Low Frequency Solar Observations with Radio Interferometers on the Lunar Surface

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Motivation

Solar Energetic Particles (SEPs) are space weather events that are potentially dangerous to astronauts outside Earth's protective atmosphere. That same atmosphere also constrains us from viewing telltale signatures of SEPs in the lowest frequencies below 15 MHz. In this range, both impulsive and gradual SEP events [1] give off bright radiation further from the sun, scaling down with the local plasma density as the SEPs travel outward. The more numerous gradual events are from SEP generation at shockwaves traveling outward with a coronal mass ejection (CME). Impulsive events are short lived bursts travelling quickly outward from a flare or jet on the surface of the Sun. A radio array on the surface of the moon could be part of a stable space weather alert system that traces the path of the SEPs to predict if astronauts need to prepare for a potential space weather event. Such an array would also be of scientific benefit, helping to clarify the basic physics of CMEs. This would include figuring out where in the CME particle acceleration is occurring.

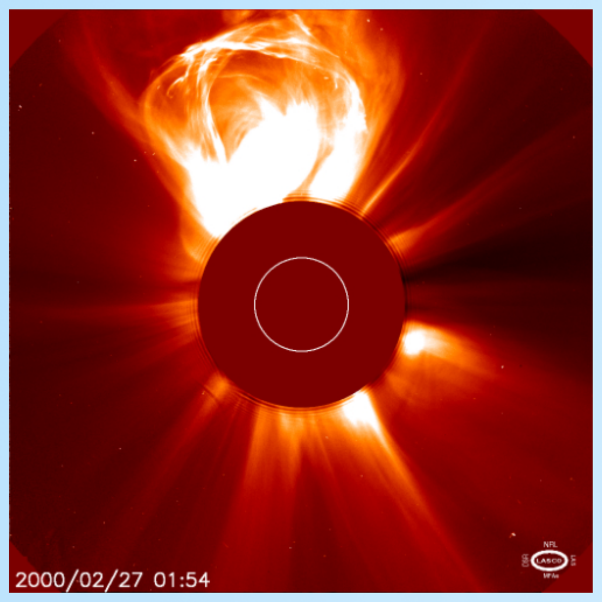

Figure 1: SOHO image of a CME

Objectives

1. **Create software to simulate the data processing pipeline for a radio interferometer on the Moon observing the Sun**
2. **Compare arrays on equator versus arrays on the poles**
3. **Analyze array capabilities for tracking SEPs**
4. **Offer recommendations for location and geometry of Lunar array as part of a space weather alert system**

Methods

- Radio imaging uses Interferometry, which yields 1 sample in the Fourier plane per pair of spacecraft
- Where the sample is depends on the projected distance between 2 receivers, as seen from the source

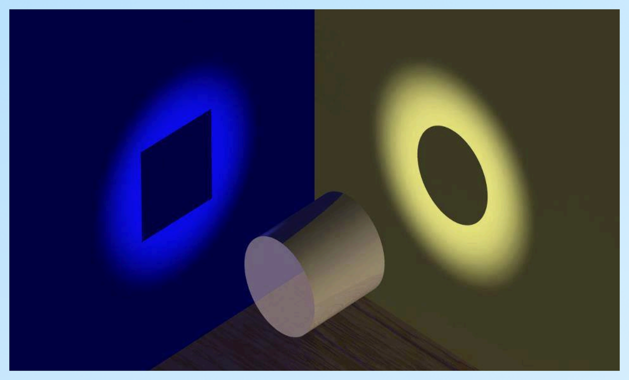

Figure 2: Example of how 3 dimensional structures like this shape or a cloud of spacecraft can have different projections relative to the source of light

- We used the SPICE toolkit [2] with the DE421 ephemeris [3] to obtain the exact geometry of the Sun in the Lunar frame.
- To optimize the search in the poles, we used Mazarico et al.'s 2010 [4] list of points on the poles which had the highest solar illumination
- We used 5m elevation data and 40m roughness and slope data from LRO's LOLA [5] to enhance realness and constrain possible arrays
- Once we had the 3D baselines in the correct geometry, we simulated each receiver's Fourier response and carried processing through to completion in radio astronomy's standard software, CASA [6].

