Imaging with FARSIDE: A Radio Telescope on the Lunar Farside

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A probe class mission concept funded by NASA to place a radio array on the lunar farside

FARSPACE

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

P.I.s:
Dr. Jack Burns, CU Boulder
Dr. Gregg Hallinan, CU Boulder

Jet Propulsion Laboratory
California Institute of Technology
NASA’s Mission to the Moon

Artemis Phase 1: To the Lunar Surface by 2024

Artemis 1: First human spacecraft to the Moon in the 21st century

Artemis 2: First humans to the Moon in the 21st century

First high power Solar Electric Propulsion (SEP) system

First pressurized module delivered to Gateway

Artemis 3: Crewed mission to Gateway and lunar surface

Commercial Lunar Payload Services
- CLPS delivered science and technology payloads

Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles

Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions

Lunar South Pole target
Why observe the Dark Ages?
- Ideal playground to test the standard models of Cosmology
- Deviations ⇒ Test exotic physics (eg: non-gravitational interaction of DM)
Where do we tune the dial?

Neutral Hydrogen is plenty in the Dark Ages!
Look for the 21cm signal from the Hyperfine transition
Hydrogen Cosmology

We are looking for <100 mK signal below 40 MHz
Atmosphere ⇒ Magnetic fields ⇒ Radio emission ⇒ Important question: Is there life in those planets?

At same frequencies: Exoplanet Magnetosphere Study

Host star: radio bursts
traces density at CME shock

Planet: Auroral radio emission
measures magnetic fields

Credit: Chuck Carter and Caltech/KISS
Where do we tune the dial, again?

Electron cyclotron maser emission

Frequency (MHz) = $B_{\text{Gauss}} \times 2.8$

Based on models, we expect most of detections to be $< 30$ MHz

- Tidal locked $\Rightarrow$ weak magnetic field
- Planetary sizes of Jupiter $\Rightarrow$ $< 30$ MHz

Expected Frequency & Max flux from known planets using Magnetic field models [Grießmeier et al. 2015]
Where do we place this radio (<40 MHz) array?

- Earth’s radio emission
- Terrestrial RFI still seen
- Solar winds

We need 100s of elements

Ionosphere blocks low frequencies

NASA RAE - 2, Alexander et. al. 1975
FARSIDE Mission concept

- Booms
- Stereo Camera
- Spool assembly
- Deployment rovers
- Tethers with antennas embedded
- High Gain Antenna
- CLPS Lander with the Base station
- Solar Panels
- CLPS Lander with the Base station
- Stereo Camera
- Booms
- Spool assembly
FARSIDE Array Layout

- Advantages:
  - Robust (fail safe)
  - Ease of deployment
  - Circular polarization for exoplanet science

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>No. of Antennas</td>
<td>128 pairs</td>
</tr>
<tr>
<td>Frequency</td>
<td>100 kHz – 40 MHz</td>
</tr>
<tr>
<td>Antenna element</td>
<td>100 m dipoles</td>
</tr>
<tr>
<td>Deployment</td>
<td>Embedded in tether</td>
</tr>
</tbody>
</table>

What is a dipole antenna?
Significance & Need

- **Polarization:**
  - Any EM wave is associated with a polarization information.
  - How the Electric field is orientated.

- **Stokes parameters:**
  - Quantifies polarization of a signal
  - I - Unpolarized, Q & U- Linear, V - Circular

- **Significance to FARSIDE?**
  - Exoplanets → Circular polarization: Electron Cyclotron Maser
  - Separates the host and planet signal

- **Importance of this study**
  - Instrument effects can cause intermixing of intrinsic source polarization.
  - Antenna offset adds more mixing (compared to co-located configurations)

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*We must model and understand these effects to maximize the performance of FARSIDE*
Stokes Leakage: Normal Case

- **Input**: Dipole beam placed orthogonally
  
  $J_{\text{beam}} = \begin{bmatrix} E_x^\theta & E_x^\phi \\ E_y^\theta & E_y^\phi \end{bmatrix}$

- Polarization components:
  - $I$, $Q$, $U$, $V$

- Diagonal terms - Ideal capture

- Off diagonals - Leakage
  - $I$ of the sky $\rightarrow$ Instrument $I, Q, U, V$
  - $Q$ of the sky $\rightarrow$ Instrument $I, Q, U, V$
  - $U$ of the sky $\rightarrow$ Instrument $I, Q, U, V$
  - $V$ of the sky $\rightarrow$ Instrument $I, Q, U, V$
Stokes Leakage: FARSIDE Case

- **Input**: beam + Offset the antennas

\[
J_{\text{offset}} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\Delta \phi} \end{pmatrix}
\]

Phase difference due to the offset in Y dipoles

\[
(J_{\text{beam}} \ast J_{\text{offset}}) \ast \text{Sky} \ast (J_{\text{beam}} \ast J_{\text{offset}})^H
\]

