ in [1 metre / c = 3.33564 nanoseconds]. Also, $\varepsilon$ and $\mu$ were treated as relative permittivity and relative permeability, respectively, interpreting the values of electric and magnetic fields accordingly.

**Plane wave source** For simplicity, radio interference was initially simulated as a plane wave coming from a certain direction. To simulate an incident plane wave in vacuum, an oscillatory excitation of unit amplitude, $\sin(\omega t)$, was superposed into the field along one of the edges of the computational zone throughout the period of simulation.
Boundary  As with any simulation in a finite grid space, the computational boundary must simulate the rest of the space. This program employs a damping zone in which the conductivity gradually increases so that the waves are absorbed very gradually to minimize reflections. Since our problem is cylindrically symmetric, only half of the cross-section of the Moon is required in the simulation. This half was put against the bottom of the grid space and a symmetric boundary was employed for that side.

In the scalar wave simulation, the term in equation (3.3) with the gradient $\nabla(\nabla \cdot E)$ has no contribution. However, in a real vector field, this term may not be negligible. In source-free media, $\nabla \cdot (\varepsilon E) = \varepsilon \nabla \cdot E + E \cdot \nabla \varepsilon = 0 \implies \nabla \cdot E = -\frac{1}{\varepsilon} E \cdot \nabla \varepsilon$. At the lunar surface $\nabla \varepsilon$ is vertical; thus, this term would be especially important for vertical component of electric field, that is, for waves at grazing incidence [66].

Vector wave simulation

To overcome the above concern and to ensure accuracy, a vector wave simulation was also developed. In terms of the vector components, equations (3.1) and (3.2) are:

$$
- \left( \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \right) = \mu \frac{\partial H_x}{\partial t}
$$

$$
- \left( \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} \right) = \mu \frac{\partial H_y}{\partial t}
$$

$$
- \left( \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \right) = \mu \frac{\partial H_z}{\partial t}
$$

$$
\left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) = \varepsilon \frac{\partial E_x}{\partial t} + \sigma E_x
$$

$$
\left( \frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial z} \right) = \varepsilon \frac{\partial E_y}{\partial t} + \sigma E_y
$$

$$
\left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right) = \varepsilon \frac{\partial E_z}{\partial t} + \sigma E_z.
$$

For simplicity, the transverse electric (TE) mode and the transverse magnetic (TM) mode were considered separately. For example, in TE mode having only $(E_x, E_y, H_z)$ components:

$$
\mu \frac{\partial H_z}{\partial t} = \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x},
$$

$$
\varepsilon \frac{\partial E_x}{\partial t} + \sigma E_x = \frac{\partial H_z}{\partial y},
$$

$$
\varepsilon \frac{\partial E_y}{\partial t} + \sigma E_y = - \frac{\partial H_z}{\partial x}.
$$

(3.4)
Finite-difference time-domain method  With these equations, the propagation of wave in time was simulated using the finite-difference time-domain method [67] in 2 dimensions. See the “vacuum” region of Figure 3.6 for the peculiar setup of a grid for the electric and magnetic field components. The location of the fields within the grid in this method implicitly enforces the zero-divergence of both electric and magnetic fields in a source-free space [65].

The notation $H^s_z(i,j)$, for example, is used for the value of the $z$-component of magnetic field at position $(x = i\Delta x, y = j\Delta y)$ and time $t = n\Delta t$, where $\Delta x$ and $\Delta y$ are spatial intervals between grid points in the $x$- and $y$-coordinates, respectively, and $\Delta t$ the temporal step size in the iteration. $H^s_z(i,j) \equiv H_z(x = i\Delta x, y = j\Delta y, t = n\Delta t)$. Using this discretization, the temporal and spatial derivatives as well as the time average are:

$$
\frac{\partial H^s_z}{\partial t} = \frac{H^{n+\frac{1}{2}}_z - H^{n-\frac{1}{2}}_z}{\Delta t} + O[(\Delta t)^2]
$$

$$
\frac{\partial H^s_z(i)}{\partial x} = \frac{H_z(i + \frac{1}{2}) - H_z(i - \frac{1}{2})}{\Delta x} + O[(\Delta x)^2]
$$

$$
H^n_z = H^{n+\frac{1}{2}}_z + H^{n-\frac{1}{2}}_z + O[(\Delta t)^2].
$$

With $\Delta x = \Delta y = \Delta s$, the 3 equations for TE mode (3.4) can then turn into equations for updating each field value, with 2nd-order accuracy in space and time:

$$
H^{n+\frac{1}{2}}_z(i + \frac{1}{2}, j + \frac{1}{2}) \approx H^{n-\frac{1}{2}}_z + \frac{\Delta t/\Delta s}{\mu} [E^n_x(j+1) - E^n_x(j) - E^n_y(i+1) + E^n_y(i)]
$$

$$
E^{n+1}_x(i + \frac{1}{2}, j) \approx \frac{\varepsilon - \sigma \Delta t/2}{\varepsilon + \sigma \Delta t/2} E^n_x + \frac{\Delta t/\Delta s}{\varepsilon + \sigma \Delta t/2} [H^{n+\frac{1}{2}}_z(i + \frac{1}{2}) - H^{n-\frac{1}{2}}_z(j - \frac{1}{2})]
$$

$$
E^{n+1}_y(i, j + \frac{1}{2}) \approx \frac{\varepsilon - \sigma \Delta t/2}{\varepsilon + \sigma \Delta t/2} E^n_y - \frac{\Delta t/\Delta s}{\varepsilon + \sigma \Delta t/2} [H^{n+\frac{1}{2}}_z(i + \frac{1}{2}) - H^{n+\frac{1}{2}}_z(i - \frac{1}{2})].
$$

(For terms on the right, only those indexes that differ from the indexes of the terms on the left are labeled.) Details of this algorithm can be found online [65]. Here, the values of $\mu, \varepsilon, and\sigma$ should reflect the property of the medium at the location of each grid point. In vacuum ($\sigma = 0$), these equations are much simpler. The spatial and temporal step sizes were chosen as with the scalar wave simulation, to sample the simulated wave sufficiently.

Plane wave source  To simulate an incident plane wave in vacuum, an oscillatory excitation of unit amplitude, $\sin(\omega t)$, was superposed into one of the electric field components $E_x$ along one of the edges of the computational zone ($j = j_0$):

$$
E^{n+1}_x(i, j_0) = \sin(\omega t) + E^n_x + \frac{\Delta t}{\Delta s} [H^{n+\frac{1}{2}}_z(j_0 + \frac{1}{2}) - H^{n+\frac{1}{2}}_z(j_0 - \frac{1}{2})].
$$
Boundary To eliminate reflections at the computational boundary, the perfectly matched layer (PML) technique [68] was used (Figure 3.5). In this technique, the electric induction law is modified to include the “magnetic current density”, which is not physical but will be useful in creating computational boundaries:

\[-\nabla \times \mathbf{E} = \mu \dot{\mathbf{H}} + \sigma^* \mathbf{H},\]

(3.5)

where \(\sigma^*\) may be referred to as the “magnetic conductivity”. This technique is based on the observation that no reflection occurs for a normally incident wave if the medium’s impedance matches that of vacuum, which requires:

\[\frac{\sigma^*}{\sigma} = \frac{\mu_0}{\varepsilon_0} \quad \text{or} \quad \frac{\sigma^*}{\mu_0} = \frac{\sigma}{\varepsilon_0}.\]

In transverse-electric (TE) mode components, the above equation 3.5 for electric induction is:

\[-\left( \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \right) = \mu \frac{\partial H_z}{\partial t} + \sigma^* H_z.\]

For the boundary to be perfectly absorbing for any incident angle, this technique requires splitting the magnetic field within the absorbing layer surrounding the computational region \((H_z = H_{xx} + H_{xy}; \text{see Figure 3.6})\) in such a way that:

\[\mu \frac{\partial H_{xx}}{\partial t} + \sigma^* H_{xx} = -\frac{\partial E_y}{\partial x},\]

\[\mu \frac{\partial H_{xy}}{\partial t} + \sigma^* H_{xy} = \frac{\partial E_x}{\partial y}.\]
\[
\begin{align*}
\epsilon \frac{\partial E_x}{\partial t} + \sigma_y E_x &= \frac{\partial H_z}{\partial y} \\
\epsilon \frac{\partial E_y}{\partial t} + \sigma_x E_y &= -\frac{\partial H_z}{\partial x}.
\end{align*}
\]

Then the finite-difference equations in the absorbing layer are [68]:

\[
\begin{align*}
H_{zx}^{n+\frac{1}{2}}(i + \frac{1}{2}, j + \frac{1}{2}) &= e^{-\sigma_y^* \Delta t/\mu_0} H_{zx}^{n-\frac{1}{2}} - \frac{1 - e^{-\sigma_y^* \Delta t/\mu_0}}{\sigma_y^* \Delta s} [E_y^n(i + 1) - E_y^n(i)] \\
H_{zy}^{n+\frac{1}{2}}(i + \frac{1}{2}, j + \frac{1}{2}) &= e^{-\sigma_y^* \Delta t/\mu_0} H_{zy}^{n-\frac{1}{2}} + \frac{1 - e^{-\sigma_y^* \Delta t/\mu_0}}{\sigma_y^* \Delta s} [E_x^n(j + 1) - E_x^n(j)] \\
E_x^{n+1}(i + \frac{1}{2}, j) &= e^{-\sigma_x \Delta t/\varepsilon_0} E_x^n + \frac{1 - e^{-\sigma_x \Delta t/\varepsilon_0}}{\sigma_x \Delta s} [H_z^{n+\frac{1}{2}}(j + \frac{1}{2}) - H_z^{n+\frac{1}{2}}(j - \frac{1}{2})] \\
E_y^{n+1}(i, j + \frac{1}{2}) &= e^{-\sigma_x \Delta t/\varepsilon_0} E_y^n - \frac{1 - e^{-\sigma_x \Delta t/\varepsilon_0}}{\sigma_x \Delta s} [H_z^{n+\frac{1}{2}}(i + \frac{1}{2}) - H_z^{n+\frac{1}{2}}(i - \frac{1}{2})].
\end{align*}
\]

Figure 3.6: The upper right corner of the finite-difference time-domain computational grid, with a perfectly matched layer (PML) at the boundary [68].

