The Lunar Farside: A Science and Exploration Imperative

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Why the Lunar Farside?

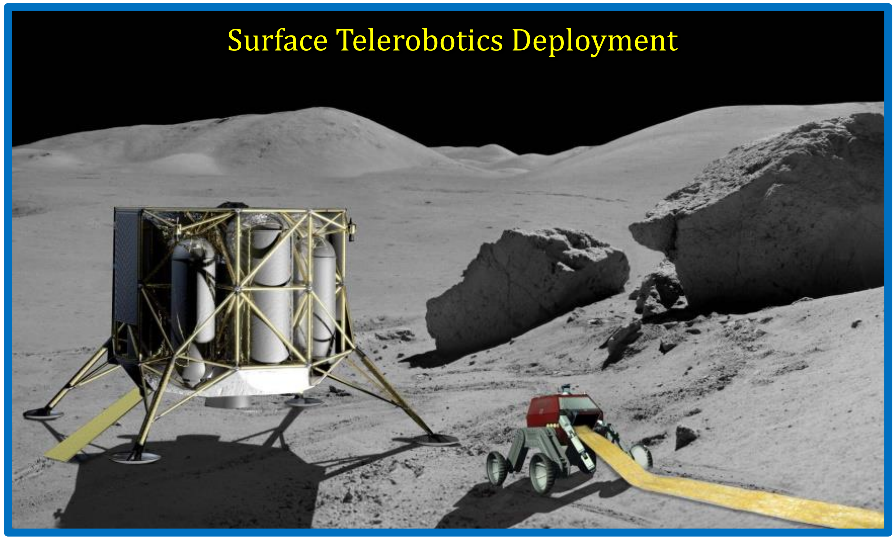
- A whole new, *unexplored* world in Earth's backyard! Nearly 4× land area of the United States.
- Opportunity to demonstrate human-robotic exploration strategies needed to explore the Moon, asteroids, & Mars.
- Farside includes the South Pole-Aitken basin – largest, deepest, & oldest impact basin in 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 $\nu \sim 10\text{-}80$ MHz.

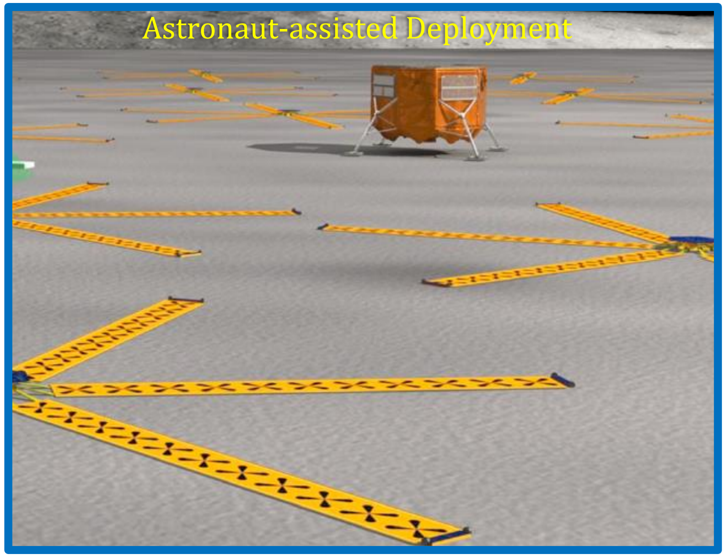
Why Emplace Radio Telescopes on the Farside?

- **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 ν^{-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 K) or lunar nearside (10^6 K), RFI brightness T_B is high. Need to suppress RFI by at least -80 dB to observe cosmological signal.

Astrophysics Community Surveys Advocate for Low Radio Frequency Cosmology on the Farside





•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?

