Results from Y1 trade study

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Status of Y1 Action Items

- Array design trade study
  - ✓ Literature review – In progress
  - ✓ Review lunar properties - Done
  - ✓ Define pathfinder – Done
  - Which side of moon?
    - Full array: farside because 21cm wants to go above 20 MHz
    - Prototype array: probably farside (Justin says Wind shows ~50% RFI between 1-20 MHz)
  - Sensitivity required to see Earth's radiation belt
    - Justin had a student calculating?
  - Prepare for decadal review – Deferred

✓ Technology roadmap - Done
  - ✓ Submitted COR strategic technology gap input
  - ✓ Successful -- two technology gaps added (priority 3):
    - ✓ Wide-bandwidth, high-spectral-dynamic-range receiving system
    - ✓ High-precision low-frequency radio spectrometers and interferometers
  - ✓ https://apd440.gsfc.nasa.gov/technology/tech_gap_priorities.html

Year 1 Planned Schedule

- Literature review (summer 2017)
  - Previous design/trade studies (LARC, ROLSS, etc.) ✓ acquired documents from ROLSS
  - Relevant technologies, TRLs, etc. -- in progress
  - Lunar conditions ✓ yes, all summarized in lunar sourcebook
    - RFI, regolith properties, environment, dust, radiation, etc.
- Science objective definition (fall 2017)
  - "Notional" full-scale science objectives ✓ Done
    - Exoplanet space weather: Detect earth-like auroral emission from nearby systems
    - 21cm: Measure dark ages power spectrum to test inflation through non-Gaussianity
  - "Notional" full-scale array description ✓ Done
    - Total collecting area: ~400,000 m^2
    - Frequency band: 1-20 MHz (possibly up to 40 MHz)
    - Angular resolution: 1 degree
    - Full Stokes
  - Select subset of science scoped to a small prototype array ✓ Done
    - Exoplanet habitability: Stellar bursts from Alpha/Proxima Centauri, monitor all M-dwarfs
    - Heliophysics: Image Type 2/3 bursts to understand acceleration mechanism
    - 21cm: Foreground maps, Galactic science
- Trade study of design options for prototype array (spring 2018) -- Started
  - Goal to identify reference prototype design and key technology development
    - 100 element dipole(like) array, 1km diameter, 1-20 MHz
    - No reference antenna, etc., yet
    - Key technology: antenna, data transfer, deployment, survivability

21cm dark ages

<table>
<tr><th colspan="4">Science Traceability Matrix</th></tr>
<tr><th>Decadal Science Goals</th><th>Science Objectives</th><th>Science Measurements</th><th>Instrument Requirements</th></tr>
<tr><td rowspan="2">1) What is the nature of inflation?</td><td>1) Are primordial matter density perturbations non-Gaussian? What is the value of f_{NL}?</td><td rowspan="3">1) Power spectrum of redshifted 21cm absorption fluctuations before stars

2) Frequency range approx. 10-40 MHz (50<z<100)

3) Angular modes between 1 and 10 degrees

4) Spectral modes between 0.05 to 4 MHz</td><td rowspan="3">1) Full Stokes aperture synthesis array on lunar farside (to avoid ionosphere and RFI) with:
* 400,000 m^2 area
* 1 km baselines
* Full-sky imaging

2) High-precision bandpass and beam calibration for foreground removal

3) Hardware that is radiation and thermally tolerant to survive the lunar environment

4) Deployer for chosen antenna design</td></tr>
<tr><td>2) What are the cosmological parameter values?</td></tr>
<tr><td>2) What is the nature of dark matter?</td><td>3) What is the temperature evolution of baryons after recombination?</td></tr>
</table>

Exoplanet habitability

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<tr><th>Decadal Science Goals</th><th>Science Objectives</th><th>Science Measurements</th><th>Instrument Requirements</th></tr>
<tr><td rowspan="2">GH - TBD</td><td>What are the flare statistics for G-M stellar types?</td><td rowspan="3">1) Monitor large area of sky for transient radio events from stellar flares