To minimize numerical reflections, the conductivity in the absorbing layer is smoothly increased outward to a maximum value: \( \sigma(\rho) = \sigma_{\text{max}} (\rho/\delta)^n \), where \( \rho \) is the distance into the layer of thickness \( \delta \) and \( n \) is a power factor. In this study, a parabolic profile \( (n = 2) \) was used. The maximum value of the conductivity (at the outermost edge) was chosen based on the acceptable amount of reflection. The amplitude of the reflected wave depends on \( \int_0^\delta \sigma(\rho) d\rho = \sigma_{\text{max}} \delta/(n + 1) \). The reflection coefficient for an incident angle \( \theta \) is then:

\[
R(\theta) = e^{-2(n+1) \sigma_{\text{max}} \delta \cos \theta / \varepsilon_0 c},
\]

thus requiring \( \sigma_{\text{max}} \) to be:

\[
\sigma_{\text{max}} = -\frac{n + 1}{2 \cos \theta \delta} c 2.3 \log R(\theta).
\]
The same profile was used for all conductivities:

\[
\frac{\sigma_x^*(\rho)}{\mu_0} = \frac{\sigma_y^*(\rho)}{\mu_0} = \frac{\sigma_x(\rho)}{\varepsilon_0} = \frac{\sigma_y(\rho)}{\varepsilon_0} = \frac{\sigma(\rho)}{\varepsilon_0}.
\]

Finally, the accuracy and reliability of these simulation programs were tested by verifying that they reproduce expected patterns of reflection, refraction, edge diffraction, and attenuation. Regarding accuracy, a finite difference method that is 2nd-order in space and time was used because going to 4th-order in space has not produced any visible difference in results.

3.2.2 Lunar electrical properties

To study the effect of the lunar electrical properties on radio wave propagation, the body of the Moon was modeled in the simulation by referring to the Lunar Sourcebook [4] for electrical properties as functions of depth. Both the permittivity and the conductivity of the lunar material depend strongly on the density, which in turn varies with depth. In the lunar regolith, to a depth of \( \sim 100 \text{ m} \), the density increases with depth \( z \) (in cm) roughly as \( \rho(z) = 1.39 z^{0.056} \text{ g/cm}^3 \) [4]. This can be used to estimate the depth profiles of these electrical properties. For the relative permittivity, data compiled in the Lunar Sourcebook [4] give the approximation:

\[
\varepsilon_r(\rho) = 1.9^\rho
\]

where the density \( \rho \) is in g/cm\(^3\).

The electrical conductivity is much more difficult to specify because it varies significantly depending on the temperature and the wave frequency. The electrical conductivity is related to the loss tangent \( L \) as:

\[
\sigma = \omega \varepsilon_r \varepsilon_0 L,
\]

where \( \omega \) is the wave frequency. For the loss tangent, the data in the Lunar Sourcebook [4] give an approximation:

\[
L = 10^{(0.440\rho - 2.943)}.
\]

Extrapolating the density-depth approximation into the lunar crust, the depth profiles of relative permittivity and loss tangent were estimated (Figures 3.7 and 3.8). These profiles were used to define the Moon in the finite-difference time-domain simulation.

3.2.3 Lunar ionosphere

In a medium with free electrons, the permittivity depends on the wave frequency \( \nu \) as

\[
\varepsilon_r \approx 1 - \left(\frac{\nu_p}{\nu}\right)^2, \quad \text{where } \nu_p \text{ is the plasma frequency.}
\]

The approximation \( \nu_p(\text{MHz}) \approx \sqrt{n_e(\text{cm}^{-3})/100} \) gives:

\[
\varepsilon_r \approx 1 - \frac{n_e(\text{cm}^{-3})}{10^4 \nu_p^2(\text{MHz})^2}.
\]

In this study, a very simple linear profile was used for the electron number density, with the maximum at the surface and linearly decreasing to roughly the local solar plasma density of 5/cm\(^3\) at an altitude of 50 km.
Figure 3.7: Depth profile of relative permittivity used in the simulation.

Figure 3.8: Depth profile of loss tangent used in the simulation.
3.3 Study I: Radio wave penetration into the lunar surface

As mentioned above, the observatory site should be free of subsurface structures that can reflect radio waves back up to disturb the observations. To what depth should we check for subsurface structures? To answer this, a study was conducted to estimate how deep the very low frequency waves penetrate into the lunar regolith. The goal is effectively to find the “skin depth” of the Moon for various radio wave frequencies.

Setup

With the vector wave simulation tool, a flat lunar surface was illuminated normally with a linearly polarized plane wave of unit amplitude until an equilibrium was reached. The effective “skin depth” was estimated by measuring how the penetrated amplitude decreases with depth and fitting it with a profile expected for a homogeneous medium with a certain skin depth \( \delta \). In a homogeneous medium, wave amplitude attenuates with depth \( z \) as \( |E| \propto e^{-z/\delta} \). By fitting the experimental profile to an exponential decay curve, an effective skin depth was estimated.

The lunar surface was characterized by electrical permittivity \( \varepsilon(z) \) and loss tangent \( L(z) \) with depth profiles as plotted in Figures 3.7 and 3.8. The study examined various frequencies in the range 10 MHz - 30 kHz, corresponding to wavelength range of 30 m - 10 km in vacuum.

Computationally, a simple vertical 1-dimensional setup was created (the computation boundaries on the sides were connected, or wrapped around). Once equilibrium was reached, the wave amplitude was recorded as a function of depth.

Results

Figure 3.9 shows the result for a 0.5-MHz (0.6-km) wave. A fraction of the incident wave is reflected off the surface; the rest attenuates roughly exponentially. The characteristic attenuation depth from the fit was defined to be the effective “skin depth” of the lunar surface: 3.74 km for a 0.5-MHz (0.6-km) wave.

This procedure was repeated for various frequencies (wavelengths). The effective “skin depth” is plotted against frequency (Figure 3.10) and wavelength in vacuum (Figure 3.11). For a homogeneous medium, skin depth is expected to increase linearly with wavelength. For the lunar regolith, however, the plot shows that longer wavelength waves do not penetrate as deeply as expected because the density increases with depth. In the wavelength range of interest, radio waves are expected to penetrate up to tens of kilometres deep.
Penetration of 0.5 MHz (0.6 km) wave

fit = 0.68 \cdot \exp(- \text{depth} / 3.74 \text{km})

Figure 3.9: Simulation result: Penetration of radio waves (0.5 MHz) into the Moon, as a function of depth. The solid line is the best exponential fit.

3.4 Study II: Interference shielding by the Moon

Now the main question is how well various locations are shielded from the terrestrial interference. For VLF radio waves of various frequencies (0.03 - 30 MHz), we aim to find the amount of attenuation at various locations on the lunar surface relative to the direction of the incident wave. We can also check these attenuation levels on the lunar orbit. At candidate sites (Daedalus, Tsiolkovsky, pole), we aim to simulate an interferometric observation by a linear array to determine the direction of the diffracted wave.

3.4.1 Setup

To study radio interference around the Moon, we must simulate radio waves incident on a spherical Moon. For simplicity, the radio interference was simulated as a continuous plane wave of a unit amplitude from one direction, one frequency at a time. Then the azimuthal symmetry of the setup allows the simulation to employ cylindrical coordinates and simply use a semicircular cross-section of the Moon (see Figure 3.12). The Moon with a radius of 1737 km was characterized using the depth profiles for electrical permittivity and loss tangent. The simulation space was set large enough to fit the Moon and a 100-km orbit around it: at least 2000 km wide and 4000 km tall. It was
Figure 3.10: Result: Effective “skin depth” of the Moon, as a function of frequency.

\[ \text{fit} = 2.2 \times \text{frequency}^{-0.81} \]

Figure 3.11: Result: Effective “skin depth” of the Moon, as a function of wavelength.

\[ \text{fit} = 5.8 \times \text{wavelength}^{0.81} \]
set wide enough to include the first diffraction minimum to the side of the Moon. For the lowest relevant frequency of $\sim 30$ kHz, this corresponded to $\sim 200$ km from the edge of the Moon.

![Simulation setup: radio waves were produced along the dotted line.](image)

Figure 3.12: Simulation setup: radio waves were produced along the dotted line.  