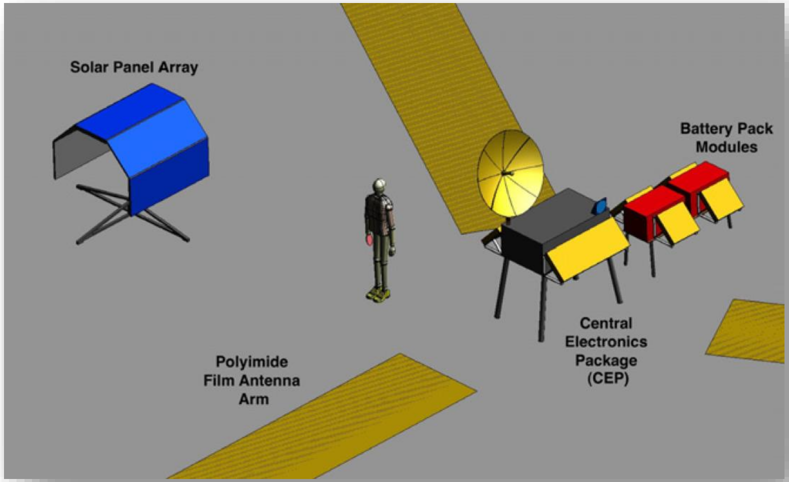
- •**Small Mission:** "Mapping the Universe's hydrogen clouds using 21-cm radio wavelengths via a *lunar orbiter* observing from the farside of the Moon".
- •**Visionary Era:** "*Cosmic Dawn Mapper* (21-cm lunar surface radio telescope array) … Detailed map of structure formation in the Dark Ages via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

Publications:

- Burns et al. 2013, *Adv. Space Res.*, 52, 306.
- Lazio, MacDowall, Burns *et al.*, 2011, *Adv. Space Res.*, 48, 1942

High-Level Trade Space for Lunar Radio Telescopes

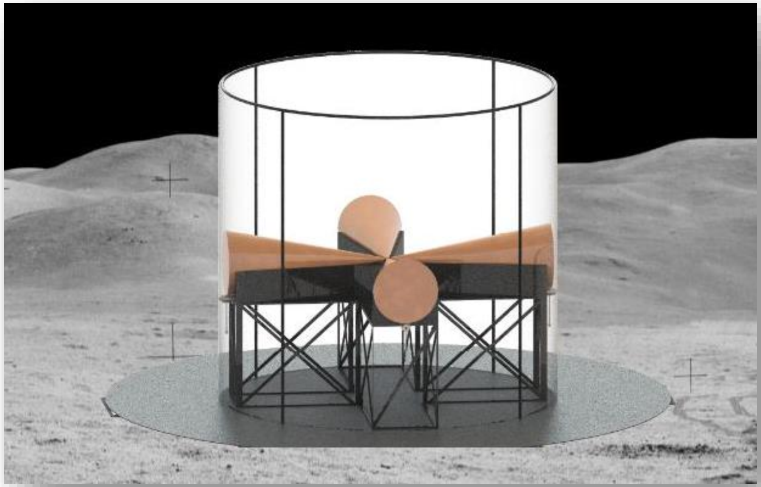
Instruments	Deployment	Environment	Power
	Location	RFI	Communications