2) Monitor large area of sky for transient radio events from auroral emission from exoplanets

* Frequency range 1-20 MHz

* Angular resolution of 1 degree to resolve stellar system of bursts</td><td rowspan="3">1) Full Stokes aperture synthesis array on lunar farside (to avoid ionosphere and RFI) with:
* 400,000 m^2 area
* 1 km baselines
* Full-sky imaging

2) Hardware that is radiation and thermally tolerant to survive the lunar environment

3) Deployer for chosen antenna design</td></tr>
<tr><td>Do M-dwarfs produce interplanetary shocks the same way sun-like stars do?</td></tr>
<tr><td>GH</td><td>What are the magnetic field strengths of exoplanets?

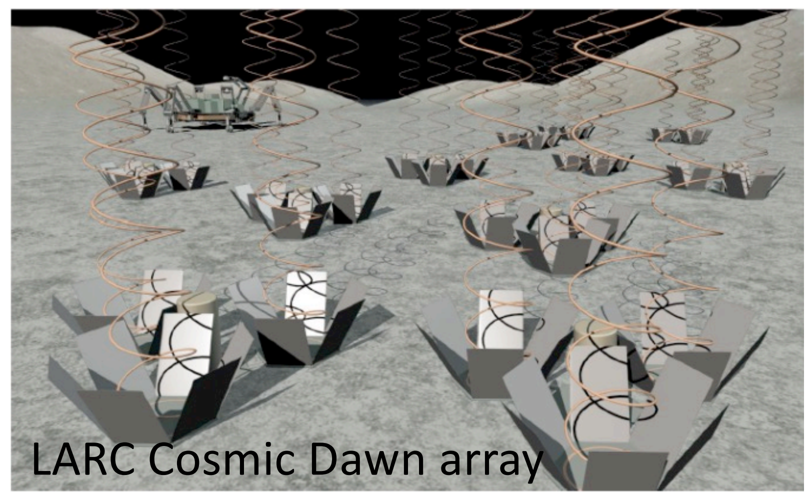
What is fraction of exoplanets with a magnetic field?

What is the number of habitable exoplanets?</td></tr>
</table>

Notational full array

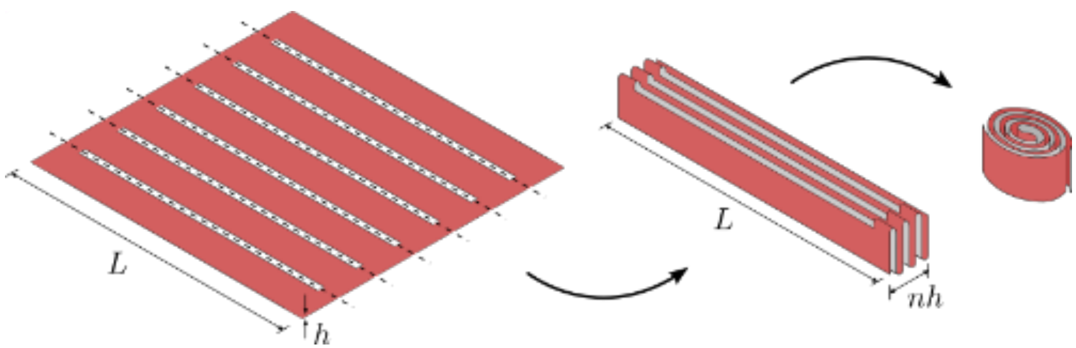
- Location:
  - Lunar farside
- Antennas:
  - Dual polarization for full Stokes
  - Probably higher-gain than dipole
- Frequency band:
  - 10-40 MHz
- 10 K sensitivity per pixel:
  - 10,000 antennas (if dipole-like)
- 1 degree resolution:
  - ~1 km baselines
- Data rate: 300 GB/s (raw)
- Power estimate:
  - Analog 10,000 elements: ~2 kW
  - Digital processing: ~10 kW
- Lifetime:
  - 5-10 years


