Results from LWA1 Commissioning: Sensitivity, Beam Characteristics, & Calibration

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10-88 MHz usable, Galactic noise-dominated (>4:1) 24-87 MHz
4 independent beams x 2 pol. x 2 tunings each ~16 MHz bandwidth

Beam SEFD ~[3,17] kJy for \( Z=[0°,65°] \),
~ independent of freq; but somewhat dependent on \{RA,δ\}
Main lobe FWHM ≈ 2.2° ((74 MHz)/ν) sec² \( Z \)
Sidelobe levels highly variable; typically ~ 10-15 dB at maxima

What this talk is about:
How do we know this?
How is the instrument calibrated? (Mutual coupling? Confusion?)
LWA1 System Architecture

Three key features:
1. We record voltages (no in-line spectrometer)
2. “TBN” mode provides all dipoles, coherently (~70 kHz BW)
3. Outrigger provides baselines ~[10,88]λ at [10,88] MHz
Use of Outrigger + TBN to Extract “Embedded” Dipole Response

Fringes: Stand 248 * Outrigger (389 m E-W baseline)
~70 kHz bandwidth
10 s integrations with ~0.01% time domain blanking
Calibration Strategy

Select a source which is:
- Strong (e.g., Cas A, Cyg A, Tau A, 3C123)
- Produces a high fringe rate (to distinguish from background)
- Produces a fringe rate which is distinct from other strong sources

Cross-correlate every dipole with the outrigger for
- at least 1 fringe rotation period (preferably many)
- but not more ~3 h (so dipole pattern response is approx. constant)

Fringe rate filtering is useful to further suppress background and other strong sources
The resulting visibility is essentially the response to the selected source

System response other than dipole is independent of direction, so:
Extrapolate to other directions using a parametric model of “standalone” dipole pattern fit to the above result (LWA Memo 178)

This approach captures the effect of mutual coupling in the measured direction, but neglects it in the extrapolation to other directions
Beam Pointing & Tracking Demo

3 hour calibration using only Cyg A

Beam output cross-correlated with outrigger to suppress confusion

74.03 MHz center
≈70 kHz bandwidth
0.01% time blanking
10 s integrations

Beam tracking Cyg A
Beam fixed @ Cyg A U.C. (Z=7 deg)

Beam tracking Cas A
Beam fixed @ location of Cas A at the moment of Cyg A U.C. (Z=41 deg)

Beam fixed @ NCP
Beam Flux Calibratibility
(Cas A – Cyg A Flux Ratio)

M.175 calibration + crude 1-parameter re-optimization
Same, with M.166-derived mutual coupling correction

M.175 calibration
(8-parameter fit to NEC simulation
of “standalone” dipole)

Known Cas A / Cyg A ratio

Ratio of uncalibrated beam outputs

Beams simultaneously tracking
Cas A & Cyg A @ 74 MHz
(1-pt pointing cal. using Cyg A)

3.5 hour experiment
Cyg A: 20 > Z > 6 deg (transit)
Cas A: 60 > Z > 34 deg

Demonstrates that flux
calibration to with ~5% is feasible
Source Tracking & SEFD Estimates

Line width indicates **uncalibrated** beam output power.

Beam pointing calibrator for each time interval indicated in **red**.

- **Tracks:**
  - TBN (70 kHz BW)
  - 74.03 MHz
  - 10 s integrations
  - 0.1% time blanking

Drift scans used to calculate SEFD; e.g.:

- **SEFD (mode used to calc.)**
  - **Tau A** (TBN)

### Observations:

- **6.4 kJy (DRX)**
- **6.3 kJy (TBN)**
- **4.8 kJy (TBN)**
- **13.3 kJy (DRX)**
- **16.9 kJy (DRX)**