- Adding the offset has a significant impact, especially on the circular polarization signal.
- Shown here for observation at 1 MHz
  - It varies with frequency
  - Errors in the offset

- Shown here for observation at 1 MHz
  - It varies with frequency
  - Errors in the offset
Simulating observations through the FARSIDE array

Input Model Image
*Only Stokes I*

Output Image
*Received: Stokes I & V*
Discussion

- FARSIDE is a mission concept to place a **low frequency radio array** on the farside on the moon.
- Compelling astrophysics ([Exoplanet study and Hydrogen cosmology](#)) that uniquely requires low frequency observations from the Moon
- For ease of deployment, the array layout has a **spatial offset between** the orthogonal dipoles
- It affects the *Polarization leakage* - we have formulated a study
- Constructed a complete pipeline to process point source sky models through FARSIDE array
- Formulated a correction scheme to tackle these offset induced polarization
Started on Sept 2019 we have grown to 600 followers, 30 posts and interviews including: Students, Postdocs, Faculty and Staff

Supported by: immense interest and support from the community

**Our Vision**
- Collecting lived experiences
- Encourage interdisciplinary dialog
- Build community
- Foster connections
- Scream “You are not alone” from the otherside of the academic journey

Interested? Email: humansofsese@gmail.com
EXTRA SLIDES
Hence the Lunar Farside!

NASA RAE-2 occultation of Earth in 1972

Wind/Waves data near the Moon in 1999
The M Dwarf Opportunity

Rocky planets are particularly frequent around M dwarfs (Dressing & Charbonneau 2013, 2015)

The nearest “habitable” planet likely orbits an M dwarf within a few pc
Type II Radio Bursts

Credit: Gregg Hallinan, Caltech
Near Rectilinear Halo orbit


The Northern and Southern L1 and L2 NRHOs are periodic in the Circular Restricted 3-Body Model, and can be transitioned into quasi-periodic orbits in a higher fidelity model.
Two-dimensional numerical electrodynamics simulations show that the relative intensity of terrestrial radio waves incident on the Moon is highly attenuated behind the farside.

The “radio quiet” region at 100 kHz (solid) and 10 MHz (dashed) defined by ≥ 80 dB attenuation plotted over a map of the lunar surface.
Timeline & Budget

### Cost Summary (FY2019$M)

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>CBE</th>
<th>Res.</th>
<th>Team X Estimate</th>
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</thead>
<tbody>
<tr>
<td><strong>Total Cost</strong></td>
<td>$1080M</td>
<td>27%</td>
<td>$1330M</td>
</tr>
<tr>
<td>MMRTG + RHU</td>
<td>$70M</td>
<td>0%</td>
<td>$70M</td>
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<tr>
<td>Launch Vehicle</td>
<td>$150M</td>
<td>0%</td>
<td>$150M</td>
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<td>Development &amp; Ops Cost</td>
<td>$865M</td>
<td>29%</td>
<td>$1040M</td>
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<tr>
<td>Development Cost</td>
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<td>30%</td>
<td>$1040M</td>
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<td>Phase A</td>
<td>$8M</td>
<td>30%</td>
<td>$10M</td>
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<tr>
<td>Phase B</td>
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<td>$90M</td>
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<tr>
<td>Phase C/D</td>
<td>$720M</td>
<td>30%</td>
<td>$940M</td>
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<tr>
<td>Operations Cost (Phase E/F)</td>
<td>$65M</td>
<td>15%</td>
<td>$75M</td>
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</tbody>
</table>
Additional Science

- Heliophysics
- Monitoring of auroral processes & lightning at Jupiter, Saturn, Uranus and Neptune
- Searches for unknown large magnetized bodies in our solar system (e.g. Planet 9)
- Triggered spectroscopy of exoplanets experiencing geomagnetic storms
- Tomography of the ISM
- Lunar Seismology: Moonquakes
- SETI
- Serendipitous!
At the same frequencies: Exoplanet Study

Host star: radio bursts traces density at CME shock

Planet: Auroral radio emission measures magnetic fields

Credit: Chuck Carter and Caltech/KISS
FARSDIE Mission concept

Credit: Micheal Walker, CU Boulder
Response of a co-located array - Normal case

- Both polarizations have the same phase center, i.e,
  - The feed is at the same position in space
  - Examples: OVRO-LWA, MWA, HERA

- To create images of the sky signals from all the antenna pairs are combined

- Only one delay to combine them appropriately.
Response of a Non co-located array - FARSIDE case

- In a non co-located array: X and Y antennas are offset
  - Do not have the same phase center
  - Examples: 21CMA

- Extra delay ($\tau_0$) between the X and Y combinations from each antenna pair.