The space surrounding the Moon was filled with an electron density of 5/cm$^3$ to simulate the local plasma due to the solar wind. Even such tenuous electron concentration will affect the propagation of very low frequency waves. The wavelength increases by $\sqrt{1/\varepsilon_r}$, compared to in vacuum. For example, a 30-kHz wave has a wavelength of $\sim 15$ km in the presence of this electron density (see equation (3.6)). Due to the interplanetary scattering, around 50 kHz is the lower limit for astronomical observations with any angular resolution from nearby Earth.

**Space and time** The simulation was run long enough for the energy density distribution to reach an equilibrium. Typically it took several times the transit time across the Moon ($3475$ km / $c \approx 11.6$ ms).

The incident wave was polarized in the transverse electric (TE) mode (only $E_x$ perpendicular to the wave direction was excited). This setup simulates the diffraction around an infinitely long cylinder. Since the problem is symmetric across the axis of the Moon parallel to the wave incidence, only one side was computed to halve the amount of computation. The boundary along the symmetry axis was made reflective to maintain the wave polarization.

**Memory & speed** The simulation was limited by random access memory and computational time. Even for a long wavelength of 10 km (near the local solar plasma cut-off), the simulation space is $200 \times 400$ wavelengths, requiring $2000 \times 4000$ points on the grid to have a resolution of 10 points per wavelength. Using float (4 bytes) for the 3 TE vector components ($E_x, E_y, H_z$) at every point, about 100 MB is required. Halving the wavelength requires 4 times more memory. As we found in the previous experiment, radio waves penetrate significantly only to a certain depth depending on the wavelength.
Thus, to reduce the computational time, points in the central core of the Moon (where only very attenuated waves reach) were not computed at all.

**Scalar simulation** To estimate the difference in diffraction results between an infinite cylinder and a more appropriate sphere, we conducted scalar wave simulations in both rectangular (infinite cylinder) and cylindrical (sphere) coordinates. Comparison was also made between scalar and vector wave simulations, as described below.

### 3.4.2 Results

On the order of 100 vector and scalar simulations were run, each taking anywhere from several hours to a few days. Radio waves are definitely diffracted to the far side of the Moon. To find the amount of attenuation, the relative energy density $u$ was obtained by time-averaging the electric field values over two cycles:

$$u \propto \langle |E_x|^2 + |E_y|^2 \rangle.$$  

Due to the presence of plasma, the absolute energy density depends on the wavelength.

Figures 3.13 and 3.14 are graphical examples of the simulation results. The energy density of the wave seems to be attenuated significantly on the far side. At a higher frequency (shorter wavelength), diffraction is less as expected.

![Figure 3.13: Energy density distribution around the Moon with a continuous 10-km (30-kHz) plane wave incident from the left.](image1)

![Figure 3.14: Energy density distribution around the Moon with a continuous 5-km (60-kHz) plane wave incident from the left.](image2)
Radio frequency dependence in attenuation

To look at the amount of attenuation more quantitatively, the energy density relative to that of the incident wave was plotted (Figure 3.15). Since this simulation study is meant to be extremely rough, the numerical values are expected to be reasonable only to within an order of magnitude or so. Also, due to the finite spatial resolution, attenuation at the lunar “surface” means at somewhere within a fraction of the radio wavelength above the actual surface.

Even for a very low frequency of 30 kHz, radio waves seem to be attenuated by as much as 80 dB on the far-side locations over 30 degrees from the limb. The flattening in the attenuation levels beyond about 140° may be simply due to the imperfect computational boundary. At higher frequencies, the attenuation only improves because the waves do not diffract as much. Even in the polar region (90°), the terrestrial interference seems to be attenuated by 2~3 orders of magnitude.

The available computational resource limited the highest frequency to 60 kHz, which is barely above the local solar plasma cutoff. While this tells us the minimum amount of attenuation, it would be helpful to guess the results for higher frequencies. To do this, the simulation was run at still lower frequencies (15 kHz and 10 kHz) to obtain data points in an attempt to extrapolate the results to higher frequencies. To make the
extrapolation more valid, solar plasma was ignored because its influence will be much larger for lower frequencies (local plasma density of $\sim 5e^{-}/\text{cm}^3$ will not even let 15-kHz wave propagate at all). Figure 3.16 shows the result using data points at three locations and four different frequencies. The attenuation level seems to vary roughly exponentially with the radio wave frequency for each of the locations, although it is difficult to tell how high in frequency this relation can be extrapolated.

Figure 3.16: Simulation result: Attenuation as a function of frequency at the locations of the Daedalus crater ($\sim 175^{\circ}$), Tsiolkovsky crater ($\sim 125^{\circ}$), and at the pole ($\sim 90^{\circ}$). This is an order-of-magnitude result.

**Comparison between scalar and vector wave simulations**

As mentioned above, comparison in results was made between simulations using rectangular and cylindrical coordinates. The use of rectangular coordinates simulates an infinitely long cylindrical Moon whereas the use of cylindrical coordinates simulates a spherical Moon. Figure 3.17 is an example of the comparison. As expected, the cylindrical Moon seems to shield the interference slightly better; however, the difference is much less than the uncertainty associated with this rough order-of-magnitude simulation.

Next, using rectangular coordinates, comparison was made between scalar and vector wave simulations (Figure 3.18). Also in this case, the difference is negligible compared to the uncertainty in the simulation, even near the poles where the waves would be at
Figure 3.17: Comparison in results between cylindrical and spherical models for the Moon (at 15 kHz, 20 km). The “orbit” data are for altitude of 100 km above the lunar surface. (The fringes are due to diffraction.)

Figure 3.18: Comparison in results between scalar and vector wave simulations, using rectangular coordinates (cylindrical Moon).
Shielding in the orbit

To see the amount of attenuation as observed from a lunar orbit, the relative energy density was plotted at a 100-km altitude as well. This is relevant to orbiters for precursor measurements or orbiting telescope.

![Attenuation of radio interference on the lunar orbit](image.png)

Figure 3.19: Attenuation of energy density on the lunar orbit at various angles around the Moon relative to the incident wave.

The result at the orbital altitude (Figure 3.19) indicates that, at these low frequencies, an orbiting observatory can take advantage of the shielding by the Moon during a much smaller fraction of its orbit than expected from geometrical shadowing. Also, a precursor orbiter mission to verify the shielding effect of the Moon should keep in mind that attenuation of the terrestrial interference on the far side is likely up to 4 orders of magnitude better on the surface than in orbit.

### 3.5 Conclusions

Even for a very low frequency of 50 kHz, radio waves seem to be attenuated by at least 12 orders of magnitude on the far-side locations over half way (~45°) from the limb. At higher frequencies, the attenuation should improve because the waves will not be expected to diffract as much. For observations at very low frequencies, the results seem to suggest that we should choose an observatory site at least 45 degrees from the limb.
Figure 3.20: Difference in attenuation of energy density on the lunar surface and on a 100-km lunar orbit ($\nu = 50$ kHz, $\lambda = 6$ km). (Because of the finite spatial resolution, “lunar surface” is somewhere in the 0-500 m altitude range.)

In a lunar orbit, an observatory would be able to take advantage of the shielding by the Moon only during a much smaller fraction of its orbit than expected from geometrical shadowing because of diffraction, especially at longer wavelengths. Also, when a precursor orbiter mission measures the shielding effect of the Moon, the attenuation of the terrestrial interference on the far side may be expected to be 1~6 orders of magnitude better on the surface than from orbit.
Chapter 4

Proposal for the First Observatory

4.1 Affordable option for initial survey

To get the project started, the first objective should be to devise a concept that is very inexpensive, and yet able to make initial discoveries at very low frequencies. As the universe at these frequencies is still unexplored, the main goal of the first array should be to survey the sky. When the Infrared Astronomical Satellite (IRAS) conducted an all-sky survey at 5’ resolution in 1983, it discovered about 350,000 new objects, increasing the number of cataloged astronomical sources by about 70% [69]. Similarly, the Röntgen Satellite (ROSAT) discovered over 150,000 X-ray sources from its sky survey during the 1990s, even with a relatively poor resolution of 12’ [70]. We can expect such success from a similar survey at very low frequencies.

For the first observatory, the main requirements are to observe at frequencies below at least 2 MHz with at least a few degree resolution, sufficient signal over noise (S/N), and enough spatial frequency coverage (uv-coverage) to detect various objects. The main constraint is the budget. Therefore, to make something happen, we must come up with the cheapest mean to gain new view of universe.

4.1.1 Realistic possibilities

With cost being the major constraint, a dedicated mission to the Moon for VLF astronomy is unlikely, even though the potential rewards could justify it. A more realistic scenario for a lunar array would be as a lightweight side project on some other mission to the Moon. A lunar far side array would therefore likely have to wait at least another couple decades since no other motivating plans exist for the far side.

Table 4.1 compares the various options for the VLF observatory site and their relative advantages. The specifications for the Earth orbit case are based on the above-mentioned
ALFA, which was proposed to orbit the Earth at 2.6 times the lunar distance [28]. While ALFA would be excellent for studying the Sun at very low frequencies, its potential for discoveries outside the Solar System is questionable because of the significant and continuous interference from the Sun, Earth, and other planets like Jupiter. A lunar orbiting array could make some astronomical observations while both the Earth and the Sun are on the other side, but the orbital instability will limit the manageable number of antennas and the sensitivity significantly. At the lunar south pole, a 5-km tall Malapert Mountain may be used to shield radio interference, as explained below. The lunar near side does not offer much advantage over a polar site, and would most likely be more expensive. The lunar far side is excellent but not affordable any time soon. In conclusion, the lunar south polar site is very appealing for an initial survey observatory.