Instruments

Hydrogen Cosmology Global Signal Telescope

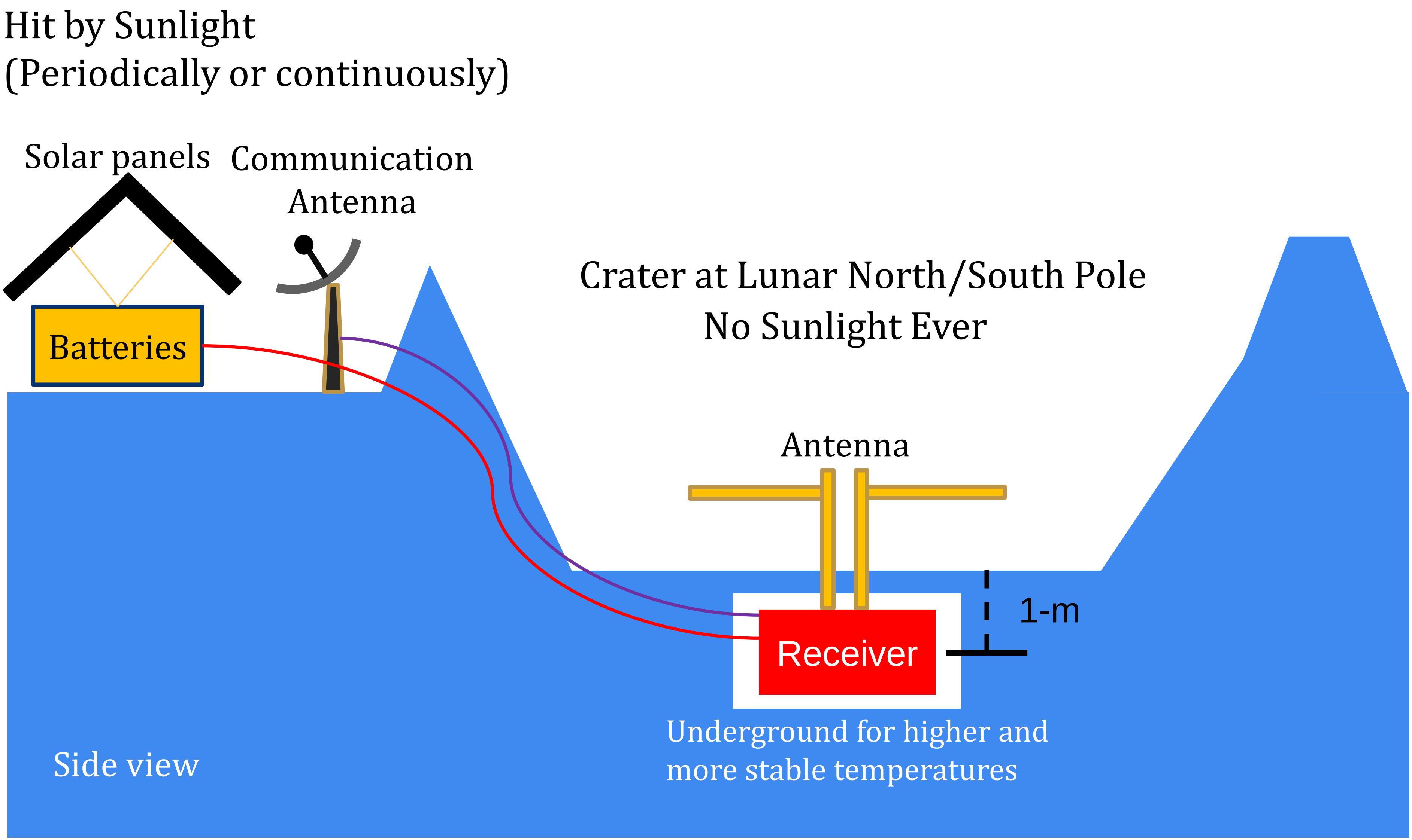
- 10-100 MHz
- Polarimeter
- Ground Plane
- Operation temperature = -250 C to +150 C
- Power < 200 W
- Data storage (< 1 GB per 24 hr)
- Data transmission (< 1 GB per day)



Cosmic Dawn Mapper

- At 10 MHz, 1° resolution requires ~2 km baselines
    - Filled aperture: 1 element / 3600sq. m
    - Circle layout: 1 element / 6 meters
- 10^5 square meters collecting area requires >1000 dipoles
- 1000 dipoles * 2 pol * 20 MHz bandwidth → ~40 GB/s
- Power ~2.5 kW

Can a Low Frequency Antenna be Sited in a Polar Crater?



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:

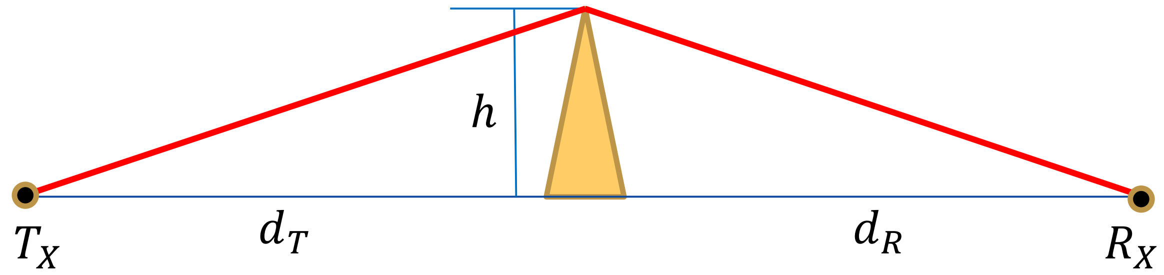
$$x = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_T}+\frac{1}{d_R}\right)}$$