DALI / ROLSS


LARC Cosmic Dawn array

Antenna technology

- Antenna mass and volume!
- Full array:
  - 1 kg (10,000 kg total mass)
  - 1000 cm^3 (10 m^3 total volume)
  - e.g. a 1U cubesat
  - Plus antenna stability, beam chromaticity
- Prototype array:
  - Relax mass/volume by order of magnitude
  - Standard beam properties



Images: Space Structures Lab (Caltech), Tethers Unlimited

Pathfinder Trade Study

Pathfinder top-level science goals

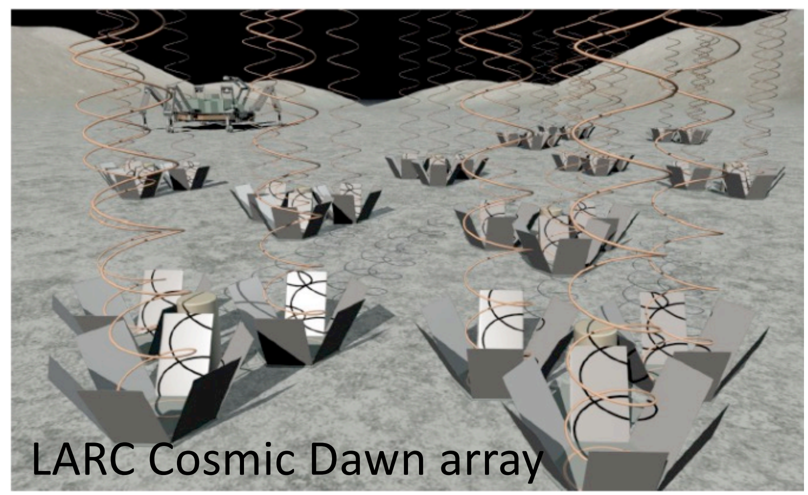
- **Exoplanets: Do M-dwarfs produce interplanetary shocks the same way sun-like stars do?**
  - Comparative study of burst statistics of two closest systems, one sun-like and one M-dwarf
  - Detect and resolve stellar bursts from **Alpha Centauri (A and B)** and **Proxima Centauri**
  - Monitor hundreds of other M-dwarfs for stellar flares
- **Heliophysics: How are energetic particles accelerated in solar bursts?**
  - Determine where and how the radiating particles are accelerated by imaging Type II and Type III solar radio bursts.
  - Monitor CMEs to improve space weather forecasting.
- **Cosmology: What are the foregrounds for 21cm dark ages?**
  - Create spectral data cubes of diffuse emission
  - Maps of radio recombination lines

Science to instrument properties

		Science goals		
		Heliophysics	**Exoplanet habitability**	**21cm Dark ages foregrounds**
Instrument property	**Frequency range**	1-10 MHz	<20 MHz (stellar bursts and Jovian-type emission)	<40 MHz
	Spectral resolution	1%	10%	10 kHz (RRLs)
	Field of view	>10 deg (all-sky for CME monitoring)	the larger the better to capture occasional 1000-fold increases in planetary radio power	the larger the better to map more of sky
	Angular resolution	2 degrees	2 degrees	1 degree
	Sensitivity	10^4 Jy	1 Jy for stellar bursts (Earth is 1 mJy at 5pc when geomagnetic storm)	1000 K
	Observing requirements	Sun and ecliptic visible	far side because of contamination from RFI and AKR, southern hemisphere	far side because of RFI
	Polarization	full Stokes for science	full Stokes -- high fidelity Stokes V imaging required for science	full Stokes for foregrounds

Notional pathfinder array – 1%

- Lunar farside
- Frequency band:
  - 1-20 MHz
- 1 Jy sensitivity:
  - 100 dipole-like antennas
- 1 degree resolution:
  - 1 km baselines
- Data rate:
  - 4 GB/s (raw)
- Power estimate:
  - Analog 100 elements: <20 W
  - Digital processing: 10-100 W
- Lifetime:
  - 1-5 years
- Mass and volume target/estimate:
  - 10^4 cm^3 per antenna = 1 m^3 total
  - 10 kg per antenna = 1000 kg total



Pathfinder array trade space

- Location
  - Science targets
- Layout configuration
  - Imaging performance
- Antenna design
  - Performance and mass/volume optimization
- Digital processing
  - Amount of digital processing to perform
- System design
  - What goes where?