Table 4.1: Possibilities for the VLF observatory site

<table>
<thead>
<tr>
<th>Terrestrial Interference a</th>
<th>Earth orbit (ALFA)</th>
<th>Lunar orbit</th>
<th>Lunar South Pole (Malapert)</th>
<th>Lunar Near Side</th>
<th>Lunar Far Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10 dB</td>
<td>~ 0 (when far side)</td>
<td>~ 0</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Solar Interference</td>
<td>1</td>
<td>~ 0 (when dark side)</td>
<td>~ 0 (night)</td>
<td>0 (night)</td>
<td></td>
</tr>
<tr>
<td>Platform</td>
<td>:l</td>
<td>:( unstable</td>
<td>:)</td>
<td>:)</td>
<td>:)</td>
</tr>
<tr>
<td>Sky coverage</td>
<td>All</td>
<td>All</td>
<td>&lt; Half</td>
<td>~ All</td>
<td>~ All</td>
</tr>
<tr>
<td>Access</td>
<td>2.6× further than Moon</td>
<td>:l</td>
<td>:) with lunar base</td>
<td>:)</td>
<td>:(</td>
</tr>
<tr>
<td>Cost</td>
<td>~ $ 150 M</td>
<td>:l</td>
<td>:l</td>
<td>:l</td>
<td>:(</td>
</tr>
</tbody>
</table>

*Relative to the interference level at the distance of the Moon.

With the growing recognition of the lunar south polar region as an ideal site for a lunar base, the next series of landers will most likely concentrate there. Particularly promising is the prospect of Malapert Mountain near the south pole as a central station for terrestrial communication, solar power, and lunar base development [71]. If the south polar region is an acceptable site for VLF astronomy, the lunar array project could utilize the transportation and communication systems of the main mission. This way, it could possibly fit within the margin of the host mission while expanding its scientific value significantly. The deployment and operation of the VLF array could also serve as an ideal technology demonstration project for subsequent missions in the lunar development.
The main constraint of a lunar array mission is the budget. However, majority of the cost would come from transportation (launch, lander, rover) and communication systems (Figure 4.1). The cost and the mass of the array itself is only a small fraction of the total. The most cost-effective approach may therefore be to deploy the array as a piggyback project on some lander mission to the Moon. The next series of lunar landers will most likely be on the south polar region because of its attraction as a prospective lunar base site. In particular, one of the earliest may land on top of Malapert Mountain to establish communication and power systems for the rest of the operations in the south polar region. Malapert is a 5-km tall mountain located at 0° longitude and 86°S latitude, 122 km from the south pole toward the Earth. Being so high, this mountain could shield terrestrial interference for an observatory situated on the opposite side of it from the Earth [71].

One of the main advantages of the lunar surface as an astronomical site is its accessibility for maintenance and upgrades. The lunar observatory is easily accessible only if there are other activities nearby.

Figure 4.1: Estimated cost of ESA’s Very Low Frequency Array on the Lunar Far Side project [16]. For cost estimates of the rover and the relay satellite at L2, the ISU report [52] was referred to.
4.1.2 Lunar south pole

There have been VLF observatory concepts for the lunar far side (including [34], [50], [52], [16]) and the near side [43], but not yet for a polar location. The pole has not been considered probably because the sky coverage would be halved at the pole and it is not suitable for studying the Sun or the planets. Still, nearly all range of galactic coordinates would be accessible from the polar site, making it satisfactory for an initial sky survey at very low frequencies. The polar site is much more accessible. In addition, no ionosphere is expected at the polar region according to Figure 3.2.

One concern with the polar site as compared to the far side is that radio quietness will be compromised because the Earth and the Sun will always be near the horizon (Figure 4.2). In particular, the Earth will always be in the same general direction, moving horizontally by $\pm 8^\circ$ and vertically by $\pm 7^\circ$ over a month due to libration. The Sun will circle along the horizon every month, also moving vertically by $\pm 1.5^\circ$.

![Diagram by Paul Spudis](Diagram by Paul Spudis)

Figure 4.2: Orientation of the orbital and rotational axis of the Moon [72].

**Malapert Mountain** Being $\sim 5$ km tall, Malapert Mountain near the lunar south pole could shield radio interference. This mountain is at 4 degrees, or $\sim 120$ km, from the south pole along the $0^\circ$ longitude line towards the Earth (Figure 4.3). One of the earliest lunar missions may land at the summit to establish a communication relay station that would be essential for future operations in the south polar region. Such a mission would be ideal for deploying an array of simple dipole antennas along the far side of the mountain.

At long wavelengths, we must check how well the interference will be shielded.

4.2 Study III: Interference shielding by Malapert Mountain

Study II in Section 3.4 seemed to show that the radio interference reaching the polar region may be attenuated by about two orders of magnitude. This already attenuated
Figure 4.3: The lunar south polar region, imaged with Earth-based radar shining from the top by Margot et al [73]. Malapert Mountain (at longitude 0 and latitude 86° S) shields radiation from the Earth and can provide a radio quiet environment.

Figure 4.4: The same image as above, but indicating permanently dark areas both visible (white) and invisible (gray) to the Earth-based radar [73].
interference can be further reduced by siting the array in the radio shadow of Malapert Mountain. The simulation tool developed above was used to estimate the additional attenuation provided by Malapert Mountain.

4.2.1 Setup

Figure 4.5 shows a rough setup of the simulation with Malapert Mountain located at 86°S along the 0°-longitude line. Again, the lunar surface was modeled using the depth profiles for electrical permittivity and loss tangent. The vector wave simulation was used in the 2-dimensional cross-section along the 0°-longitude. Incident waves in TE and TM modes were separately examined.

![Figure 4.5: Rough sketch of the simulation setup, with the 5-km tall Malapert Mountain on a surface sloped by 4° relative to the direction of Earth (left). Plane-wave radio interference was generated along the dashed line on the left. The lunar south pole is to the right.](image)

To model the mountain, the digital elevation data acquired by Margot et al [73] was used (Figure 4.6). Data is missing on the far side of the mountain because it is invisible from Earth. However, there is clearly a basin or a crater there because the elevation drops to 4 km below the mean. As shown in the figure, a very simple curve was used to roughly model the elevation profile of the mountain and the basin on its far side.

The terrestrial interference was again simulated as a plane wave, incident from the direction of the Earth. Interferences of various frequencies were examined. However, as mentioned in Section 2.2, the interplanetary scattering limits the lower end of the reasonable observing frequency to \( \sim 1 \text{ MHz} \). At 1/2 MHz, the achievable resolution is already limited to \( \sim 7° \). The simulation was run until equilibrium was reached, typically taking several times the transit time across the simulation space (200 km / c \( \approx 0.7 \text{ ms} \)).
4.2.2 Results

Figures 4.7 and 4.8 show the results at 0.5 MHz and 1 MHz, respectively. Figure 4.9 is a more quantitative plot. Again, the numerical values should be taken as only reasonable to within an order of magnitude or so. The results showed no significant difference between TE and TM modes.

In a ~50-km long region on the far side of the mountain, the already attenuated wave seems to attenuate further by at least an additional 30 dB. Altogether, terrestrial
interference is expected to be weakened by at least 5 orders of magnitude. The shielding effect is even better for higher frequencies, as evident from the result for 1.0 MHz in Figure 4.9. The far side of Malapert Mountain is a promising site for a radio observatory.

**4.3 Concept for the first lunar south polar VLF array**

A lunar south polar array could be realized as a small part of one of the upcoming series of lunar landers. These missions could be launched within 10 years. Thus, it is essential to prepare a realistic and affordable proposal soon. Below are very preliminary considerations for a possible first step toward the first lunar VLF array. Testing the initial array on the lunar surface will be valuable for designing an optimal observatory eventually for the lunar far side. It could also help begin lunar development to contribute toward further development on the Moon and beyond, including Mars.

**4.3.1 Requirements & constraints**

The objective is to set up an operating observatory that will open the new spectral window by best taking advantage of the unique environment of the Moon. The observatory should cover a spectral range of at least 3-10 MHz, with an angular resolution better than a degree.
Spectral range must include what is impossible from the Earth, to make new discoveries. Frequencies below $\sim 3$ MHz should be explored, up to the Earth’s ionospheric cut-off of $\sim 10$ MHz. The solar wind plasma places the lower limit of $\sim 30$ kHz. desired. Angular resolution must be better than RAE and at worst a few degrees or limited by the interplanetary and interstellar scattering. The resolution depends on the baseline $D$ and the sine of the altitude in the sky. Temperature sensitivity must be high enough to achieve sufficient $S/N = f \sqrt{\Delta \nu \tau} = \frac{n A_{\text{eff}}}{D^2} \sqrt{\Delta \nu \tau}$, where $f$ = filling factor of the interferometer, $n$ = number of antenna elements, $\tau$ = integration time per beam (potentially unlimited), and $\Delta \nu$ is the bandwidth (limited by the data rate). The sensitivity will be limited by interference from the Earth, Sun, and planets near the horizon. Aperture (u,v) plane coverage affects the image quality, and is determined by the number of antennas. Sky coverage must be enough to sample the universe sufficiently, preferably including all galactic latitudes. From the lunar south pole only the southern celestial hemisphere is observable, but all range of galactic latitudes is accessible. Duration must be long enough for all-sky survey in a sufficient range of frequencies: at least one year (preferably during a solar minimum). Lifetime may be limited by the communication system. Lunar advantage is crucial: the observation must be impossible from elsewhere (orbits, libration points, lunar orbits). The advantage of the lunar environment must be verified.