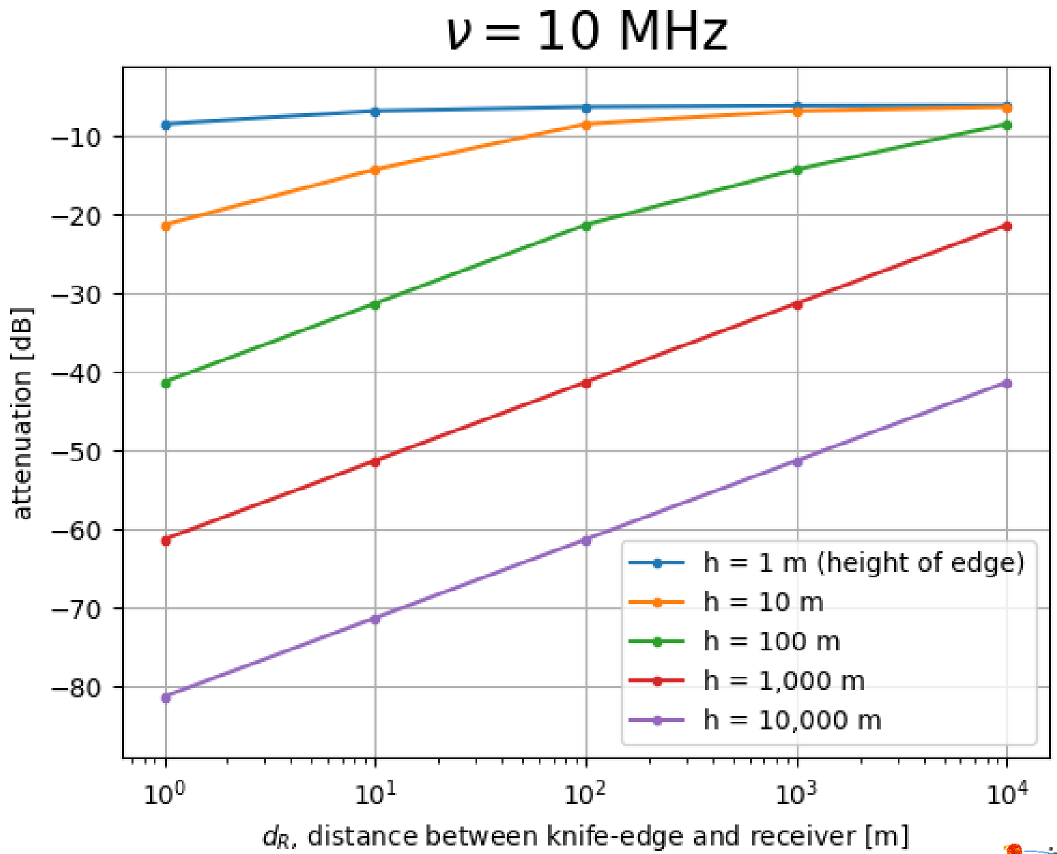
<u>Attenuation</u>

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