Location Trade

- Phase 1
  - L1. Latitude and longitude range
    - Time on Sun, Alpha/Proxima Cen targets
    - Number of M-dwarfs visible
    - Amount of Galaxy visible
    - RFI/AKR attenuation (probably just an exclusion zone)
- Phase 2
  - L2. Candidate sites
    - Thermal range (nighttime low, daytime high)
    - Surface properties (rocks, slope)

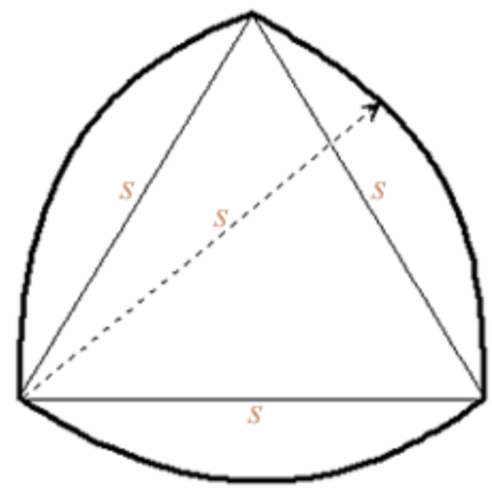
Antenna Trade

NOTE: Restrict to low-gain, dual polarization antennas

- Phase 1
  - A1. Planar antennas sitting directly on regolith vs. 3D?
    - This is gate: Can we consider dipole-like antennas directly on regolith?
    - EM modeling of antenna properties on lunar regolith
- Phase 2
  - A2. Specific designs
    - Mass, volume, RF performance
    - Deployment complexity

Layout Configuration Trade

- C1. Imaging performance
  - Triangle
  - Reuleaux triangle
  - Square
  - Circle
  - Spokes
  - Pseudo random uniform density



