Station-Level Calibration for LWA-1

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Station-Level Calibration (SLC) Docs

- **LWA Memo Series**

[149] S. Ellingson, Performance of Simple Delay-and-Sum Beamforming Without Per-Stand Polarization Corrections for LWA Stations, Jan 2009.
[147] S. Ellingson, Some Initial Results from an Electromagnetic Model of the LWA Station Array, Dec 2008.
[142] S. Ellingson, Sky Noise-Induced Spatial Correlation, Oct 2008.
[141] S. Ellingson, Interaction Between an Antenna and a Shelter, Sep 2008.
[140] S. Ellingson, Polarimetric Response and Calibration of a Single Stand Embedded in an Array with Irregular Wavelength-Scale Spacings, Aug 2008.
[138] S. Ellingson, Single-Stand Polarimetric Response and Calibration, Jun 2008.
[136] S. Ellingson, Dispersion in Coaxial Cables, Jun 2008.
[129] S. Ellingson, Interaction Between an Antenna and a Fence, Mar 2008.
[115] S. Ellingson, Dispersion by Antennas, Dec 2007.
[75] S. Ellingson, A Design Study Comparing LWA Station Arrays Consisting of Thin Inverted-V Dipoles, Jan 2007.
[73] S. Ellingson, Effective Aperture of a Large Pseudorandom Low-Frequency Dipole Array, Jul 2007
[67] S. Ellingson, Collecting Area of Planar Arrays of Thin Straight Dipoles, Dec 2006.

- **LWA Engineering Memos**

[SLC0004] S. Ellingson, References Applicable to Station-Level Calibration, Jul 2008.
[SLC0003] S. Ellingson, Suggestions for Experimental Verification of Instrumental Responses, Oct 2008.

- **Other References Cited**

[155] J. Hartman, Antenna pattern measurements from a two-element interferometer, Apr 2009.
[R+04] A.E.E. Rogers *et al.* (2004), "Calibration of Active Antenna Arrays Using a Sky Brightness Model," *Radio Science*, 39.
[WB06] S.J. Wijnholds & A.-J. Boonstra (2006), "A Multisource Calibration Method for Phased Array Radio Telescopes," *Proc. 4th IEEE Workshop Sensor Array & Multichannel Processing*, Waltham, MA.

Definitions

- *Steering Vector*: The set of antenna terminal voltages resulting from a plane wave from a given direction at a given frequency.

  Beamforming coefficients are the elements of the conjugated steering vector.

- *Array Manifold*: Complete set of steering vectors as a function of direction and frequency.

  Mutual coupling between antennas is accounted for here.

- *Instrumental Response:* The transfer function from antenna terminal voltages to digitizer inputs.

  Includes FEE, RPD, SEP, ARX. Potential for coupling here, too.

- *Station-Level Calibration*: Process of:
  - Determining array manifold and instrumental responses
  - Implementing corrections (either “on the fly” or post-acquisition)

- Purpose of SLC is to:
  - Enable “go to” beam pointing
  - Know (accurately estimate) beam sensitivity and shape
  - Make sense of TBN/TBW output

Why SLC is Complicated

- Mutual coupling makes gain and phase of each antenna significantly different. In fact, difference is a function of direction [149,147,67]
- Gain and phase of every cable is different due to unequal lengths.
- Dispersion by antennas [115] and cables [136].
  - LWA uses delay & sum BF, but delay depends on frequency
- LWA-1 has no "built-in" or "active" calibration sources.
  All we have is:
  - "As built" information
  - External non-cooperative sources (e.g., astronomical, RFI)
  - Estimates or extrapolations from physical models
    - Electromagnetics (Moment method models)
    - Temperature

Why SLC is Simple

- Ignoring mutual coupling in beamforming does not significantly degrade sensitivity or polarization performance* [149]
  - High confidence in this finding, but comprehensive follow-up is appropriate (ongoing work)
  - Mutual coupling does distort main lobe and jostle sidelobes, but neither effect is of much consequence for LWA-1 science goals
- Experience shows that instrumental responses can be extremely stable
  - E.g., gain to within fractions of a percent over days
  - Rapid update is not necessary or desirable
- LWA-1 dipoles see a very bright sky background
  - This is almost as good as having embedded calibration sources
  - LWA-1 also sees a few bright discrete sources and various anthropogenic (typically, broadcast) sources with high S/N – these are “calibrators of opportunity”

* *Note:* This is not the same as the statement “mutual coupling does not degrade performance”! In some cases performance is degraded, and in other cases it is improved [73]. The finding here is simply that performance after optimal correction for mutual coupling is about the same as performance after no correction for mutual coupling

What is Calibrated & How

- No correction for antenna coupling
  - Appears unnecessary for BFUs *(see previous slide)*
  - Can be implemented post-acquisition for TBW/TBN
- Equalization of instrumental gain is distributed across ARX and DP
  - Jointly optimized for optimum sensitivity-linearity tradeoff ("GNI") by MCS
- Inverse cable dispersion filter
  - Implemented in "fine delay" FIRs in DP's BFUs.
  - Convolved with delay filter impulse response
- No correction for antenna dispersion
  - Beamformer outputs will have a combined antenna dispersion in them. *N.B. Pulsar & coherent transient enthusiasts*
  - Upgrades:
    - Estimate of combined antenna dispersion as observation metadata
    - Per-antenna dedispersion, using (again) BFU fine delay FIRs

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LWA Long Wavelength Array

What is Calibrated & How

continued from previous slide...