Conclusions & Future Work

- **Polar arrays, while appealing in their higher average illumination, ultimately are unfit due to their consistently bad uv coverage, undermining their ability to image Radio SEP bursts**
- **Equatorial arrays in favorable layouts only need 5 receivers for sufficient coverage**
- **Simple and compact equatorial arrays are the best Lunar option for reliable SEP forecasting. 2 would provide near-total coverage, while 3 would provide total coverage.**
- **Next step is to find the 3 best places for a set of equatorial arrays and to show how forecasting would be done.**
- **This will eventually be one system of many in a synthesized alert system, integrating different measurements to optimize space weather strategies.**

Polar Arrays

- **Advantages:** Moon long theorized to have "points of eternal light" (PEL) near poles that had nearly constant illumination. In practice, illuminated ~80% of the time
- Would be great for power needs and potential SEP coverage
- Constraints: small size (baselines ~O(10 km)), low roughness and low ground slope

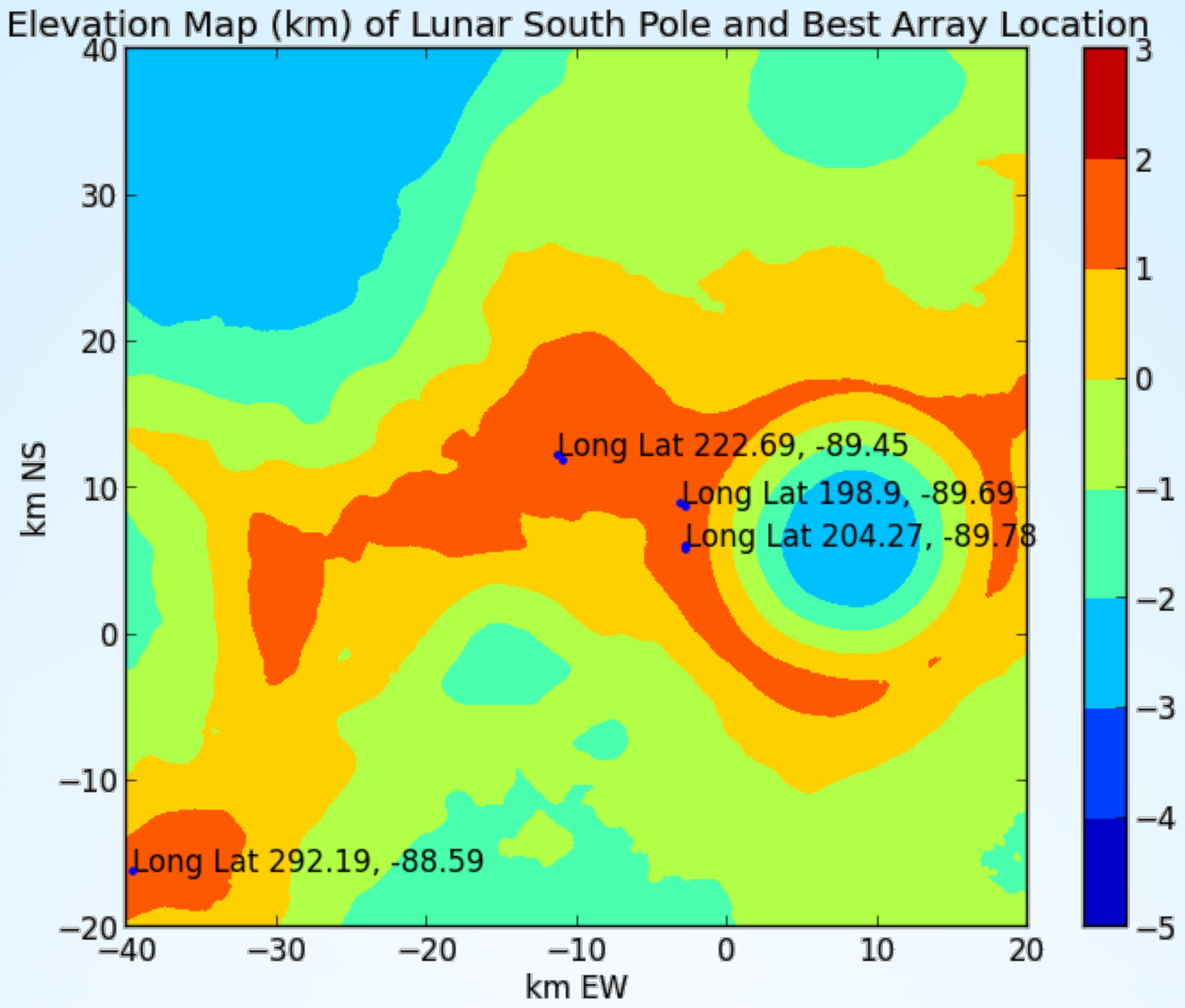

Figure 3: Elevation map of the Lunar South Pole made with extrapolated 5m LOLA data. Plotted on top of it is the best polar array location we could find. There are 7 antenna, with 3 groups of 2 near the middle of the plot