Budget This project will have to be a small part of a funded lunar lander, for example a New Frontiers mission ($650M$). Schedule of the International Space Station and upcoming lunar missions will constrain when a suitable lander is proposed to piggyback on. The first lander on the lunar south pole will likely be the South Pole Aitken Sample Return mission to be launched around 2009-2013 [74]. Pace of developing launchers, landers, rovers, and communication systems will constrain when a mission to Malapert Mountain can be realized.

4.3.2 Summary of options

The two conflicting areas of interest are performance and cost. Table 4.2 lists in rows the factors influencing performance or cost, and in columns the drivers of both. These drivers are the options open for trades.

The maximum baseline ($D$) is the major driver determining the resolving power and influencing the deployment difficulty. The number ($n$) of antenna elements in the array is the major driver for spatial frequency coverage (influencing image quality) and for the mass, volume, and deployment requirements. While a linear array would be simpler to deploy, we should leave open the option for a 2-dimensional layout able to take snapshot images for better calibration (improving the dynamic range). Also, the relative advantages of various locations should be weighed with respect to the interference level.
and deployment difficulty.

Table 4.2: Factors influencing performance (top rows) and cost (bottom rows), and their drivers.

<table>
<thead>
<tr>
<th>DRIVERS(^a) =&gt;</th>
<th>Max baseline</th>
<th># elements</th>
<th>Layout</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest frequency</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>uv coverage</td>
<td>+</td>
<td>+</td>
<td>2D</td>
<td></td>
</tr>
<tr>
<td>(\frac{S}{N} \propto n^{\frac{3}{2}} \sqrt{\Delta \nu T})</td>
<td>+</td>
<td></td>
<td>minimize interference</td>
<td></td>
</tr>
<tr>
<td>Dynamic range</td>
<td>+</td>
<td>2D</td>
<td>minimize interference</td>
<td></td>
</tr>
<tr>
<td>Interference</td>
<td>+</td>
<td></td>
<td>minimize interference</td>
<td></td>
</tr>
<tr>
<td>Coverage</td>
<td>+</td>
<td></td>
<td>maximize FOV</td>
<td></td>
</tr>
<tr>
<td>Mass, volume</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deployment</td>
<td>-</td>
<td>-</td>
<td>linear</td>
<td>smooth terrain minimize distance</td>
</tr>
<tr>
<td>Communication</td>
<td></td>
<td></td>
<td></td>
<td>minimize distance</td>
</tr>
<tr>
<td>Power</td>
<td>-</td>
<td></td>
<td></td>
<td>minimize distance</td>
</tr>
</tbody>
</table>

\(^a\)For each driver and the factor it drives, the favorable option is indicated (the most important effects in bold).

### 4.3.3 Observatory site

The site is proposed to be in the south polar region of the Moon, on the side of Malapert Mountain shadowed from the Earth’s radio interference. When considering interference, libration must be accounted for. Every month, the Earth would move up and down by 7°.

The shadowed area should be at least 30 km to hold the array. The entire dark and gray regions in Figure 4.4 are prospective sites. Subsurface reflections should be checked. Based on the elevation data by Margot et al [73], the slope of the mountain on its far side is expected to range 10° ~ 30°. The slope of Malapert Mountain may be too steep or rugged for a rover to transverse. Topography data at 1/2-metre vertical resolution with a 10-metre spot size are essential in designing a rover able to transverse the terrain. The terrain should also be smooth enough for the antenna elements to be able to communicate their data to some central station. Also, the observability of all galactic latitudes as well as the galactic center would be very favorable. For accessibility, the site is better to be near a lunar base or close to the Malapert summit. On the other hand, the site must avoid radio interference from local activities. It is still an open question whether or not some nearby craters could offer an even better site.
4.3.4 Array

The polar site has the unique quality such that all the baselines of the interferometer rotate in a circle with the Moon itself. Thus, even a simple linear array will create a circular aperture over the course of half a lunar rotation. For parts of the sky away from the zenith, the aperture plane is elliptical, becoming narrower by the sine of the altitude. For example, at 30° above the horizon, the angular resolution worsens by a factor of \( \sin(30°) = 1/2 \) in the altitudinal direction.

Compared to a 2-dimensional array scattered over an area, a roughly linear array will require the least number of antenna elements for a given maximum baseline. It would be simpler to deploy. Because a linear array cannot take snapshot images, a novel method for calibration of flux density and fringe amplitude may need to be developed. For a linear configuration, phase calibration only requires the knowledge of antenna positions; however, amplitude calibration requires further investigation.

**Maximum baseline** The array should span at least 17 km to achieve 1° resolution or better at 1 MHz. The maximum baseline is the major driver determining the resolving power at frequencies above 1 MHz and influencing the deployment complexity. At very low frequencies, interstellar and interplanetary scattering severely limits the best possible angular resolution at any given frequency. Thus, the maximum baseline needs to be no longer than \( \sim 200 \) km for most VLF imaging applications. An array size of 50 km is sufficient to achieve the scattering limited resolution of 10’ at 3 MHz for the majority of the sky. The simulation results above (Figure 4.9) indicate a reasonable shielding of terrestrial interference over a 50-km region on the far side of Malapert Mountain.

**Number of elements:** The number of antennas in the array is the major driver for spatial frequency coverage (influencing image quality) and for the mass, volume, and deployment requirements. The antennas should be arranged in a configuration that provides a uniform coverage in spatial frequency with minimum redundancy of baselines. This means having various intervals among the antenna elements, from short to long, as depicted in Figure 4.10. Densely packed part of the array should be located near the basin where the attenuation of the terrestrial interference is expected to be the best.

The number of antennas could range 10~300 or so. For a wide frequency range, filling factor depends strongly on the wavelength [16]. The instantaneous and long-term synthetic aperture of a given configuration can be studied using computers [33]. About 50 elements should be able to cover a 50-km linear array with a minimum baseline on the order of the observing wavelength. Although the antennas may be orientated randomly, aligning single dipoles toward Earth could reduce their sensitivities to terrestrial interference.
4.3.5 Preliminary concept

As a preliminary baseline, a linear array is proposed with about 50 short dipole antennas over a distance of about 50 km on the far side of Malapert Mountain. It could be a few hundred kilogram payload on a lander mission to the Malapert summit, which then could be deployed by a rover depositing the antennas as it travels down the slope. The baseline of 50 km will provide at 3 MHz the 10' resolution (which is the interplanetary scattering limit), even at 30 degrees above the horizon. The VLF array will map the entire visible sky through aperture synthesis, one frequency band at a time. Mapping at each band will take 2 weeks (half a lunar rotation), or longer for better sensitivity. This could be inexpensive if it is flown as an extra payload (of a few hundred kilograms) on a lunar lander mission whose primary purpose is to establish a communication relay station between the south polar region and the Earth. Funding could also come as a technology demonstration or validation project for a lunar rover, remotely controlled robotic operations, and communication infrastructure.

4.3.6 Communication architecture / data delivery

Data from each antenna would be delivered to a central station for correlation and relayed through a communication system at the Malapert summit to the Earth. Data may be delivered by cable connection, radio link, or infrared / optical link. Bandwidth $\Delta \nu$ should be higher for better sensitivity, but lower for easier interference suppression. Data rate will likely be limited by the communication costs.

4.3.7 Array deployment & operation

With ESA’s design [16], each antenna unit could be stowed in a box 25 cm on each side and weighing only 5 kg. With 50 antennas, the total mass would be on the order of a few hundred kilograms. The entire package could fit in a 1 m$^3$ volume.

Various options exist for method of deploying the array. Burns [33] thought that deployment robot would be the most difficult engineering hurdle. It will require a high
performance rover with robotic manipulation. Detailed topology (contour maps) will be required to assess how trafficable the site is.

An ideal mission to piggyback on would be a lander to the Malapert summit for establishing a communication link between Earth and the lunar south polar region. A possible sequence for setting up the VLF array might go as follows:

1. Land on the Malapert summit; establish communication with Earth; set up a solar power system.
2. Set up the central station for communication with any future activities in the south polar region (including VLF astronomy).
3. Deploy a rover carrying the VLF array units (packaged in $1 \text{ m}^3$).
4. Maneuver the rover down the far slope; stop at a convenient spot near a pre-designated location and deposit an antenna unit; ensure communication link between the antenna unit and the central station. This operation might take about 1/2 hour per unit [16].
5. Move on down the slope to deposit the rest of the antenna units in the linear array. The location of each unit does not need to be exact, nor does the array need to be exactly in a line.
6. Where necessary, set up simple intermediate relay stations along the way.

This could be an ideal technology validation project for rover transportation and robotic deployment on the Moon. Once the rover deploys the array, we can calibrate the observatory by sending commands to each antenna unit through the central station at Malapert summit. Data from each antenna would be delivered back to a central station and relayed to the Earth. Assuming that this Malapert station can transmit data at a high rate, cross-correlations of signals from the antennas may be performed on Earth. Operating the VLF observatory would be an excellent test of the communication system for the lunar south pole before other missions arrive.

