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| **Purpose/Objective:** To provide information about astronomy that can be accomplished from the lunar surface and/or lunar orbit | |
| **Abstract:** Following the adoption of the ITU-R Question 260/7 “Radio astronomy in the shielded zone of the Moon”, this new Report identifies frequency ranges of particular interest for radio astronomy operations from lunar surface and/or lunar orbit. | |

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| Preferred frequency bands for radio astronomy facilities on the Moon | |

## Summary

Following the adoption of the ITU-R Question 260/7 “Radio astronomy in the shielded zone of the Moon”, this new Report identifies frequency ranges of particular interest for radio astronomy operations from lunar surface and/or lunar orbit.

## Attachment: 1

ATTACHMENT

Working Document towards a Preliminary Draft New Report ITU-R RA.[SZM-freq]

Preferred frequency bands for radio astronomy facilities on the Moon

(Question ITU-R 260/7)

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# 1 Introduction

Radio astronomy is a broad endeavor that seeks to further our understanding of the universe from studying individual celestial objects to large-scale structure and the dynamics of our universe. Because the electromagnetic spectrum is so heavily used on Earth for radiocommunications and other active services, access for passive scientific research is severely limited. For this reason, the Shielded Zone of the Moon (SZM)[[1]](#footnote-2) provides a unique environment for astronomy, free from terrestrial transmissions over the whole frequency spectrum. Additionally, the lack of a lunar ionosphere as well as the lack of appreciable water vapor and oxygen in the lunar environment enables scientific observations that are not possible from Earth.

Recommendation ITU-R RA.314 summarizes preferred radio frequency bands for astronomy observations, including both emission lines (dictated by nature) and broadbands. One of the most important emission lines for astronomy is the neutral hydrogen line at approximately 1420 MHz. Because hydrogen is ubiquitous in the universe, observations of this emission can enable studies of the universe’s structure over time, including probing the Epoch of Reionization (EoR), Cosmic Dawn (first stars), and the Dark Ages (pre-stellar exotic physics). However, because the universe is expanding, more distant cosmic radiation is redshifted. For this reason, observations of neutral hydrogen emissions can extend below 65 MHz for distant cosmic structures. Future radio telescopes located in the SZM will enable such measurements in the absence of human-made contamination, and therefore will have the potential to provide the most robust measurements of the evolution of structure in the universe.

A number of radio astronomy missions for the lunar far side have been proposed and are expected to be carried out well within this and the next decade. NASA’s Commercial Lunar Payload Services (CLPS) program is scheduled to deliver the first low frequency radio telescope (*Radiowave Observations at the Lunar Surface of the photoElectron Sheath*, ROLSES) to the lunar south pole in the first quarter of 2024. This will be followed by the first radio astronomy observations from the lunar far side in 2025/26 by the CLPS instrument *Lunar Surface Electromagnetic Experiment at Night* (LuSEE-Night), Some examples of NASA-funded concepts include the *Farside Array for Radio Science Investigation of the Dark ages and Exoplanets* (FARSIDE; 256 dipole antenna interferometer), *FarView* (100,000 dipole cosmology array using in-situ manufacturing), and the *Lunar Crater Radio Telescope* (LCRT). Further discussion of these and other proposed lunar facilities for radio astronomy can be found in Report ITU-R RA.[SZM]. While these early missions and concepts primarily operate at low frequencies between 10 kHz and 50 MHz, it is crucial to protect a broader bandwidth for future astronomy missions to achieve the full scientific potential of the lunar far side.

This report identifies frequency ranges of particular interest for radio astronomy operations from lunar surface and/or lunar orbit, especially those observations which would not be possible from Earth either due to terrestrial radio transmissions or due to properties of the Earth’s atmosphere. As described in Recommendation ITU-R RA.479, it is crucial to establish protections for such scientific missions as early as possible.

# 2 Frequency usage by RAS in the lunar environment

Although current mission concepts described in Report ITU-R RA.[SZM] are for lunar radio telescopes observing at low frequencies (10 kHz to 50 MHz), this early limitation is due to practical reasons and is not representative of the full potential of future radio observatories to be built on the Moon. Future facilities will observe in frequency bands inaccessible from Earth due to atmospheric effects and/or contamination from human-made terrestrial transmissions. Recommendation ITU-R RA.479 identifies frequency ranges of particular interest for future radio astronomy observations that are expected to be undertaken from the lunar far side and/or lunar orbit. These are described below.