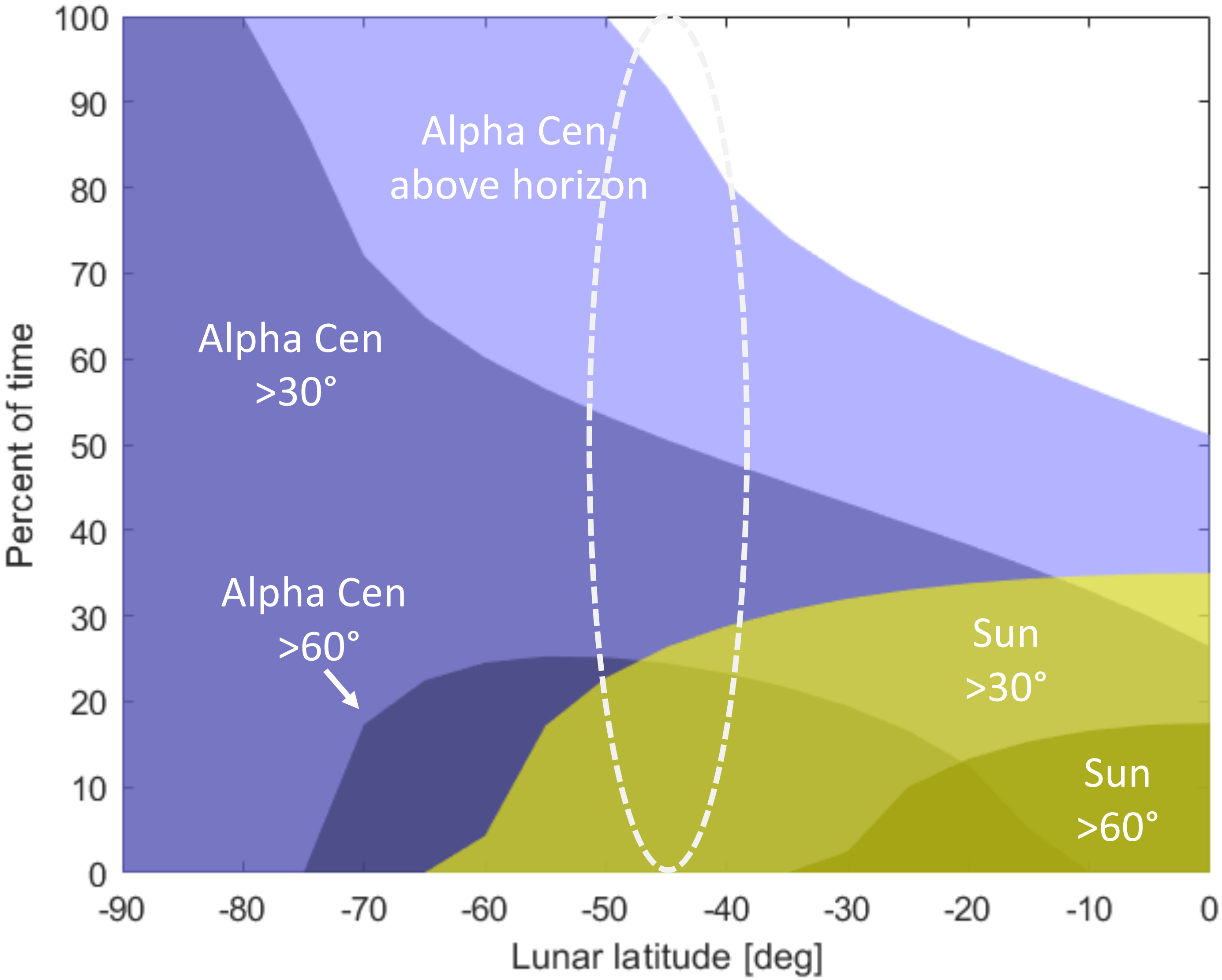
Digital trade

- D1. Beam forming vs. full correlation
  - *I don't see any reason to consider beamforming for only 100 antennas and 20 MHz bandwidth, but if we do…*
  - Computational load
  - Complexity of monitor and control
- D2. Downlink raw vs. derived data products?
  - What are reference derived products? Light curves and solar images?
  - Data volume, computational load