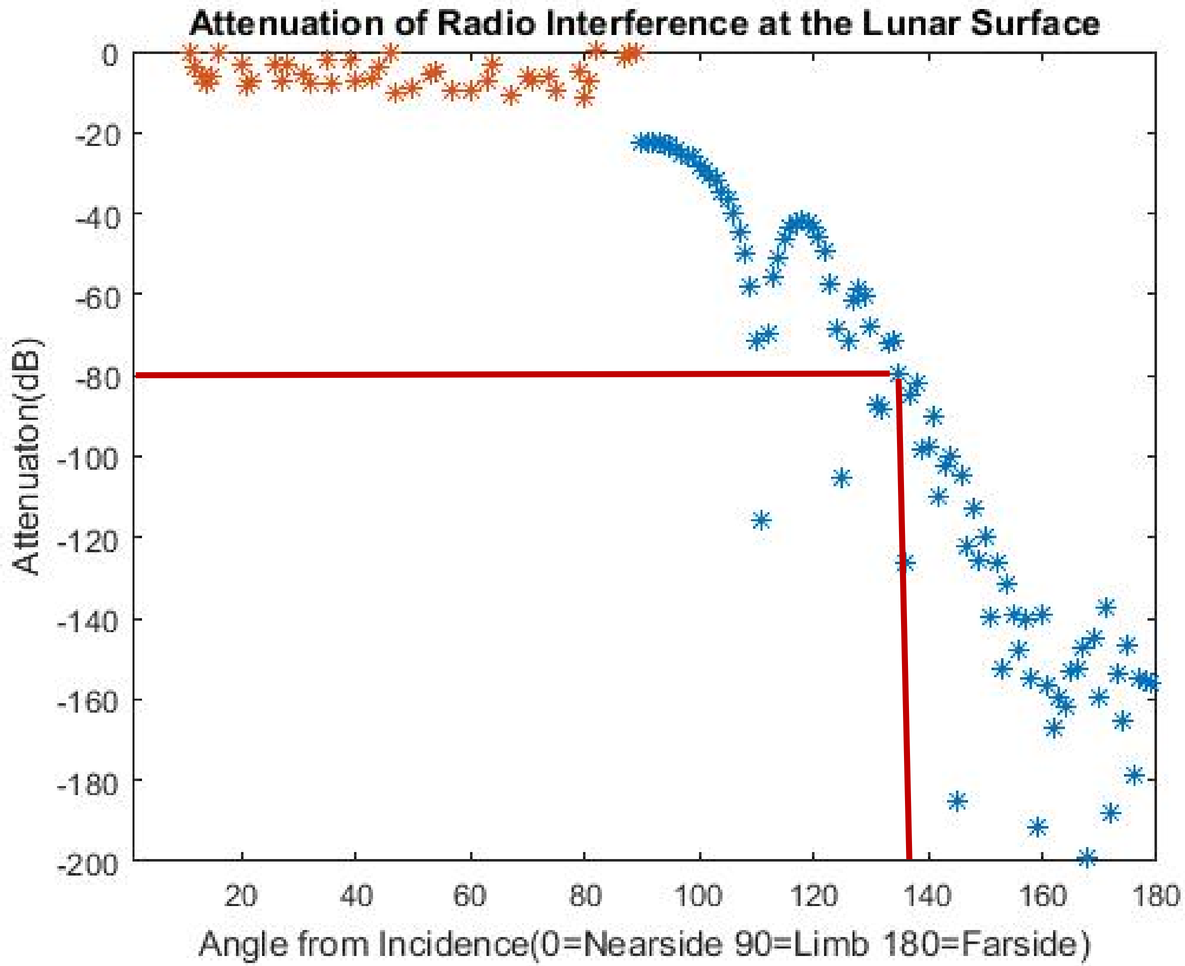
Problems:

- Insufficient attenuation
- Crater rim blocks sky & corrupts antenna beam.



