LoCo Memo #51

Beam Mapping Memo #09
Observing Campaign for LWA Beam measurements

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Objective of this memo is to define an observing campaign to measure the average gain and beam variations of the LWA antenna. This will serve as a path finder for the long term goal of mapping the beam of a single LWA dipole.

See also: This is memo 9 in a series on the development of beam mapping fixed arrays with a steerable reference dish. Further details can be found in memos 1-8 Memo Readme.

The measurement of redshifted 21cm from Cosmic Dawn and Epoch of reionization requires a very high sensitivity due to bright foregrounds, ionosheric effects and terrestrial radio frequency interference (RFI). Currently, all the experiments aiming this measurement are limited by systematics. One of the major sources of systematics is understanding of the beam, and how it affects the sky signal. A precise measurement demands a precise understanding of levels of mainlobes and sidelobes. This memo lays out a potential observing plan to help understand the average beam of an LWA dipole.

Assumptions:

1. Variation between individual LWA dipoles is small
2. The average response of the beamformed station beam is not dominated by mutual coupling between antennas
3. X and Y polarization are rotated by 90 deg with respect to each other
4. The gain of the signal chain has a inverse temperature dependence based on thermal and whether conditions

This project initially started as a demonstration of pulsar holography technique using the combination of VLA, LWA-1 and LWA-SV. Due to current limitations of VLA 4-band:

1. The beam of the 4-band system is not well characterized.
2. Only two spectral windows are good (74-76 MHz and 76-78 MHz). The rest are dominated by RFI.
3. Due to the arrangement of the 4band antennas and polarization combiner, the X and Y polarizations have very different responses.
4. We are limited in the amount of VLA time we can use.
5. VLA configurations change every 6 months, making the measurement more technically involved.

Beam Mapping Campaign:

The measured flux from an antenna is the product of the true flux of the source, gain of the beam and the gain of signal chain. The gain of the beam is the function of the spatial co-ordinates (altitude, azimuth) and the gain of the signal chain is the function of the time of the year when the observations are made. So,

$$F_{measured} = F_{True} * B(\theta, \phi) * g(t)$$

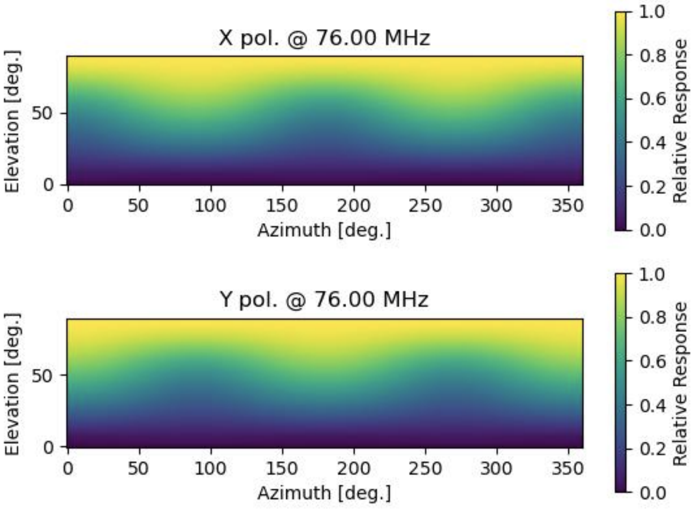
→ Equation 1

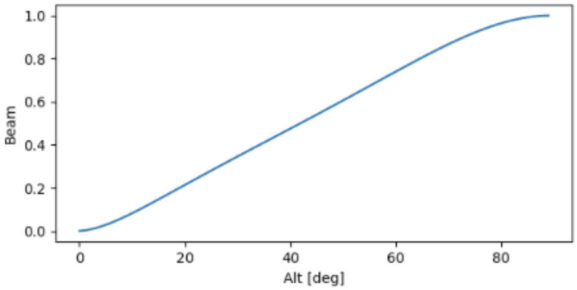
Observing different sources within short timeframe (same night) makes sure g(t) is constant, so we can measure B(θ,Φ) at different alt and az, and repeating the same observations at different times will make sure a constant B(θ,Φ) to measure changes in g(t).