**Power requirements & storage**

An issue remaining to be solved is powering of each antenna unit. According to the ESA design [16], each unit will require about 1/2 watt for electronics and 1/2 watt for communications. Solar power at the observatory site is scarce because it avoids radiation from not only the Earth but also the Sun most of the time. A power station on the Malapert summit could possibly distribute power to the antenna units through a cable or a wireless transmission, but neither of these possibilities appears simple. By the time this mission becomes a reality, very lightweight radioisotope thermoelectric generators (a few kilograms each) may become available. Any necessary batteries must be able to operate at very low temperatures.
Cost

The following table lists the estimated costs from design studies for lunar VLF arrays.

Table 4.3: Order-of-magnitude cost estimates (in millions of $ or ESA accounting units)

<table>
<thead>
<tr>
<th></th>
<th>ISU\textsuperscript{a} (nearside)</th>
<th>ISU\textsuperscript{a} (farside)</th>
<th>ESA\textsuperscript{b} (farside)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 elements/ 100 m</td>
<td>300 elements/ 17 km</td>
<td>300 elements/ 40 km</td>
</tr>
<tr>
<td>Antennas</td>
<td>80</td>
<td>1200</td>
<td>130</td>
</tr>
<tr>
<td>Launch</td>
<td>130</td>
<td>1000</td>
<td>120</td>
</tr>
<tr>
<td>Lander</td>
<td>150</td>
<td>450</td>
<td>150</td>
</tr>
<tr>
<td>Rover(s)</td>
<td></td>
<td>460</td>
<td>400</td>
</tr>
<tr>
<td>L2 relay satellite</td>
<td></td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Ground</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>TOTAL</td>
<td>460</td>
<td>3410</td>
<td>1100</td>
</tr>
</tbody>
</table>

\textsuperscript{a} in 1993 US $ [52]
\textsuperscript{b} in 1997 ESA Accounting Unit [16]

For the lunar south polar array proposed here, the cost should be less than that of a dedicated near side system. Referring to the ESA cost estimates, the dipole antenna elements weighing a few 100 kg total are expected to cost about $40M to design and $0.16M per unit to manufacture. With 50 antenna units, the total would be $50M. Transportation cost of the piggyback mission would be significantly less than if a whole launch needed to be dedicated for the mission. Designing the rover modification for the array deployment would probably require the greatest effort and resources.

In any case, the cost of this mission would be less than that of one nice meal for an average tax payer. Moreover the money goes into providing jobs for people. The cost per individual would be even less if this project is done as an international collaboration.
Chapter 5

Recommendations for Precursor Measurements

To progress further toward proposing and realizing the VLF astronomy from the Moon, we need to learn about the actual environment of the Moon and search the lunar surface for the best sites. It is crucial to identify a practical site with definite advantages to be able to propose the first array in complete detail. To do this, we must make some direct measurements of the lunar environment and the potential sites.

Most of the required measurements would be of interest to lunar scientists (for example, ionosphere, subsurface structures, and magnetic field) or crucial for lunar development in general (like topology). Much of the current knowledge about the Moon is based on data from the 1970s. Lunar scientists and astronomers should work together to propose missions that will maximally satisfy the common interests.

We must propose and make necessary measurements to support the VLF observatory on the Moon. To confirm the lunar advantage, we must make direct measurements of the lunar environment. To choose a site and make a proposal for the first array, we must study the potential sites in detail. We should specify the required measurements so that we can fully utilize the upcoming opportunities. Missions like SMART-1, LunarSat, and SELENE will be able to make many of these measurements in this decade – it is important to make the most out of these opportunities by ensuring that these missions will make the desirable measurements. These missions will not be able to make all of the desirable measurements; therefore, we should make recommendations for further measurements to be considered in future missions. It is crucial to ensure that the space exploration community knows what measurements are demanded in contrast to the existing data and why they are important.
5.1 Lunar environment characterization

5.1.1 Lunar ionosphere

The feasibility of VLF observations from the Moon relies on the absence of any significant electron density above the lunar surface. As mentioned earlier, the electron concentration sets the lowest observable frequency.

So far, only day-time measurements from the 1970s are available. It is most important to find the cut-off frequencies at various locations including the polar regions and at various times during the lunar rotation, especially during the lunar night. This will require measuring the maximum electron density at the surface, that is, at altitudes $< 1\sim 2$ km. It will also be useful to study refractive effects even above the cut-off frequency. In collaboration with ionospheric physicists, it may be useful to find the true ionized fraction, scale height, variability, and correlation scales. These measurements will require active sounding from the lunar orbit or surface. LunarSat will have a radar and plasma experiment with 5-metre dipoles able to operate at 0-5 MHz and study the ionosphere at 50-500 kHz. SELENE’s Radio Science instrument will investigate the lunar “ionosphere”. It will be able to make dual-frequency phase-lag measurements using its S-band (2 GHz) and X-band (8 GHz) [75].

5.1.2 Earth interference

The levels of interference should be measured at various locations on the Moon, including the far side of Malapert Mountain, in a frequency range 50 kHz - 30 MHz and compared to the galactic background. The amount of attenuation may be compared with the simulation results above. The effect of lunar libration (by $8^\circ$) should also be studied. Initially, the attenuation levels at the lunar orbit can be used to deduce the levels on the surface based on the above simulation results. For example, SELENE’s Lunar Radar Sounder will study spectrum of plasma waves as well as the solar and planetary radio waves in a wide frequency range of 10 Hz - 30 MHz [76]. It will observe plasma waves in the magnetosphere, the solar wind at the lunar distance, and wave phenomena in the lunar wake. Eventually, surface measurements using dipole receivers will give definite measurements of the noise from the Earth and the Sun in the lunar radio environment.

5.2 Site Selection

In planning a mission to set up an observatory on the Moon, the choice of the site is a very influential factor that affects many elements of the mission design, including communication architecture and deployment method. Therefore, identifying candidate sites is a crucial first step for further progress. It is also imperative for planning precursor missions to examine the candidate sites.
5.2.1 Topology

The site must be able to accommodate a long-baseline array spanning 10s of kilometres. A larger site will permit expansion of the array to 100s of kilometres. The site must be flat enough for antennas to be in direct sight of a central receiver and smooth enough for a safe landing and deployment. Basins and maria-filled craters are targets to investigate. These include craters like Tsiolkovsky, Aitken, and Daedalus.

So far, the highest resolution topology of the Moon has been obtained by Lunar Orbiter V with a horizontal resolution $\Delta x = 2\sim20$ m depending on the location, by the Apollo 15 laser altimeter, by Clementine High Resolution Camera with $\Delta x = 20\sim30$ m, and by Clementine Laser Altimeter with $\Delta x = 100$ m and a vertical resolution $\Delta z = 40$ m. See Figure 5.1. Soon, SMART-1 and LunarSat are planning to take images of the lunar south polar region. For example, the LunarSat camera will be able to image the southern hemisphere with a 10-metre resolution, and the south polar region in particular with a horizontal resolution of 3.5 m or less. SELENE Terrain Camera and Laser Altimeter will make a global map of the lunar surface with $\Delta x = 10$ m and $\Delta z = 5$ m. At the earliest opportunity, topological survey should be conducted by an orbiter with laser or radar sounding and high resolution imaging. A 1/2-metre resolution in altitude with a 10-metre grid size would be desirable [16]. Topography of the dark areas in the south polar region will be especially interesting.

Figure 5.1: The lunar south polar region, by Clementine probe [77]
5.2.2 Subsurface reflections

The site should be checked to ensure there are no disturbing reflections of radio waves off of any subsurface structures down to several wavelengths (∼10 km). The only available data are from the Apollo Lunar Sounder Experiment. Electrical survey of candidate sites through detailed radar sounding at the surface would be necessary. In the frequency range 50 kHz - 30 MHz, a radar sounder should measure the reflected amplitudes and time delays. LunarSat’s 5-metre dipoles will be able to conduct radar sounding at 0-5 MHz. SELENE Lunar Radar Sounder, with two orthogonal 30-metre dipole antennas, will probe the lunar subsurface at 4-6 MHz to a depth of ∼ 5 km with a 100-metre vertical resolution [78].

5.2.3 Magnetic field

The site should have a low magnetic field. Effects of the Moon’s own weak magnetic field remain unknown. Magnetic survey should be conducted from an orbiter, and then from the surface. LunarSat and SELENE Lunar Magnetometer will make initial measurements.

5.2.4 Other criteria

Before finalizing on the site, several additional factors should be checked. Visibility of desirable parts of the sky is important. For example, being able to observe the Galactic center at declination of -30° is a big advantage. Thermal environment should be studied at the candidate sites for thermal control. Also, any potential interference from lunar orbiters or bases should be checked. At the same time, accessibility for deployment and service is also important.

5.2.5 Candidates

For the lunar far side VLF array, the current candidates are all large craters: Daedalus (Figure 5.2), Tsiolkovsky (Figure 5.3), and Aitken (Figure 5.4). For very low frequency observations, Tsiolkovsky’s location may not be far enough behind the limb to avoid the diffracted interference from the Earth.