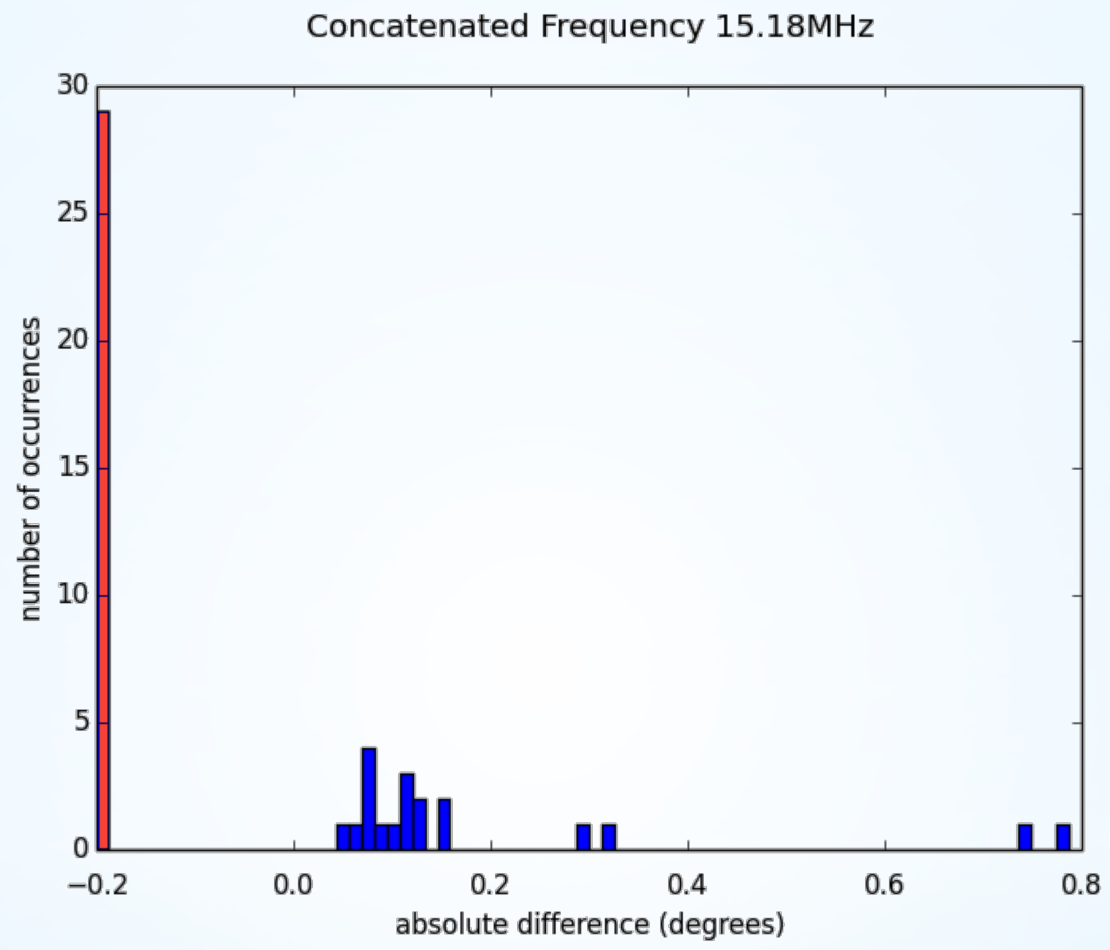

Figure 4: Histogram of error in recovered position of radio hotspot for polar array. The array was attempting to track the hotspot .5 degrees out of the phase center. -.2 here means that CASA's clean algorithm could not even form an image with the poor uv coverage provided by this array. Out of 48 trials sampling a lunar year 29 failed to even form an image, while the rest were only moderately accurate.