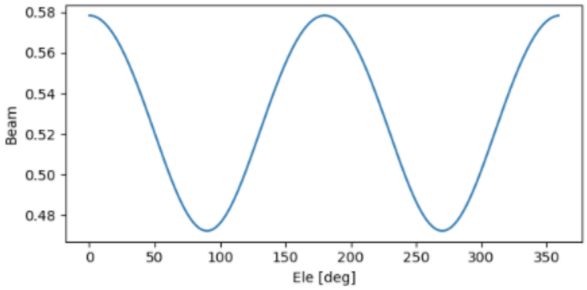
Observing in eLWA mode we would use the VLA and LWA to track calibration sources. The LWA will operate in beamform mode which is the standard mode used for eLWA. Using the cross correlations and LWA auto correlations by comparison against the calibrated and stable VLA. Variables include the number of sources observed and the observing time cadence, spatial co-ordinates and the temperature dependent gain variations. So with the proposed observations, we can measure the following:

1. Gain of the average LWA antenna beam at four different altitudes that are each 3.75 deg wide
2. Temperature dependent gain variations of the signal chain
3. LWA average beam at declinations of 2-8 sources (with multiple beams in the digital beamformer)

Although beams can be modeled using EM softwares such as FEKO, CST or HFSS, for the purposes of redshifted 21 cm measuresemets a real measurement in the field is a better indicative of studying the effects of beam on the sky signal. One such model obtained from EM software for LWA beam is shown here. This model of LWA beam is from Jayce's LSL package at 76 MHz: [code:LWA beam LSL]







Sensitivity Calculations:

For the purposes of measuring redshifted 21 cm signal, we should understand the beam at all frequencies to an accuracy of 0.01% in the mainlobes and 1% in the sidelobes to achieve sufficient foreground suppression (Jacobs 2017, Ewall-Wise 2017). Our previous efforts with beam mapping with pulsars show that, even with brightest of the radio pulsars, we fain to achieve the required SNR without long integrations of several months to obtain a beam cut at a single declination. An added challenge is lack of bright radio pulsars at all declinations. We therefore shift the focus towards using bright A team sources that are orders of 3-4 magnitude brighter than the brightest pulsars at these low frequencies of <100MHz. Some of the preliminary sensitivity calculations are done in Memo 01, here we use the full LWA-1 array with 352 dipoles.

$$Sensitivity = \frac{SEFD}{\eta_a \sqrt{N(N-1)\Delta\nu \tau_{acc}}}$$

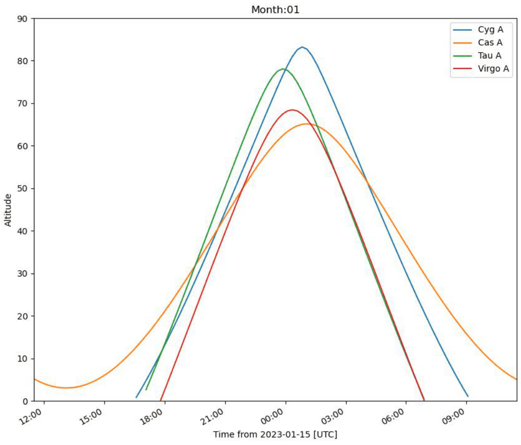
→ **Equation 2**

$SEFD_{LWA}$ = 1e6 Jy (array: from here for 75MHz, single dipole: from here for 74MHz, fig 3), if antenna efficiency is 0.6 and we measure the beam at a spectral resolution of 1MHz and use all 352 dipoles of OVRO-LWA, **we can achieve sensitivity of 0.025 Jy with an integration of 15 minutes**. Using this, beam accuracy is calculated by taking the ratio of true flux of the souce to the obtained noise level of 0.025 Jy. This will translate to following beam accuracies for bright A team sources:

Source	**True flux at 76 MHz (Jy)**	**Sepctral index**	**RA**	**Dec**	**Beam accuracy**
Cas-A	18422.8	-0.920	23 23 27.94	+58 48 42.4	0.0001%
Cyg-A :	16791.5	-0.661	19 59 28.35	+40 44 02.1	0.0001%
Tau-A :	1734.3	-0.349	05 34 31.97	22 00 52.1	0.001%
Virgo-A :	1957.8	-0.709	12 30 49.42	12 23 28.0	0.001%

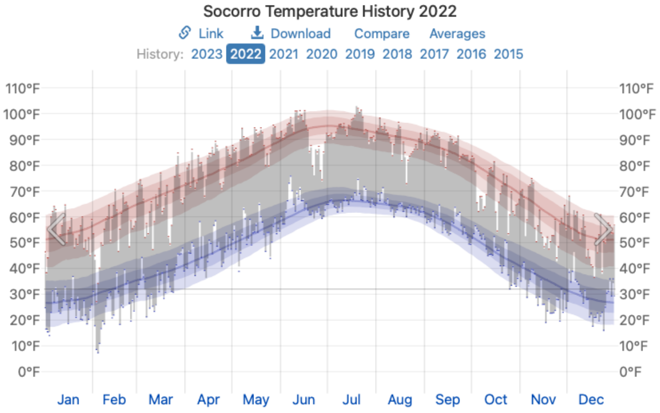
The 10 hours of observations can be divided in a way that enables measuring each term in Equation 1. To measure temperature dependent gain variations, observations should be spread across the year in different seasons. To measure the spatial gain of the beam, the sources should be at different declinations.

The next step is to determine the sources and their positions in the sky. I used `astroplan` package and

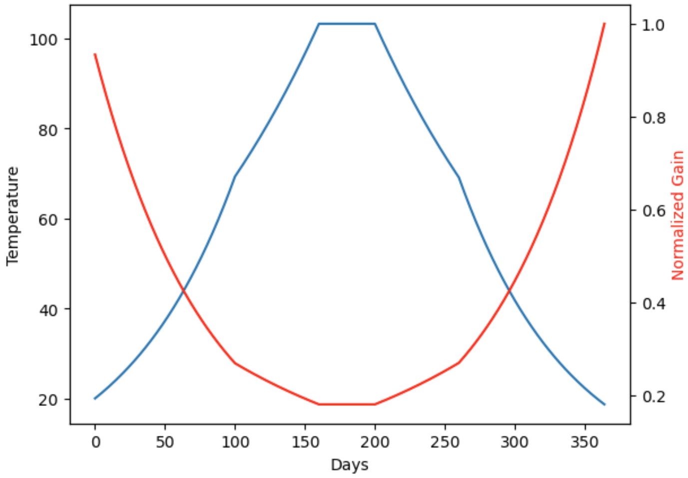


used the co-ordinates of the VLA to determine positions of four A-team sources: Cas-A, Cyg-A, Tau-A and Virgo-A. Here's an animation of the altitudes of these sources throughout the year, sampled on the 15th day of each month.