## 2.1 Lunar radio astronomy in the 10 kHz to 50 MHz range

The ionosphere poses limitations to ground-based radio astronomy below 50 MHz. Although ground-based radio telescopes have detected cosmic radio waves at frequencies down to 1.5 MHz, capturing signals below 20 MHz due to ionospheric absorption is rare, only feasible in unique places and during specific times. Furthermore, the turbulent ionosphere refracts incoming radio waves making high fidelity cosmological observations below 50 MHz impossible. Terrestrial radio noise, both from human sources and natural phenomena, significantly hinders the ability to conduct detailed radio astronomy within this range. In particular, auroral kilometric radiation (AKR), radio noise originating from the Earth’s magnetosphere, is the primary noise source under 800 kHz, making this low-frequency range largely unreachable from Earth orbit. However, this frequency range is critical for studying various cosmic phenomena, such as the galactic non-thermal background, spectra from other galaxies, pulsars, and the radio emissions from the Sun, Jupiter, and exoplanets for which there are no alternative methods of observation. Measurements from the SZM could enable studies of such phenomena, otherwise impossible from Earth.

## 2.2 Lunar radio astronomy in the 50 to 300 MHz range

Active services on Earth extensively utilize this part of the radio spectrum, making it particularly challenging to perform radio astronomy observations within this band. Several faint radio recombination lines of carbon and nitrogen could be observed in this band absent terrestrial sources of contamination. Furthermore, astronomers are actively looking for the redshifted spectral line of hydrogen (HI) in primordial galaxies at frequencies below 150 MHz. Observations of pulsars, quasars, and steep spectrum sources are particularly crucial in this frequency band. For these reasons, this range of frequencies is of particular interest for scientific missions in the SZM.

## 2.3 Lunar radio astronomy in the 300 MHz to 3 GHz range

Some of the most heavily studied spectral lines are found in this portion of the spectrum. Notably, this band is faced with increasing competition on Earth as diverse needs for spectrum use grow, particularly within the commercial sector. The lines of greatest importance to radio astronomy are listed in Recommendation ITU-R RA.314[[2]](#footnote-3). Several of these are outlined in Table 1:

Table 1

**Spectral lines of interest to radio astronomy in the 300 MHz to 3 GHz range**

|  |  |
| --- | --- |
| **Spectral Line** | **Frequency** |
| Hyperfine transition of deuterium | 327.4 MHz |
| Neutral hydrogen (H I) | 1 420.4 MHz |
| OH radical line | 1 612.2 MHz |
| OH radical line | 1 665.4 MHz |
| OH radical line | 1 667.4 MHz |
| OH radical line | 1 720.5 MHz |

Portions of the spectrum containing these lines and their limited blue-shifted and red-shifted extensions are allocated to radio astronomy on Earth. Although heavily used by astronomers, these are not always sufficiently protected from space-based interference, inhibiting achievement of their full scientific potential. Additionally, the bands allocated to radio astronomy are often significantly narrower than the full redshift range of interest. For example, red-shifted HI observations provide information on the formation of galaxies and the early Universe, the subject of cutting-edge research efforts. Astronomers have also predicted the existence of red-shifted OH mega-masers, observable at frequencies as low as 500 MHz and below. Highly red-shifted objects emitting in the HI or OH lines are expected to be of great interest to astronomers well into the next century. Since the SZM is likely to be nearly interference free, great interest in lunar-based observations of these faint objects is expected. Continuum observations in the 300 MHz to 3 GHz range are carried out in the 1.4 GHz (1.400-1.427 GHz), 1.6 GHz (1.66-1.67 GHz), and 2.7 GHz (2.69-2.7 GHz) bands. The 2.29-2.3 GHz deep space band is also used to make very long baseline interferometry (VLBI) observations.

## 2.4 Lunar radio astronomy in the 3 to 20 GHz range

The shielded zone of the Moon will provide a unique environment for observing spectral lines that are difficult to observe from the Earth. In particular, radio astronomy has very few allocations for Earth-based observations in the bands listed in Table 2. This portion of the spectrum is utilized by active services, rendering a number of spectral lines of interest to radio astronomy difficult to observe from the Earth.

Table 2

**Spectral lines of interest to radio astronomy in the 3 to 20 GHz range**

|  |  |
| --- | --- |
| **Spectral Line** | **Frequency** |
| Methylidyne (CH) | 3 263.8 MHz |
| Methylidyne (CH) | 3 335.5 MHz |
| Methylidyne (CH) | 3 349.2 MHz |
| Formaldehyde (H2CO) | 4 829.7 MHz |
| Formaldehyde (H2CO) | 14.49 GHz |
| Methanol (CH3OH) | 6.7 GHz |
| Methanol (CH3OH) | 12.2 GHz |
| Cyclopropenylidene (C3H2) | 18.3 GHz |

Continuum observations are also conducted in a number of bands in this spectral range. The continuum bands used by radio astronomers are in the neighbourhood of the following bands: 4.99-5.0 GHz, 10.68-10.7 GHz and 15.35-15.4 GHz. Radio astronomers also make use of the 8.40-8.50 GHz deep-space band.