In summary, the most crucial measurement is probably high-resolution topography. In-situ measurements with dipole receivers will be extremely helpful in determining the plasma cut-off frequency and interference levels, and for testing observations. Planners of lunar missions should keep in mind these interests to make the most out of the missions. Many of the required measurements are interesting even for the sake of learning about the Moon.
Figure 5.2: Daedalus crater (100 km diameter, 5°S, 178°E) [79]

Figure 5.3: Tsiolkovsky crater (100 km diameter, 20°S, 129°E) [80].
Figure 5.4: Aitken crater (50 km diameter, 17°S, 173°E) [81].
Chapter 6

Vision and Prospect

This chapter presents a vision of how the VLF radio observatory on the Moon could be realized, especially through international cooperation.

6.1 Timeline

The timeline depends heavily on the schedule for the International Space Station and the development speed of launchers, landers, rovers, and communication satellites crucial for lunar exploration and development.

6.1.1 Common lunar exploration scenario

Space agencies of Europe, Japan, and China all share very similar visions for exploration of the Moon. In the 1990s, ESA and Japan each laid out similar lunar exploration scenarios involving 4 phases (Figure 6.1). Both scenarios begin with an initial phase of robotic exploration of the Moon, followed by a 2nd phase of robotic operations on the surface. Missions like SMART-1, LunarSat, Lunar-A, and SELENE are under phase I. The 3rd phase involves lunar resource utilization and preparation for human outpost envisioned for the final phase. ESA’s more recent Aurora program complements the original vision.

In 2001, China also announced a 3-staged lunar exploration plan named the “Chang’e” program [83]. By 2005, China hopes to send a probe to the Moon to study its topography and resource distribution. By 2010, China plans to complete the first phase with lunar orbiters. The second phase involves soft-landing on the Moon and surveying the lunar surface with rovers. The 3rd phase is a sample return. Ultimately, China intends to send humans to the Moon.

Within the context of this scenario, the VLF astronomy program may be envisioned to proceed as follows.
6.1.2 Orbiter precursors $\sim$2010

By 2007, SMART-1, Lunar-A, LunarSat, and SELENE will have gathered useful data about the lunar environment and some of them will hopefully have carried dipole antennas to attempt astronomical observations while on the far side of the lunar orbit.

Also around 2007, the Low Frequency Array (LOFAR) will begin to operate at frequencies as low as 10 MHz [9]. LOFAR will be an excellent ground-based precursor to verify such things as dipole arrangement and computational algorithms. Lessons from these observations will be invaluable in proposing the lunar VLF array.

Then, by 2010 a lunar orbiting precursor array may be realized. For example, Bougeret [17] suggested a 2-element orbiting interferometer with a radio spectrograph with an extensive frequency coverage (0.5-16 MHz). Such a precursor could assess radio and plasma waves in the lunar environment (ionosphere) and make the first arcsecond-resolution images of a few hundred brightest sources (1-2 arcsec maps for high Galactic latitude sources).

6.1.3 Surface arrays 2010$\sim$2020

From $\sim$2010, lunar landing missions may become begin. Earlier landers would be excellent opportunities for testing VLF dipole observations from the lunar surface. Around 2009, the South Pole Aitken Sample Return mission is expected to be launched [74].
With a minimal cost, it could carry a couple of VLF receivers to quantify the amount of lunar ionosphere, external interference, and subsurface reflections.

For Japan’s SELENE-II lander, a proposal has been put forward to include a very low frequency observation instrument to be tested on the surface [84].

To observe at even lower frequencies, a VLF array near the lunar south pole could then be proposed and its intensive design started. By 2010, its development phase could begin. If by then lunar missions are more common, a lunar orbiter or lander could carry a few VLF dipole antennas for preliminary observations. By 2015 or possibly earlier, a mission to the lunar south polar region could deploy the first surface array. Any lunar mission that can include this very low frequency astronomy project will contribute to a significant milestone in human view of the universe.

![Diagram showing possible schedule for the lunar south polar VLF array project.]

**Figure 6.2: Possible schedule for the lunar south polar VLF array project.**

### 6.1.4 Lunar far side 2020–

Discoveries made by the initial survey could excite the public and prompt the space explorers to propose a full-scale lunar far side array for the most sensitive studies of newly discovered objects and phenomena.

### 6.2 Call for international cooperation

We can achieve the maximum benefit from this project by carrying it out through international collaboration. By combining effort, more people will better enjoy the excitement of this new exploration of the universe. International cooperation in missions to outer space, especially to the Moon, could have a significant impact on world peace, beyond scientific or economic.

Many nations share similar ambitions toward the Moon, including the United States, European Union, Japan, China, India, Canada, and Russia. The VLF observatory seems to be the one Moon-based telescope concept that NASA leadership continues to be interested in. ESA has funded a substantial design study for it and will likely play an
integral role in this mission concept. Japanese space agency is also enthusiastic about astronomical observations from the Moon. During the past few years, dozens of scientists have gathered in Japan to investigate the very low frequency radio observations from the Moon [84]. Russia would also be able to make a valuable contribution to this mission, perhaps in launchers. India and Canada are planning joint mission to the Moon around 2007 [85]. The vice administrator Sun Laiyan of Chinese National Space Administration said: “We plan to begin our research on exploration of the Moon in future. We’d like to cooperate in the aerospace field with all amiable countries in the world” [86]. China’s vice chairman Song Jian said: ”As a member of UN Committee on the Peaceful Uses of Outer Space (COPUOS), Chinese government always supports all the activities that promote peaceful utilization of outer space, and strictly follows the provisions and spirit of The Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries. Chinese government is of the view to strengthen the exchange and cooperation with all the nations under the principles of equality, mutual benefit, and co-development [87]. All these and other nations could unite forces toward a common purpose.

6.3 Conclusion

Moon Being the most visible and familiar object in common for everyone on Earth, the Moon has a great potential to contribute toward inspiration and unification of humankind. Eventually having a constant human presence there could help people relate themselves to something as far as the Moon and be inspired.

Astronomy The Moon offers many opportunities; the study of the universe by taking advantages of the unique lunar environment is one of the more peaceful and educational activities. Since astronomy is a science purely motivated from curiosity about the vast universe we live in, astronomical missions may be an ideal kind for peaceful international cooperation. What could be more peaceful than people of various backgrounds working together toward the Moon to expand our views to our universe? In particular, study of the universe at very low frequency is likely only possible from the Moon. Such observation could lead to amazing discoveries and open a new field in astronomy.

Realization To realize this dream, the first step is to begin building upon 40 years of foregoing effort. Chapter 2 attempted to cite most of the references on the idea of Moon-based very low frequency observatory, at least in English. The consensus seems to be that the lunar far side observatory would be the only way for sensitive astronomy and very low frequencies and that it is technically feasible. It is crucial to raise the public
interest to make this project more attractive for the people. To verify the advantage of setting up the observatory on the lunar surface, the simulation study estimated how much the terrestrial interference may be attenuated at various locations around the lunar far side. However, another general view was that the lunar far side observatory is unlikely funded until far side access becomes easier and cheaper. Meanwhile, a concept for an affordable preliminary observatory was suggested to conduct an initial sky survey at very low frequencies. The idea is to piggyback on a lunar lander to the south polar region and using Malapert Mountain as a shield against terrestrial interference. The simulation study seemed to show that the mountain can shield the interference promisingly well. Precursor measurements involving both lunar orbiters and landers will be required to ascertain the actual lunar environment.

Astronomers, planetary scientists, and space explorers should cooperate for exploration of, on, and from the Moon. Let us begin forming an international team to propose the very low frequency study of the universe. I believe the Moon offers unique and significant opportunities for inspiring and uniting everyone on Earth.
Figure 6.3: http://sdc.gsfc.nasa.gov/ESDCD/GRX/Earth.Moon.gif
Appendix A

Moon’s Physical Characteristics

From http://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html:

Table A.1: Moon’s bulk and environmental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Moon</th>
<th>Earth</th>
<th>Moon/Earth ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equatorial radius</td>
<td>1738 km</td>
<td>6378 km</td>
<td>27 %</td>
</tr>
<tr>
<td>Polar radius</td>
<td>1736 km</td>
<td>6357 km</td>
<td>27 %</td>
</tr>
<tr>
<td>Mass</td>
<td>7.35 ×10^{22} kg</td>
<td>5.97 ×10^{24} kg</td>
<td>1/81</td>
</tr>
<tr>
<td>Mean density</td>
<td>3.350 g/m^3</td>
<td>5.515 g/m^3</td>
<td>0.6</td>
</tr>
<tr>
<td>Surface gravity</td>
<td>1.62 m/s^2</td>
<td>9.80 m/s^2</td>
<td>1/6</td>
</tr>
<tr>
<td>Escape velocity</td>
<td>2.38 km/s</td>
<td>11.2 km/s</td>
<td>1/5</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>10^{4-5} particles / cm^3</td>
<td>10^{19} particles / cm^3</td>
<td>10^{−14−15}</td>
</tr>
<tr>
<td>Seismic energy</td>
<td>10^{10-14} J/year</td>
<td>10^{17-18} J/year</td>
<td>10^{−3−8}</td>
</tr>
</tbody>
</table>