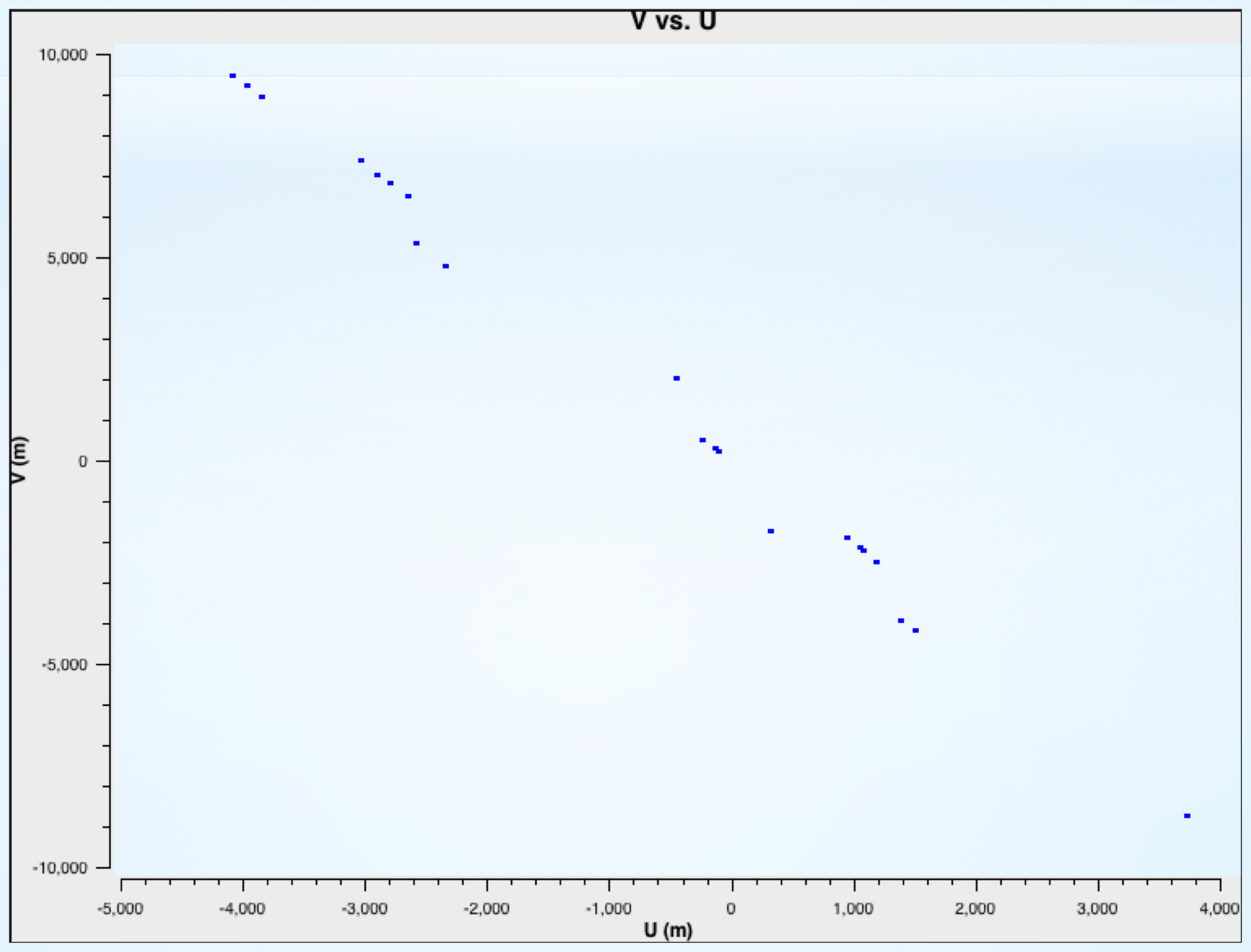

Figure 5: A typical example of the poor UV coverage provided by polar arrays. This happens for all such polar arrays because the PELs projected coordinates always face the sun at the steepest of angles, resulting in a weak linear coverage.

Equatorial Arrays

- **Advantages:** Easier to do since many more options around entire equator, but has set 50-50 day/night times
- Faces the sun head on almost half the time, so you can design efficient array layouts to get good coverage over most of the day