## 2.5 Lunar radio astronomy in the 20 to 1 000 GHz range

Attenuation by neutral atmospheric gases inhibits scientific observations in this frequency band. Water vapor attenuation in the Earth’s atmosphere rises steeply above 10 GHz, peaking at 22.235 GHz. Oxygen lines also attenuate emissions heavily in the vicinity of 60 GHz and 120 GHz, as well as the water lines near 183 GHz. Within the frequency windows between these absorption lines, astronomical observations become progressively more difficult with increasing frequency due to increasing attenuation from the absorption line wings, as well as increasing phase fluctuations. These difficulties can render measurements with high angular resolution intractable, even at high-altitude, dry observations sites. Thus, the lack of an atmosphere and extremely dry conditions make the SZM ideal for astronomical observations in this frequency range.

# 3 Interference protection criteria for lunar radio astronomy

*{Editor’s note:* *This section is still under development. Propagation characteristics from ITU WP 3J are needed to inform protection criteria for lunar radio astronomy. The below tables are in the format of those in Recommendation ITU-R RA.769 for threshold levels for interference based on power received by a single antenna. The values to be included in these tables are yet to be determined. Please refer to Recommendation ITU-R RA.479-5 section 2 to provide clarity on which stations and services are bound by the defined protection criteria.}*

• Definition of threshold levels of harmful interference (RR No. **22.22.2**)

Table 3

**Threshold levels of interference detrimental to radio astronomy continuum observations**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Centre frequency *fc* (MHz)** | **Assumed bandwidth *∆f* (MHz)** | **Minimum antenna noise temperature *TA* (K)** | **Receiver noise temperature *TR* (K)** | **System sensitivity (noise fluctuations)** | | **Threshold interference levels** | | |
| **Temperature *∆T* (mK)** | **Power spectral density *∆P* (dB(W/Hz))** | **Input power *∆PH* (dBW)** | **pfd *SH ∆f* (dB(W/m2))** | **Spectral pfd *SH* (dB(W/(m2 ⋅ Hz)))** |
| **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** | **(8)** | **(9)** |
|  |  |  |  |  |  |  |  |  |

Table 4

**Threshold levels of interference detrimental to radio astronomy spectral-line observations**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Frequency *f* (MHz)** | **Assumed spectral line channel bandwidth *∆f* (kHz)** | **Minimum antenna noise temperature *TA* (K)** | **Receiver noise temperature *TR* (K)** | **System sensitivity (noise fluctuations)** | | **Threshold interference levels** | | |
| **Temperature *∆T* (mK)** | **Power spectral density *∆Ps* (dB(W/Hz))** | **Input power *∆PH* (dBW)** | **pfd *SH ∆f* (dB(W/m2))** | **Spectral pfd *SH* (dB(W/(m2 ⋅ Hz)))** |
| **(1)** | **(2)** | **(3)** | **(4)** | **(5)** | **(6)** | **(7)** | **(8)** | **(9)** |
|  |  |  |  |  |  |  |  |  |

# 4 Summary

Radio astronomy is an expansive field dedicated to enhancing our comprehension of the universe by examining everything from individual celestial bodies to the vast structures and dynamics governing the universe. Earth's heavy use of the electromagnetic spectrum limits the capacity for passive astronomical research, making the Moon's shielded zone a vital location for interference-free observations. The lack of a lunar ionosphere and negligible water vapor and oxygen make the Moon an ideal site for unique scientific studies not possible on Earth. The ITU-R RA.314 and ITU-R RA.479 recommendations detail preferred radio frequencies for such observations. Radio telescopes to be built in the SZM can measure these emissions without Earth-based contamination, thus offering new insights into the universe's structure and evolution. Future lunar missions aim to utilize broad bandwidths to maximize the scientific potential of the SZM. Protection of these frequencies is crucial for the advancement of radio astronomy.

# 5 Related ITU-R Recommendations/Reports

Recommendation ITU-R RA.314 – *Preferred frequency bands for radio astronomical measurements*

Recommendation ITU-R RA.479 – *Protection of frequencies for radioastronomical measurements in the shielded zone of the Moon*

Recommendation ITU-R RA.769 – *Protection critera used for radio astronomical measurements*

Report ITU-R RA.[SZM]

# 6 Abbreviations/Glossary

AKR Auroral Kilometric Radiation

CLPS Commercial Lunar Payload Services

EoR Epoch of Reionization

FARSIDE Farside Array for Radio Science Investigation of the Dark ages and Exoplanets

LCRT Lunar Crater Radio Telescope

LuSEE Lunar Surface Electromagnetic Experiment

RAS Radio Astronomy Service

ROLSES Radiowave Observations at the Lunar Surface of the photoElectron Sheath

RR Radio Regulations

SZM Shielded Zone of the Moon

VLBI Very Long Baseline Interferometry

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1. The SZM consists of the shielded area of the Moon's surface together with an adjacent volume which is shielded from interference originating within a distance of 100 000 km from the centre of the Earth (Article 22, RR No. 22.22.1). [↑](#footnote-ref-2)
2. Several lines not identified as having high significance have led to the discovery of important astrophysical information. Also, astronomers continue to discover more lines of significance over time. [↑](#footnote-ref-3)