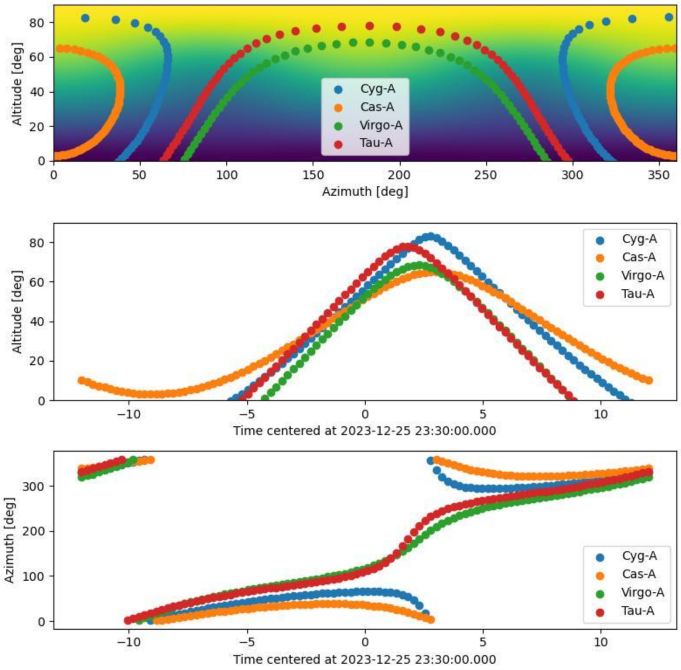
To model the temperature dependent gain variations, I constructed a rough model with linear increase/decrease in temperature that mimics the daily highs/lows in temperature at Socorro, NM as reported by [2022 Weather History in Socorro New Mexico, United States](). The model is normalized to coldest day of the year.



The daily range of reported temperatures (gray bars) and 24-hour highs (red ticks) and lows (blue ticks), placed over the daily average high (faint red line) and low (faint blue line) temperature, with 25th to 75th and 10th to 90th percentile bands.



With these models and four A team sources, in principle, if we had a full night of LWA time, this is what the beam cut would look like:

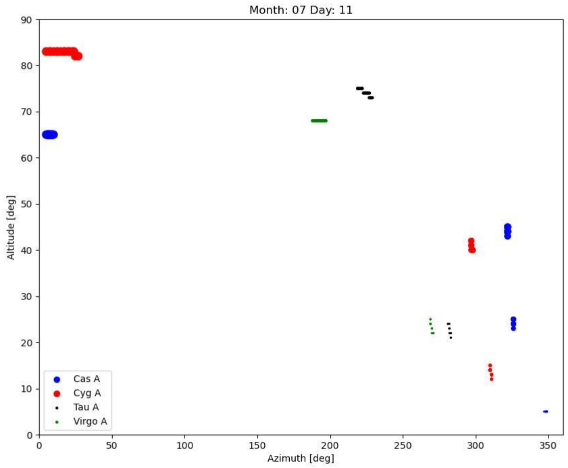


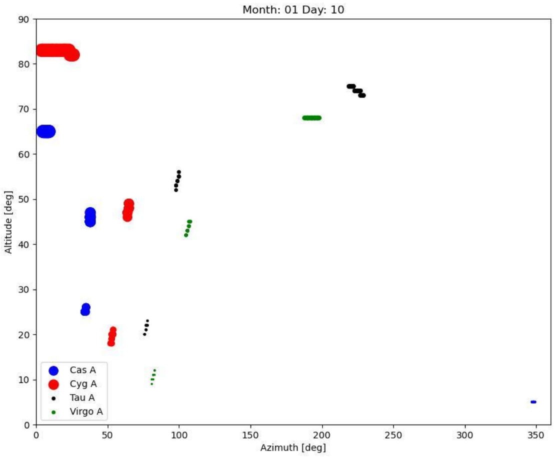
But since, we can’t get an entire night of VLA time, sampling at different altitudes is the next best option. Here’s a simple proposed sampling that observes 10 hours on each source.

- Observe once every three months to sample multiple locations in the local co-ordinate system, for 10 days (consecutive or otherwise)
- Each night of observation will be 1 hour long, to further spead out local co-ordinate coverage, and split into chunks of 15 minutes
- 15 minute chunks can be selected based on altitude samples. Let’s start with sampling ~4 deg (approximately 15 minutes) at every 20 deg change in altitude. An example for this could be 5 deg, 25 deg, 45 deg and 65 deg. In other words, we want to start observing when the source hits the sampled altitude for 15 minutes and wait until it hits the next altitude sample.