System trade

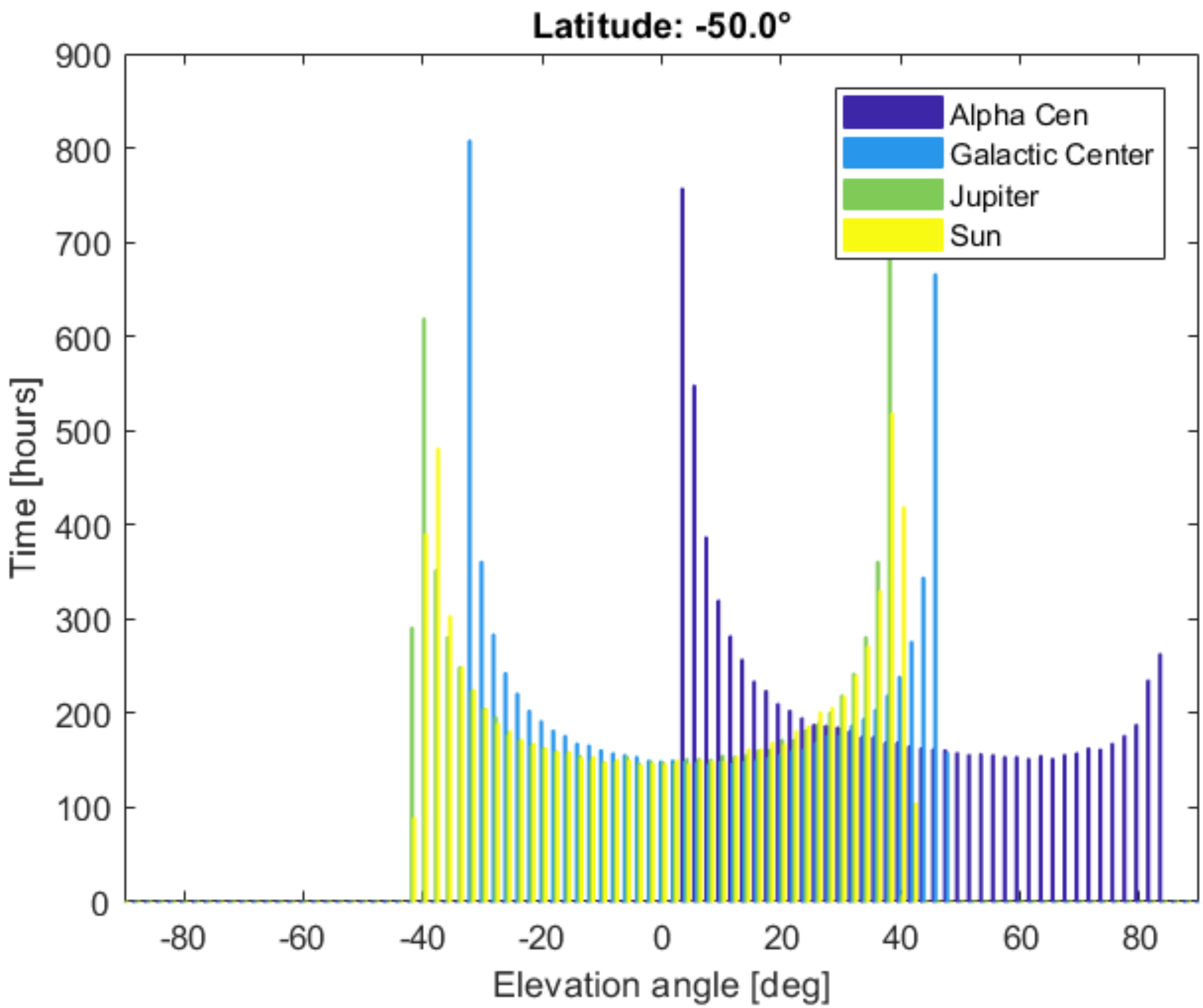
- S1. Wired vs. wireless RF/data transport from antennas?
  - Mass, volume, power, performance (copper, fiber, microwave, optical)
  - Deployment complexity
  - Note: What are rules on space-to-space transmitters?
- S2. Relay spacecraft in lunar orbit vs. L2?
  - Power/technology for communication
  - Duty cycle, complexity for buffering, etc.
- S3. Correlate on surface vs. spacecraft?
  - Power and survivability of correlator
  - Complexity of communication
- S4. Central station on surface vs. no central station?
  - Coupled to all above
  - Could antennas communicate directly to orbital asset?

L1 – Latitude/longitude bounds



- Metric: amount of time sun and Alpha/Proxima Cen (dec. −61°) are visible
- To-do: Time on known nearby M-dwarfs

