The Lunar Farside: A Science and Exploration Imperative

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Why the Lunar Farside?

- A whole new, *unexplored* world in Earth’s backyard! Nearly $4 \times$ land area of the United States.
- Opportunity to demonstrate human-robotic exploration strategies needed to explore the Moon, asteroids, & Mars.
- Farside includes the South Pole-Aitken basin – largest, deepest, & oldest impact basin in the inner solar system.
- Farside always faces away from Earth and is the only pristine radio-quiet site to pursue observations of the early Universe’s *Cosmic Dawn* at $\nu \sim 10$-80 MHz.
Why Emplace Radio Telescopes on the Farside?

- **Earth’s Ionosphere** (e.g., Vedantham et al. 2014; Datta et al. 2016; Rogers et al. 2015; Sokolowski et al. 2015)
  - Refraction, absorption, & emission.
  - Spatial & temporal variations related to forcing action by solar UV & X-rays => 1/f or flicker noise acts as another systematic or bias.
  - Effects scale as \( \nu^{-2} \) so they get **much worse** approaching 10 MHz.

- **Radio Frequency Interference (RFI)**
  - RFI particularly problematic for FM band (88-110 MHz).
  - Reflection off the Moon, space debris, aircraft, & ionized meteor trails are an issue everywhere on Earth (e.g., Tingay et al. 2013; Vedantham et al. 2013).
  - Even in LEO \( (10^8 \text{ K}) \) or lunar nearside \( (10^6 \text{ K}) \), RFI brightness \( T_B \) is high. Need to suppress RFI by at least -80 dB to observe cosmological signal.
Astrophysics Decadal “New Worlds, New Horizons”: “A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our Cosmic Dawn?”

NASA Astrophysics Division Roadmap (2013): How Does our Universe Work?

- **Small Mission**: “Mapping the Universe’s hydrogen clouds using 21-cm radio wavelengths via a lunar orbiter observing from the farside of the Moon”.
- **Visionary Era**: “Cosmic Dawn Mapper (21-cm lunar surface radio telescope array) ... Detailed map of structure formation in the Dark Ages via 21-cm observations”.

Publications:

High-Level Trade Space for Lunar Radio Telescopes

- Instruments
- Deployment
- Environment
- Power

- Location
- RFI
- Communications

Solar Panel Array
Polyimide Film Antenna Arm
Central Electronics Package (CEP)
Battery Pack Modules

Lunar Science for Landed Missions Workshop, 10-12 January 2018
Instruments

Hydrogen Cosmology Global Signal Telescope

- 10-100 MHz
- Polarimeter
- Ground Plane
- Operation temperature = -250°C to +150°C
- Power < 200 W
- Data storage (< 1 GB per 24 hr)
- Data transmission (< 1 GB per day)

Cosmic Dawn Mapper

- At 10 MHz, 1° resolution requires ~2 km baselines
  - Filled aperture: 1 element / 3600 sq. m
  - Circle layout: 1 element / 6 meters
- $10^5$ square meters collecting area requires >1000 dipoles
- 1000 dipoles * 2 pol * 20 MHz bandwidth $\rightarrow$ ~40 GB/s
- Power ~2.5 kW
Can a Low Frequency Antenna be Sited in a Polar Crater?

Solar panels
Communication Antenna

Batteries

Hit by Sunlight (Periodically or continuously)

Crater at Lunar North/South Pole
No Sunlight Ever

Antenna

Receiver

1-m

Underground for higher and more stable temperatures

Side view
Radio Frequency Interference (RFI) within a crater at the Lunar Pole

Simulating RFI in a polar crater, with the edge of the crater as a knife-edge. The transmitter ($T_X$) is on Earth, and the receiver ($R_X$) is in the crater, at a distance $d_R$ from the edge. The RFI attenuation at $R_X$ is computed using:

$$x = h \sqrt{\frac{2}{\lambda} \left( \frac{1}{d_T} + \frac{1}{d_R} \right)}$$

**Attenuation**

- $A = 0$, if $x < 0$
- $A = 6 + 9x + 1.27x^2$, if $0 < x < 2.4$
- $A = 13 + 20 \log(x)$, if $x > 2.4$

**Problems:**

- Insufficient attenuation
- Crater rim blocks sky & corrupts antenna beam.
From simulation by Datta et al. (2018). At latitude of -80° and frequency of 1 MHz, -80 dB is achieved at ≈45° from the lunar limb.
RFI Constraints on Telescope Location

=> Northwestern quadrant of Schrödinger impact basin is sufficiently quiet.
• Data are required for the electrical conductivity & permittivity of the regolith, to model the response of low-frequency antennas.
• On dayside, UV & X-rays positively-charge surface with 1–5 V whereas nightside has negative surface potential with $\geqslant$-500 V. Charged dust grains are levitated (Fig. 1).
• Changes in surface potential by 10x occur during solar energetic particle event $\Rightarrow$ Need to stay grounded to plasma.
• Elevated dust (Fig. 1) can cause visibility problems, especially for teleoperation.
• Strong electric fields occur in terminator & shadowed regions. Gradients cause negatively charged particles to accelerate away from the surface (Fig. 2). Effect on electronics mitigated by placing electronics underground (<1 m), & within Faraday cages.

Figure 1. Top: Observations of elevated dust by Surveyor (Colwell 2007). Bottom: Lunar surface is positive charged on dayside & negatively charged on nightside (Farrell et al. 2007).

Figure 2. Localized electric field effects (Farrell et al. 2007).
The Lunar Environment

Longitude-average temperature model  (Source: LRO Diviner)
Power Requirement: 0.2 – 2.5 kW
• Assuming above accounts for instrument and thermal control electronics.
• Battery + solar panels (outside crater if necessary).
• RTG (radioactive).
• Power beamed from Deep Space Gateway.

Data Downlink Requirement: < 1 GB per 24 hr to 40 GB/sec
• Use Deep Space Gateway as communication relay for first generation instruments.
Summary and Conclusions

- **Lunar Farside** is the only location in the inner solar system quiet enough to conduct observations of Cosmic Dawn down to $\sim 10$ MHz.
- **Possible instruments:** Single antenna for Global 21-cm Signal and Array of Dipoles to measure the spatial structure in the early Universe.
- Polar craters do not provide enough attenuation of RFI for siting a low frequency radio telescope.
- But, **locations $<$80° latitude and 45° from the lunar limb on the farside are suitable sites.** This includes a NW quadrant of Schrödinger.
- **Lunar environment:**
  - Elevated dust and changes in surface potential are possible issues. Need to stay grounded to local plasma. **Siting electronics below ground and/or in Faraday cages are probably needed.**
  - Day/night temperature variations are an issue, but for elevations $<70^\circ$ temperatures vary from 0°C to -150°C.
- **Power, communication, and deployment** of an initial low radio frequency observatory can be facilitated by the Deep Space Gateway.