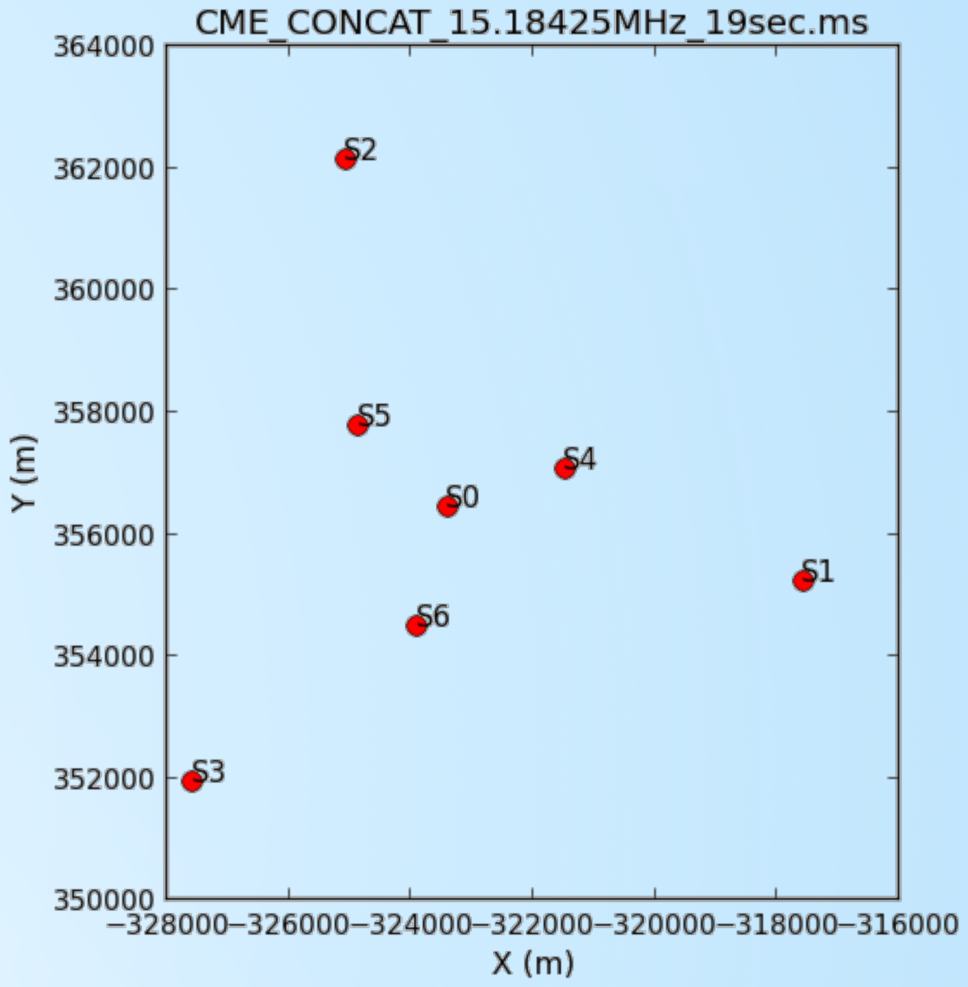

Figure 6: Equatorial array candidate. In later figures referring to 6 and 5 receivers, the array is the same but missing S6 and S0 respectively.

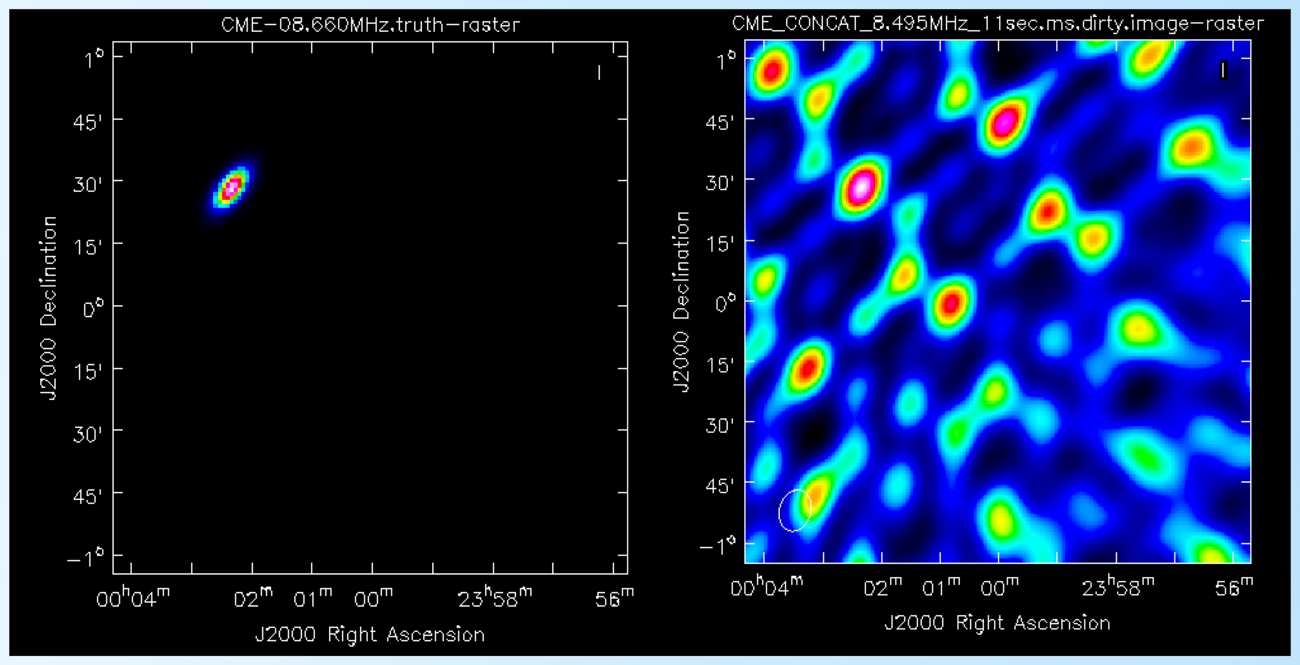

Figure 7: *Left*: Idealized Radio Hotspot, size informed by electron density models & observing frequency [7].
Right: Reconstruction by Equatorial Array. Requires data from multiple frequency bands to give enough baselines to get image