- Additional corrections when combining data from different antennas
Eye of the array: PSF & UV coverage of FARSIDE

Spiral arm layout

Simulated for RA = 0hr & dec = 30 deg

- XX/YY & XY UV coverage and PSF are different
- Offsets fills the UV space more
- Lower slidelobe levels
Hydrogen Cosmology

Hydrogen as a Probe

Hydrogen atom & its spin axis

Prior to reionization ⇒ dark Ages & cosmic dawn
Hydrogen is plenty!

What is the signal?

Emission due to spin flip transition

- When the spin axis changes from aligned to anti-aligned
- Produces radiation at 1.42 GHz
Beam Jones matrix for every \((l, m)\)

1.) \(J_{\text{beam}} = \begin{bmatrix} E_x^x & E_x^\phi \\ E_\phi^x & E_\phi^\phi \end{bmatrix}\)
2.) \(J_{\text{offset}} = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\Delta \phi} \end{bmatrix}\)
3.) \(J = J_{\text{offset}} \times J_{\text{Beam}}\)

Generate Beam map
1.) 100m dipole on regolith
2.) Two simulated beams for X & Y dipoles
3.) Beam \((\theta, \phi)\) \(\rightarrow\) Beam \((l, m)\); 181 x 361 \(\rightarrow\) 100 x 100

Generate sky map
1.) Def array location: lon=180, lat=0
2.) Set LST = 20 hr
3.) RA & dec \(\rightarrow\) Az, El
4.) \(Sky_n (90-El, Az) \rightarrow Sky_n (l, m)\)

Sky Coherence matrix for every \((l, m)\)
1.) Give I, Q, U and V values
2.) \(C = \begin{pmatrix} I + Q & U - iV \\ U + iV & I - Q \end{pmatrix}\)

\[ J = J_{\text{offset}} \times J_{\text{Beam}} \]

Generate the UV coverage for each source
1.) Hour angle \((H_o) = \text{LST} - \text{RA}\)
2.) Generate baselines\((x, y, z)\)
3.) \(u(H_o, \text{dec}, (x, y, z)) \& v(H_o, \text{dec}, (x, y, z))\)
4.) Grid the \(u\) \& \(v\) \(\Rightarrow\) shape \((l \times m)\)

\[ \text{FFT} \]

\[ \text{iFFT} \]

Identify sources \((n)\)
Eg: \(Sky_1 \Rightarrow \text{Cyg A}, Sky_2 \Rightarrow \text{Cas A}, Sky_3 \Rightarrow \text{Sgr A}\)

Generate sky map
1.) Def array location: lon=180, lat=0
2.) Set LST = 20 hr
3.) RA & dec \(\rightarrow\) Az, El
4.) \(Sky_n (90-El, Az) \rightarrow Sky_n (l, m)\)

\[ \text{Image}_I(\theta, \phi) = \text{Image}_{xx}(\theta, \phi) + \text{Image}_{yy}(\theta, \phi) \]
\[ \text{Image}_Q(\theta, \phi) = \text{Image}_{xx}(\theta, \phi) - \text{Image}_{yy}(\theta, \phi) \]
\[ \text{Image}_U(\theta, \phi) = \text{Image}_{xy}(\theta, \phi) + \text{Image}_{yx}(\theta, \phi) \]
\[ \text{Image}_V(\theta, \phi) = -j \text{Image}_{xy}(\theta, \phi) + j \text{Image}_{yx}(\theta, \phi) \]
Applying correction

Simple math for the correction. ⇒

Tests:

1.) One zenith source:
   a.) What to expect: No offset effect, and correction should return the original image
   b.) The three columns in the next image should be the same

2.) One off zenith source:
   a.) What to expect: The non offset and offset images will be different for U and V - or - XY and YX. The corrected image of U & V (or - XY and YX) should be same as the non offset case
The differences in the I & Q fluxes between the offset and no offset cases is nearly zero as expected (slide 13).

Analysing the V polarization

- @ 2 MHz
  - For no offset: (peak) V/I ratio ~ $10^{-3}$
  - Offset case: (peak) V/I ratio ~ 0.041
- @ 0.6 MHz
  - For no offset: (peak) V/I ratio ~ $2 \times 10^{-5}$
  - Offset case: (peak) V/I ratio ~ 0.02

Analysing the U polarization

- @ 2 MHz, a difference of 35% in the U fluxes
- @ 0.6 MHz, a difference of 4% in the U fluxes
Final Discussion

- FARSIDE is a timely Probe class mission.
- Radio Array, behind the moon & Low frequencies.
- Increase interest in:
  - Lunar exploration
  - Development of the Lunar gateway
  - Advancement of more capable landers
  - NASA’s investment in the Artemis program
- Main science cases: Exoplanet, global 21cm
- Been Studied:
  - Sensor elements,
  - Array layout,
  - electronics(OVRO-LWA),
  - mission architecture,
  - relay satellite & data processing
- Launch in ~2028 & data 6 months hence.