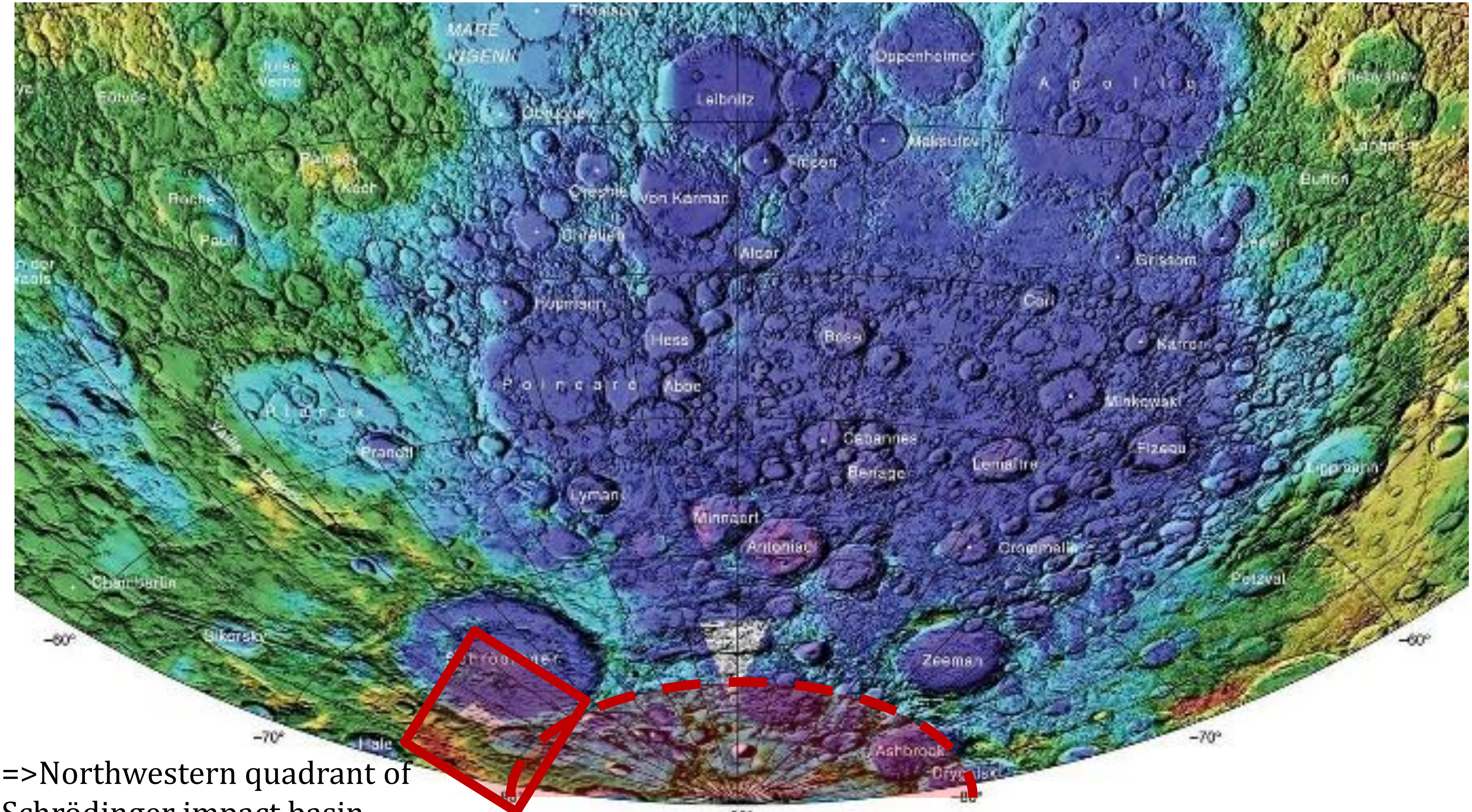


Global Farside Radio Frequency Interference



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.

The Lunar Environment

- 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 ≳-500 V. Charged dust grains are levitated **(Fig. 1).**
- Changes in surface potential by 10x occur during solar energetic particle event

=> 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.

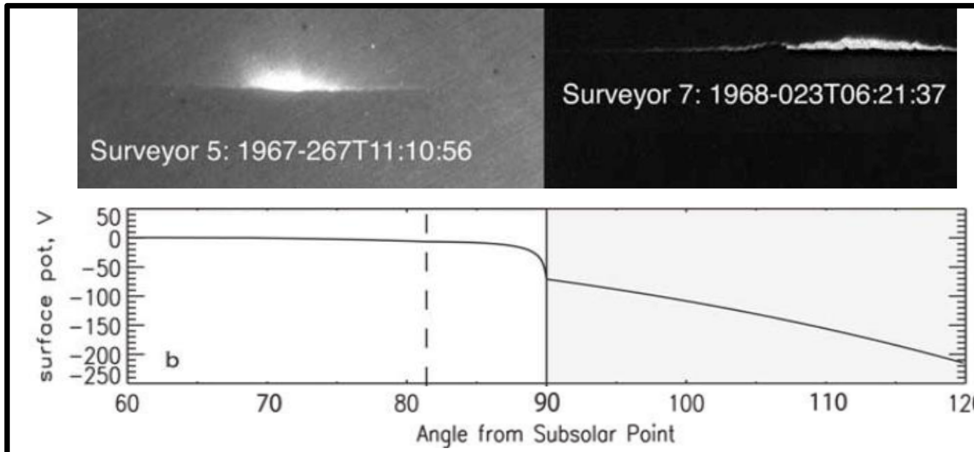


Figure 1. *Top:* Observations of elevated dust by Surveyor (Colwell 2007). *Bottom:* Lunar surface is positive charged on dayside & negatively charged on nightside (Farrell et al. 2007).