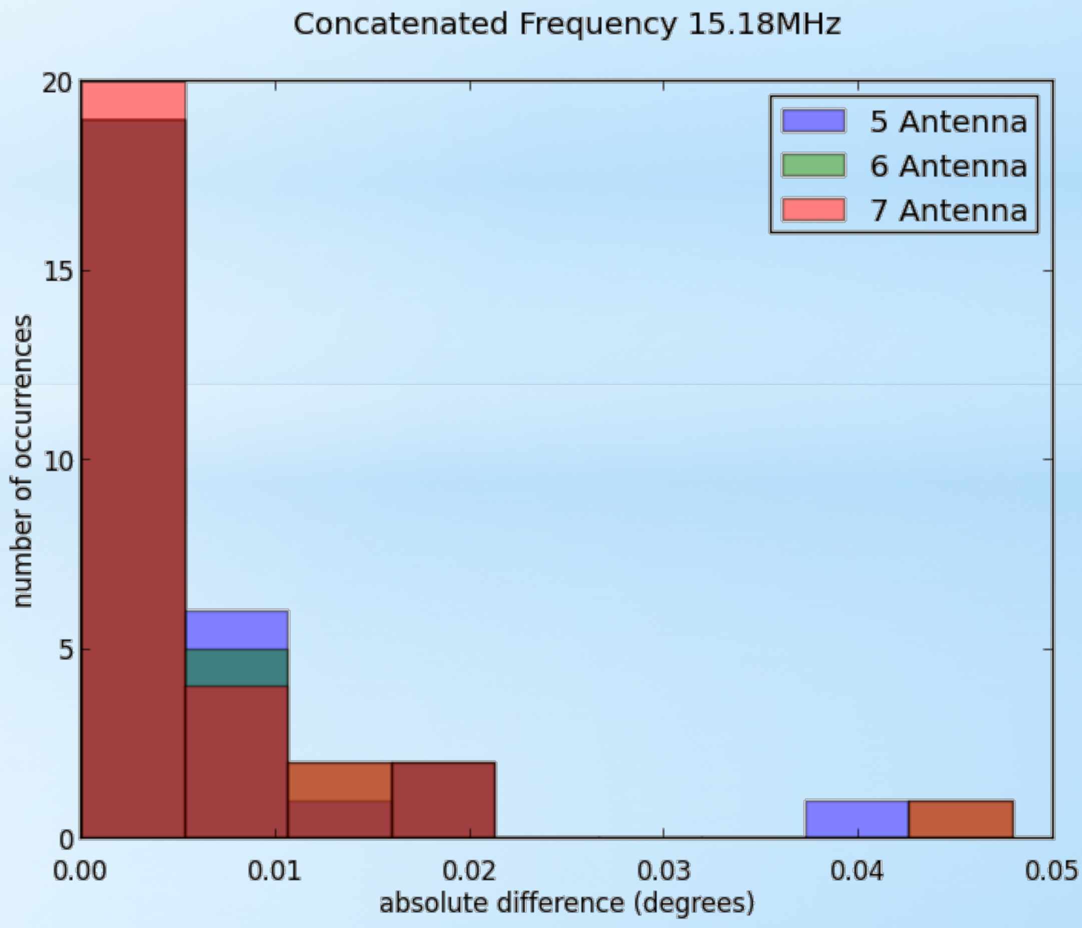

Figure 8: Histogram of error in recovered position of radio hotspot for equatorial array. The excellent quality of the hotspot pointing doesn't seem to diminish when going down to 5 receivers.

References

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