The Radio Quiet Environment Above the Lunar Farside and its Application to 21-cm Experiments

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21-cm Hydrogen Cosmology

- Left: The redshifted 21-cm spectrum provides information about the universe during the Dark Ages and Cosmic Dawn
- Right: Reported measurement of 21-cm Cosmic Dawn absorption trough centered at 78 MHz reported by EDGES
Observational Difficulties

- The 21-cm spectrum must be observed through extremely bright foregrounds.
- Differences in foreground and 21-cm spectrum can be leveraged to extract cosmological signal.

**Foreground Characteristics**
- Spectrally smooth
- Spatial structure
- Polarized

**Signal Characteristics**
- Spectral structure
- Isotropic
- Unpolarized

Burns et al. 2019
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
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

- **Nearside**
- **Farside**
- **Radio Quiet Zone**

RFI from Earth
Knife Edge Approximation

RFI from Earth

Knife Edge

Radio Quiet Zone
Knife Edge Approximation

Diffraction around straight edge is analytically solvable, first bySommerfeld 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

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

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

Diagram of E_x and H_y fields with time steps at \((n-1/2)\Delta t\), \((n)\Delta t\), and \((n+1/2)\Delta t\).
2-dimensional Lunar Simulations

$v = 60$ kHz, $\lambda = 5$ km

Nearside

Farside

Lunar Electrical Properties:

$\bar{\rho} = 3.34 \text{ g/cm}^3$

$\varepsilon = 1.919\rho$

$\varepsilon \sim 8.8$

$\tan \delta = 10^{(0.44\rho - 2.943)}$

$\tan \delta \sim 0.034$

Values from Lunar Sourcebook

Simulations performed using MEEP for Python (Oskooi et al. 2010)
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/1ro/Iro-l-lola-3-rdr-v1/Irolol_1xxx/DATA/lola_gdr/cylindrical/img/ladem_16.img
Lunar topography plays only a small part, but tends to increase attenuation of RFI behind farside, especially above the surface.
Possible Surface Locations for Radio Experiments

Lunar Reconnaissance Orbiter Camera

<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>
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 of the Moon does not significantly affect the size of the radio quiet zone.

- Sites closer to the lunar limb such as the Schrödinger crater are quiet enough to perform some low frequency astronomical observations.