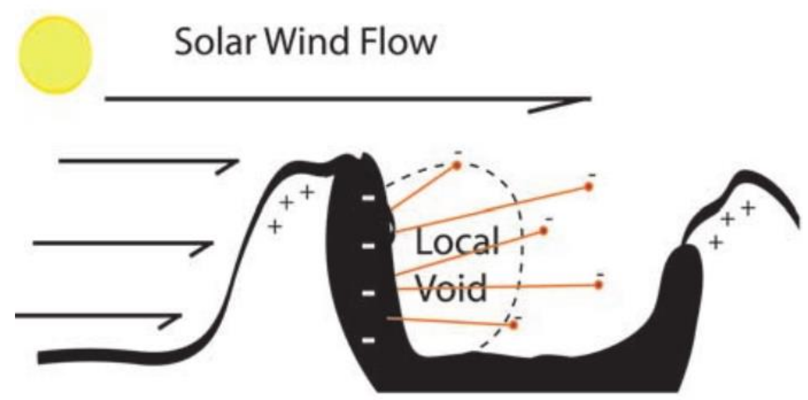
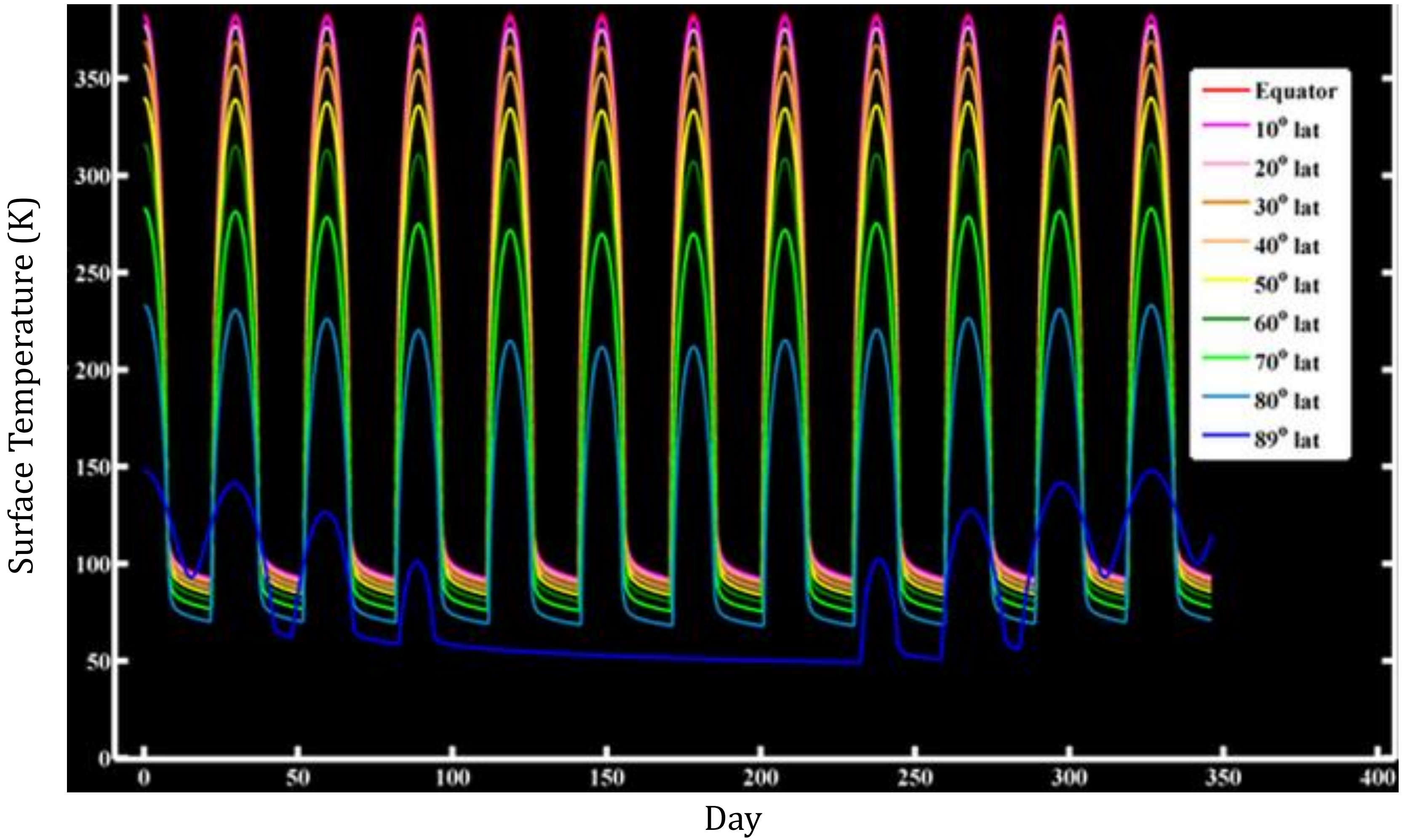


Figure 2. Localized electric field effects (Farrell et al. 2007).

The Lunar Environment

Longitude-average temperature model (Source: LRO Diviner)



Power, Communications, and the Deep Space Gateway

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 ~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° 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.