### Source Positions:

- **Tau A**
- **3C123**
- **Cyg A**
- **Cas A**

### Notes:

- **no data**
Main Lobe Characterization

74 MHz
Z = 7 deg
FWHM = 4.4 deg
FSL = -8.9 dB

38 MHz
Z = 7 deg
FWHM = 8.5 deg
FSL = -9.6 dB

74 MHz
Z = 45 deg
FWHM = 9.0 deg
FSL = -9.6 dB

38 MHz
Z = 45 deg
FWHM = 17.6 deg
FSL ~ -7.6 dB
Sidelobe Characterization

Cyg A Transit Pointing (Z = 7 deg)
Cyg A drifting through beam
Cas A drifting through sidelobes

Cas A Pointing at time of Cyg A Transit (Z = 45 deg)
Cas A drifting through beam
Cyg A drifting through sidelobes

74 MHz
Sidelobe Characterization

Cyg A Transit Pointing
(Z = 7 deg)

Cyg A drifting through beam
Cas A drifting through sidelobes

Cas A Pointing at time of Cyg A Transit
(Z = 45 deg)

Cas A drifting through beam
Cyg A drifting through sidelobes

74 MHz

“Conical” Windowing
Effects of Mutual Coupling

A concern for arrays of closely-spaced low-gain antennas

What we know (in the context of LWA1):

- **Dipole patterns**: Variations on the order of a couple dB (M.166)

- **Beam main lobe**: Small but perceptible effect on pointing & FWHM (Pretty good results are possible by ignoring mutual coupling)

- **Beam sensitivity**: Variations up to about 30% depending on RA/Dec and zenith angle (M.166)

- **Beam sidelobes**: Much higher than would be predicted in the absence of mutual coupling
Additional Comments

LWA1 delay-and-sum (“DRX”) beamformers are current calibrated by fitting delay to narrowband response sampled over tuning range of instrument.

Optimum (“max-SNR”; LWA M.166) beamforming in development
Simulations predict gains ~50% in sensitivity, esp. for high Z

Precision control of beam shape & polarization in development
Important for Dark Ages cosmology, RRLs

Spatial nulling:
Not needed (but possibly useful) for RFI mitigation
Useful for mitigating confusion from discrete strong sources
LWA1 is uniquely well-suited to development of nulling techniques
(esp. streaming per-dipole voltages)
Summary

Confirmed LWA1 beamforming performance:

Beam SEFD ~[3,17] kJy for \( Z=[0^\circ,65^\circ]\),
\( \sim \) independent of freq; but somewhat dependent on \{RA,\( \delta \}\)

Main lobe FWHM \( \approx 2.2^\circ \left(\frac{74 \text{ MHz}}{\nu}\right) \text{ sec}^2 Z \)

Sidelobe levels highly variable; typically \( \sim 10-15\) dB at maxima

A useful path to calibration of large, wide FOV, low freq. beamforming arrays is:

Orthogonally-oriented long baselines
\( \text{(strong sources at high fringe rates)} \)

Access to individual dipole signals, or at least cross-correlation of every dipole against each outrigger
Backup Slides
Active Dipole Output Spectrum

Sky noise dominates $T_{\text{sys}}$ over most of tuning range

Most RFI is $< 30$ MHz & $> 88$ MHz
(88-108 MHz aliases harmlessly outside digital passband)

Antenna through digitizer (12 bits @ 196 MSPS)
10 s integration, early afternoon local time
6 kHz spectral resolution
Radiometric Stability

2048 channels over 50 kHz near 38 MHz

Discarding 20% of samples having largest magnitude (overkill)

Noise-limited integrations of up to 10 hours are possible
Confirmation of Galactic Noise-Dominated $T_{\text{sys}}$

Uncalibrated single-dipole total power drift scans

Close agreement to model – can even identify polarizations this way

Figure 2: Dipole total power measurements (1 MHz bandwidth, 61 ms integration per point). Variation is due to the changing sky brightness temperature distribution as seen by the dipole. The solid red line is our prediction obtained by convolving the sky model of de Oliveira-Costa et al. (2008) with a model of the dipole pattern obtained from electromagnetic simulation. No RFI mitigation or editing has been applied.