Characterizing the Radio Quiet Region Behind the Lunar Farside for Low Radio Frequency Experiments

Neil Bassett
University of Colorado Boulder
Center for Astrophysics and Space Astronomy

In collaboration with:
David Rapetti (CU Boulder/NASA Ames), Jack O. Burns (CU Boulder), Keith Tauscher (CU Boulder), and Robert MacDowall (NASA Goddard)
Motivation

Farside Array for Radio Science Investigations of the Dark ages and Exoplanets (FARSIDE)

- 200 kHz - 40 MHz
- Interferometric array of 128 antennas directly on lunar surface
- 21-cm power spectrum, direct imaging of exoplanet magnetospheres

Dark Ages Polarimeter PathfindER (DAPPER)

- 17 - 107 MHz
- Single Antenna in 50x125 km orbit of the Moon
- 21-cm global signal measurement
Ionospheric effects

- Right: Ionospheric attenuation as a function of frequency for four different Total Electron Content (TEC) values

Observations below ~30 MHz must be performed above Earth’s ionosphere to avoid corruption of 21-cm spectrum

Datta et al. 2016
Earth-based Radio Frequency Interference (RFI)

Bentum & Boonstra 2011

Bentum & Boonstra 2011
Earth-based Radio Frequency Interference (RFI)

Even above ionosphere, terrestrial communications may interfere with low frequency measurements.

Observations must be performed in a radio quiet environment where Earth-based RFI is mitigated.
Lunar Radio Environment Geometry

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Knife Edge Approximation

Knife Edge

Radio Quiet Zone

RFI from Earth
Knife Edge Approximation

Diffraction around straight edge is analytically solvable, first by Sommerfeld in 1896.

More accurate treatment requires non-analytic methods, i.e. computer simulations.

Pluchino, Antonietti, & Maccone 2007
Finite Difference Time Domain (FDTD) Method

\[
\frac{\partial E_x}{\partial t} = -\frac{1}{\epsilon_0} \frac{\partial B_y}{\partial z}
\]

\[
\frac{\partial B_y}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_x}{\partial z}
\]

Yee Grid Discretization

\[
\frac{E_x^{n+1/2}(k) - E_x^{n-1/2}(k)}{\Delta t} = -\frac{1}{\mu_0} \frac{B_y^n(k + 1/2) - B_y^n(k - 1/2)}{\Delta z}
\]

\[
\frac{B_y^{n+1}(k + 1/2) - B_y^n(k + 1/2)}{\Delta t} = -\frac{1}{\mu_0} \frac{E_x^{n+1/2}(k + 1) - E_x^{n+1/2}(k)}{\Delta z}
\]
2-dimensional Lunar Simulations

\[ \nu = 30 \text{ kHz}, \ \lambda = 10 \text{ m} \]

Lunar Electrical Properties:
\[ \bar{\rho} = 3.34 \text{ g/cm}^3 \]
\[ \varepsilon = 1.919\bar{\rho} \]
\[ \varepsilon \sim 8.8 \]
\[ \tan \delta = 10^{(0.44\bar{\rho} - 2.943)} \]
\[ \tan \delta \sim 0.034 \]

Values from Lunar Sourcebook

Simulations performed using MEEP for Python (Oskooi et al. 2010)

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RFI Attenuation

Science observations are taken in region where RFI is suppressed by at least 80 dB to prevent contamination
Lunar Topography

Data from Lunar Orbiter Laser Altimeter (LOLA) instrument on Lunar Reconnaissance Orbiter

http://pds-geosciences.wustl.edu/lro/lro-l-lola-3-rdr-v1/lrolol_1xxx/DATA/lola_gdr/cylindrical/img/loladem_16.img
Lunar Topography

Lunar topography plays only a small part, but tends to increase attenuation of RFI behind farside, especially above the surface.
Lunar Density Profiles

Constant average density profile provides lower limit on size of quiet region

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Extrapolating to Higher Frequencies
Extrapolating to Higher Frequencies

![Graph showing the relationship between width and frequency.](image-url)
Extrapolating to Higher Frequencies

\[ \omega = \omega_{max} - a\nu^{-b} \]
Extrapolating to Higher Frequencies

[Graph showing the relationship between Width (deg) and Frequency (kHz)]

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**Possible Surface Locations for Radio Experiments**

- **Lunar Reconnaissance Orbiter Camera**
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- **Solid = 100 kHz**
- **Dashed = 10 MHz**

### Table: Radio Frequency Interference (RFI) at 100 kHz

<table>
<thead>
<tr>
<th>Crater</th>
<th>Latitude</th>
<th>Longitude</th>
<th>RFI (100 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schrodinger</td>
<td>75.0° S</td>
<td>132.4° E</td>
<td>-41 dB</td>
</tr>
<tr>
<td>Tsiolkovsky</td>
<td>20.4° S</td>
<td>129.1° E</td>
<td>-125 dB</td>
</tr>
<tr>
<td>Daedalus</td>
<td>5.9° S</td>
<td>179.4° E</td>
<td>-199 dB</td>
</tr>
</tbody>
</table>

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*Figure showing possible surface locations for radio experiments with noted RFI levels at 100 kHz. The areas marked with solid and dashed lines represent different frequency bands for potential experiments.*
Conclusions

- In order to extract 21-cm spectrum below 30 MHz, observations must be performed in a radio quiet environment above the Earth’s ionosphere.

- The Moon blocks terrestrial radio signals, providing a unique radio quiet zone behind the lunar farside.

- Electromagnetic FDTD simulations show that the suppression of RFI on the farside is sufficient (≥ 80 dB) to perform cosmological 21-cm observations both on the surface and in lunar orbit.

- The topography and density profile of the Moon do not significantly affect the size of the radio quiet zone.

- At frequencies above 10 MHz, nearly all of the farside, including the South Pole Aitken Basin, are shielded from terrestrial RFI at the 80 dB level.