Table A.2: Moon’s orbital parameters (for orbit about the Earth)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from Earth</td>
<td>384,400 ± 21,100 km</td>
</tr>
<tr>
<td>Revolution period (sidereal)</td>
<td>27.3217 days</td>
</tr>
<tr>
<td>Synodic period</td>
<td>29.53 days</td>
</tr>
<tr>
<td>Mean orbital velocity</td>
<td>1.023 km/s</td>
</tr>
<tr>
<td>Inclination to ecliptic</td>
<td>5.145 deg</td>
</tr>
<tr>
<td>Inclination to equator</td>
<td>18.28 - 28.58 deg</td>
</tr>
<tr>
<td>Obliquity to orbit</td>
<td>6.68 deg</td>
</tr>
<tr>
<td>Recession rate from Earth</td>
<td>3.8 cm/year</td>
</tr>
<tr>
<td>Mean apparent diameter</td>
<td>0.52 deg</td>
</tr>
<tr>
<td>Apparent visual magnitude</td>
<td>-12.74</td>
</tr>
</tbody>
</table>
Table A.3: Major types of radiation in the lunar environment [4]

<table>
<thead>
<tr>
<th>Type</th>
<th>Solar Wind</th>
<th>Solar cosmic rays</th>
<th>Galactic cosmic rays</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy per nucleon</td>
<td>∼0.3-3 keV</td>
<td>∼1 to &gt;100 MeV</td>
<td>∼0.1 to &gt;10 GeV</td>
</tr>
<tr>
<td>Energy per electron</td>
<td>∼1-100 eV</td>
<td>&lt;0.1-1 MeV</td>
<td>∼0.1 to &gt;10 GeV</td>
</tr>
<tr>
<td>Fluxes (protons/cm²sec)</td>
<td>∼3 × 10⁸</td>
<td>∼ 0 – 10⁶</td>
<td>2-4</td>
</tr>
<tr>
<td>Lunar penetration depths</td>
<td>&lt; µm</td>
<td>mm ~ cm</td>
<td>cm ~ m</td>
</tr>
</tbody>
</table>

**Lunar surface temperatures and their variations** [4]:

- Equator: 255 ± 140 K
- Polar: 220 ± 10 K
- Shadowed polar craters: 40 (?) ± 0 K
Bibliography


81


## List of Tables

2.1 Summary of very low frequency array designs .......................................................... 25  
4.1 Possibilities for the VLF observatory site ................................................................. 52  
4.2 Factors influencing performance (top rows) and cost (bottom rows), and their drivers. .................................................................................................................. 60  
4.3 Order-of-magnitude cost estimates (in millions of $ or ESA accounting units) ................................................................................................................................. 64  
A.1 Moon’s bulk and environmental parameters ............................................................... 77  
A.2 Moon’s orbital parameters (for orbit about the Earth) .............................................. 77  
A.3 Major types of radiation in the lunar environment [4] ............................................ 78
List of Figures

1.1 A 10 MHz map of the southern sky at $\sim$5° resolution, by Cane & Erickson in 2001 [10].............................................................. 7
1.2 All-sky image at $\sim$2 MHz from the Radio Astronomy Explorer 2 satellite in 1970s [11].............................................................. 7
1.3 A new window for astronomy at very long wavelengths / very low frequencies. (All-sky maps credits: NASA) ....................................................... 7
1.4 Flux densities of active radio sources in the 10 kHz - 100 MHz range, from a 1997 ESA report [16], adapted from Zarka et al [23]. This shows the significance of interference compared to the background. $A_e$ is the effective area of the antenna.............................................................. 10
1.5 Overview flux spectra of the principal sources of noise in the terrestrial environment below 10 MHz, from Desch 1990 [24]. The flux densities of the Earth-based sources are as seen from almost half way to the Moon. While the spectral estimates may be relatively outdated, this plot shows the “Spherics”, including both man-made and lightning emissions, dominant above $\sim$1 MHz.............................................................. 11
1.6 Solar bursts, AKR, and Jupiter’s emissions seen by the Radio Receiver Band 1 (RAD1) of WAVES investigations on the WIND spacecraft [26]. .............................................................. 12
1.7 Man-made radio transmissions seen by RAD2 of WIND/WAVES [26].............................................................. 12
1.8 Radio Astronomy Explorer 2 satellite with its dipole antennas [20] .............................................................. 13
1.9 Example of a lunar occultation of the Earth as observed with the upper-V burst receiver of the lunar-orbiting RAE-2 satellite, from Alexander et al [20]. This shows the significance of the terrestrial noise even at the distance of the Moon, and its elimination behind the Moon.............................................................. 14

2.1 Angular resolution as a function of radio frequency, including dependence on interplanetary/interstellar scattering and interferometer baselines. From Bougeret (1996) [17] .............................................................. 20
2.2 A crossed-dipole antenna in ESA’s design [16]. Each element can be packaged in a 25 cm $\times$ 25 cm $\times$ 25 cm box.............................................................. 23
3.1 An example of a lunar occultation of a solar storm, from Alexander et al (1975) [20].

3.2 The lunar ionosphere, based on the Apollo lunar surface experiments [62]. The negative surface potential in the night side would likely keep electrons away.

3.3 Day-side lunar ionosphere profile, as inferred from the Luna 19 and 22 measurements. The data point uncertainty is ±200/cm$^3$. The apparent drop near the surface may not be statistically significant. From Vyshlov 1976 [63], adapted by Woan 2000 [59].

3.4 Typical upper lunar crust structures under a large crater [4]. The observatory site should be chosen to ensure that any subsurface structures do not disturb the observations by reflecting the penetrated waves back up to the antennas on the surface.

3.5 Perfectly matched layer (PML) technique for the simulation boundary [68].

3.6 The upper right corner of the finite-difference time-domain computational grid, with a perfectly matched layer (PML) at the boundary [68].

3.7 Depth profile of relative permittivity used in the simulation.

3.8 Depth profile of loss tangent used in the simulation.

3.9 Simulation result: Penetration of radio waves (0.5 MHz) into the Moon, as a function of depth. The solid line is the best exponential fit.

3.10 Result: Effective “skin depth” of the Moon, as a function of frequency.

3.11 Result: Effective “skin depth” of the Moon, as a function of wavelength.

3.12 Simulation setup: radio waves were produced along the dotted line.

3.13 Energy density distribution around the Moon with a continuous 10-km (30-kHz) plane wave incident from the left.

3.14 Energy density distribution around the Moon with a continuous 5-km (60-kHz) plane wave incident from the left.

3.15 Attenuation of energy density on the lunar surface at various angles around the Moon relative to the incident wave.

3.16 Simulation result: Attenuation as a function of frequency at the locations of the Daedalus crater (∼175°), Tsiolkovsky crater (∼125°), and at the pole (∼90°). This is an order-of-magnitude result.

3.17 Comparison in results between cylindrical and spherical models for the Moon (at 15 kHz, 20 km). The “orbit” data are for altitude of 100 km above the lunar surface. (The fringes are due to diffraction.)

3.18 Comparison in results between scalar and vector wave simulations, using rectangular coordinates (cylindrical Moon).
3.19 Attenuation of energy density on the lunar orbit at various angles around the Moon relative to the incident wave. .......... 49
3.20 Difference in attenuation of energy density on the lunar surface and on a 100-km lunar orbit (\(\nu = 50\) kHz, \(\lambda = 6\) km). (Because of the finite spatial resolution, "lunar surface" is somewhere in the 0-500 m altitude range.) 50

4.1 Estimated cost of ESA’s Very Low Frequency Array on the Lunar Far Side project [16]. For cost estimates of the rover and the relay satellite at L2, the ISU report [52] was referred to. .......................... 53
4.2 Orientation of the orbital and rotational axis of the Moon [72]. ........ 54
4.3 The lunar south polar region, imaged with Earth-based radar shining from the top by Margot et al [73]. Malapert Mountain (at longitude 0 and latitude 86° S) shields radiation from the Earth and can provide a radio quiet environment. ................................. 55
4.4 The same image as above, but indicating permanently dark areas both visible (white) and invisible (gray) to the Earth-based radar [73]. .... 55
4.5 Rough sketch of the simulation setup, with the 5-km tall Malapert Mountain on a surface sloped by 4° relative to the direction of Earth (left). Plane-wave radio interference was generated along the dashed line on the left. The lunar south pole is to the right. ......................... 56
4.6 Topology around Malapert Mountain, based on radar data by Margot et al [73]. .......................................................... 57
4.7 Energy density distribution for 0.5-MHz plane wave incident on Malapert Mountain from the direction of the Earth (left). ............... 57
4.8 Energy density distribution for 1-MHz plane wave incident on Malapert Mountain from the direction of the Earth (left). ............... 57
4.9 Shielding of interference (0.5 and 1.0 MHz) by Malapert Mountain (peaked at about 120 km from the south pole). This is in addition to the 20~30 dB attenuation already experienced by terrestrial radio waves in the polar region, based on the above simulation results. ............. 58
4.10 A general view of the linear array setup in the Earth shadow of Malapert Mountain. ................................. 62

5.1 The lunar south polar region, by Clementine probe [77] ............... 67
5.2 Daedalus crater (100 km diameter, 5°S, 178°E) [79] .................... 69
5.3 Tsiolkovsky crater (100 km diameter, 20°S, 129°E) [80]. ............... 69
5.4 Aitken crater (50 km diameter, 17°S, 173°E) [81]. ....................... 70

6.1 Similar lunar exploration scenarios by ESA (top) and Japan (bottom) as of the mid-1990s [82]. ................................. 72
6.2 Possible schedule for the lunar south polar VLF array project.  . . . . . 73
6.3 http://sdcd.gsfc.nasa.gov/ESDCD/GRX/Earth.Moon.gif . . . . . . . . . . . 76