Let’s define a “campaign” as one set of observations for roughly 10 consecutive days. So throughout the year, we expect to have ~4 observing campaigns. With LWA-1’s dual beam (where two independent beams can be set up in the digital beamformer), the total observation time can be cut in half by simultaneously observing two sources. Further, for OVRO-LWA that is capable of beamforming 8 independent simultaneous beams, we can observe 8 different sources effectively for only 10 hours/year.

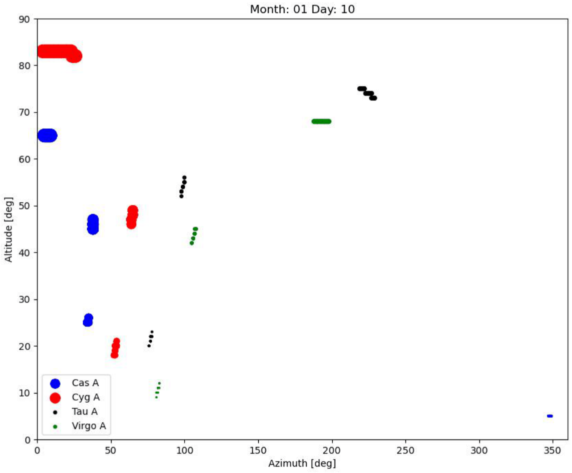
So for any given night, this might look like one of these:

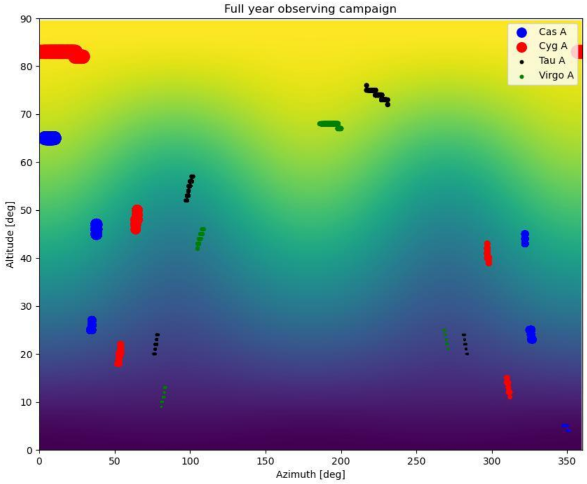




Repeating the observations for roughly 10 days in a row ensures that the temperature dependent gain variations are reasonably comparable in each observing campaign and a comparison between each campaign can help understand how gain changes throughout the year. Similarly, setting the same altitudes of the sources ensures that we have roughly ~10 hours on target to map the beam at each those altitudes. A comparison of each altitudes, helps understand how the beam changes as a function of altitude.

This animation here shows the sampled beam cuts from each night of observation throughout the year. At the end of the observing campaign, we expect to use the observations to map the sampled beam cuts in the 2D space. The figure below shows the expected beam cuts against the dipole beam of LWA. Although this is the average beam of LWA, that is sampled at limited azimuth and altitude, at the end of one year of observation, the ultimate goal is to fill out the full 2D space for a single dipole.





Conclusion

This memo gives a potential observing plan to accurately measure the average LWA antenna beam at four different declinations using A team sources. These bright sources help achieve high beam accuracy and the estimated accuracy levels help distinguish the cosmological signal from the bright foregrounds (at least at the declinations of these sources). To barely reach the required accuracy of 0.01%, we only need 1-2 hours of integration (lower for brighter sources, Ex: Cas-A needs 0.11 minutes in every block of observation, instead of 15 minutes). If we set an upper limit of 1 hour/source throughout the year, the minimum source flux to achieve the required sensitivity is ~790Jy. Thus, making this method of observation a potentially plausible in precise understanding of the beam for cosmological 21cm observations.