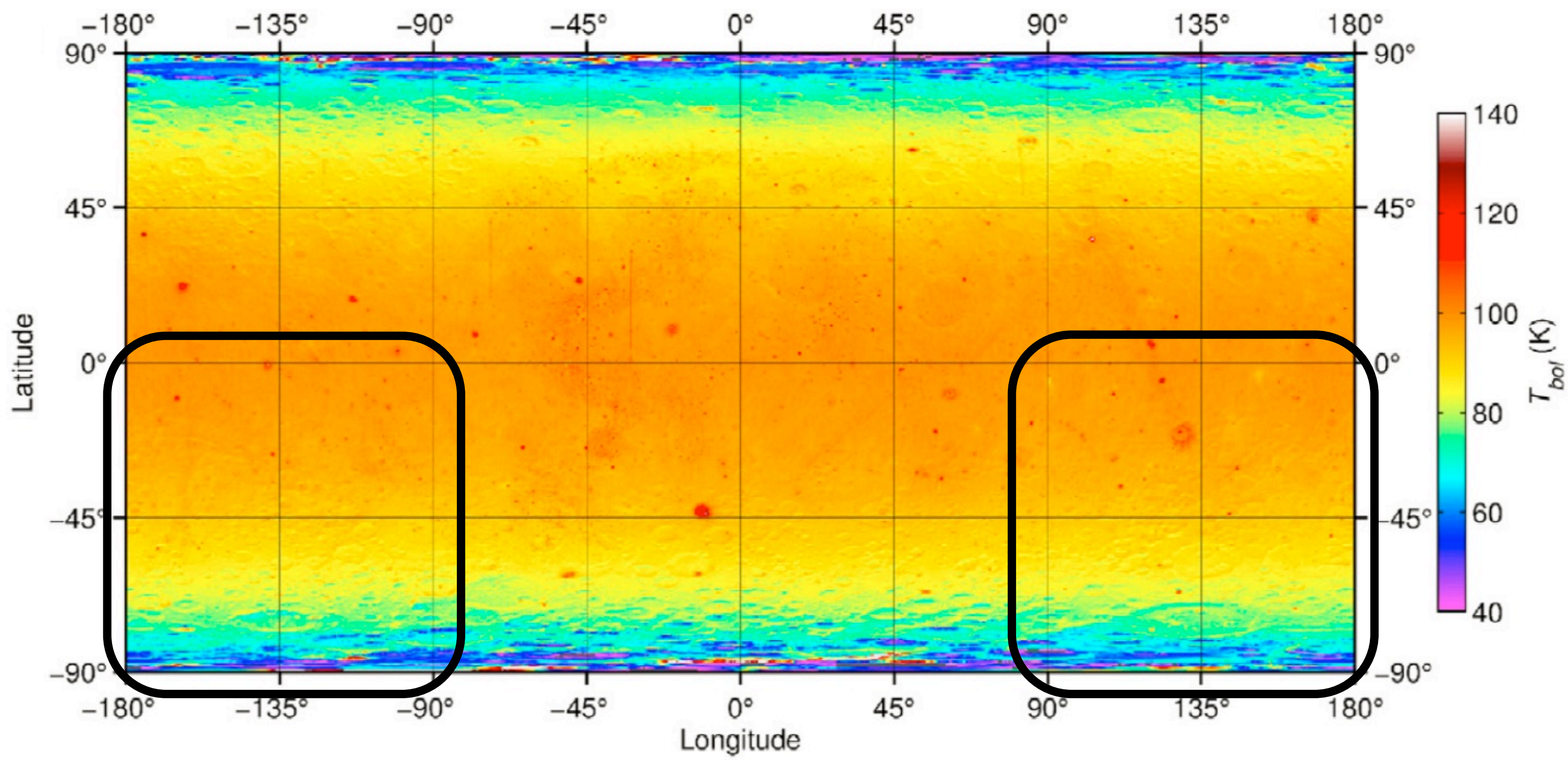
L1 – Latitude/longitude bounds



- Motivates low-gain antennas because targets move through entire sky

Mean low lunar temperatures

- At -45° latitude, minimum is ~90 K (high temps are 300-350 K)
- Warmest places are young craters with rocks (~5 K warmer)
- Diurnal variations extend to ~30 cm below surface
- Currently investigating candidate sites



LRO Diviner / Williams et al. 2017