- Opportunity for conversion to "standard" polarizations via post-beamforming 2x2 matrix multiply in DP BFUs.
  - Perfect at one frequency, "reasonable" over wide ranges [140,138]
- Calibration updates implemented at integration period boundaries (or even more slowly), rather than continuous updating
- Managed by MCS
  - Users may modify or override calibration "policies" (caveats)
  - Calibration state preserved as observation metadata

How Calibration Parameters are Determined

- "As built" (install-time) measurements and simple assumptions
  - e.g., cable lengths, types, depths, gain/phase vs. frequency, model for parameter variation with depth and temperature; Analogous parameters for FEE, ARX; Simple models for antenna gain/phase patterns
  - This may be all we ever need for to meet LWA-1 science goals

- Refine instrumental gain estimates from sky power measurement
  - Use TBN/TBW
  - Comparison to sky model & daily trend
  - Also useful for detection of deterioration and malfunction
  - Currently studying a method for extracting instrumental *phases* using dipole correlations with sky model. *Analogous to a procedure proposed for LOFAR [WB06], but believed to be better approach for LWA.*

- Refine path (manifold+instrumental) phase estimates from non-cooperative sources when possible/practical (more on this later)
  - Use TBN/TBW
  - Initially for verification
  - Eventually might be used to refine calibration parameters *but we should not be distracted by this possibility*

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How Calibration Parameters are Determined

continued from previous slide...

- Sanity check whenever possible *(good use of extra beams)*
  - Periodic measurement of beam patterns using drift scans against bright discrete sources
  - Periodic measurement of beam patterns using sky model e.g., [R+04]
  - Periodic measurement of beam sensitivity by switching between hot/cold regions
  - These things will work better at higher frequencies than lower frequencies

- If/when necessary, fill gaps and make refinements using:
  - EM model
    e.g., for embedded antenna gain/phase patterns, which will be very difficult to get by any other method
  - Empirical models
    e.g., for cable gain vs. temperature

Array Manifold Issues

- As explained previously: There will be large differences between antennas due to mutual coupling, but not much to be gained by knowing the details or doing anything about it!

- Bigger concern: Proximity of shelter and fence.
  – Large structured effect on antenna patterns possible [129,141]
  – Extent to which this is a problem for beam pattern/polarization is not yet known *(work underway)*

- Antenna pattern measurement data for LWA-1?
  – Already understood what is going on qualitatively and anecdotally
  – Exhaustive measurements not needed for LWA-1 science or calibration
  – A few carefully-selected measurements will useful for validating EM models & refining instrumental calibration
  – The emphasis/priority should be on measurements of beam shape

Antenna Patterns Measured *in situ*

- 2-way interferometry on bright source(s) [SLC0003, 155, 142]
  - Provides gain only over track of source
  - Provides only phase *difference*
  - Very poor performance at low elevations [155], where need this data is the greatest
  - Basic technique requires long baseline (“outrigger” antenna) to decorrelate sky noise, which reduces sensitivity and contributes bias otherwise [142]
- Situation may actually be better using just station elements
  - Desensitization due to sky noise correlation is worse, but integration time can be longer; many re-looks possible (daily)
  - Compensation for sky noise correlation bias is possible using a sufficiently good sky model ([111] may already be good enough)
  - 32,640 baselines: Highly overdetermined, however solution may involve a difficult phase unwrapping procedure
- EM modeling is a better approach at this phase in the project
  - <u>An EM model validated by just a few measurements will be far more useful than a much larger set of measurements without a model.</u>
  - Many pitfalls, computationally intensive, but we have a pretty good “leg up” on this already

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Other Calibration Opportunities

- Pulsars
- Active sun
- Broadcast TV
  - We have very good understanding of ATSC and associated propagation (Lee Dissertation, 2008)
  - Complicated by terrain and ionospheric multipath scattering
- TV broadcast reflected from meteor ionization trails ("meteor scatter")
  - Useful primarily for phase calibration *(but that's where the greatest need is...)*
- We should not be distracted by these possibilities until we have sufficient operational experience with LWA-1

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Pending & Future SLC Tasks

- **Anticipating effect of fence and shelter for proposed site design**
- **Anticipating effects of antenna dispersion after beamforming**
  - Considering also efficacy of pre-beamforming correction
- **A_e/T_{sys} estimates**
  - Confirm findings of [149] (i.e., that "simple" beamforming is OK) for broader range of pointings
  - Commissioning preparation
- **EM model for LWA-1**
  - A validated model is desired for observation planning, data interpretation & LWA-2 design
  - Ultimately may be useful in commissioning, calibration, understanding sidelobes
- ***in situ* array manifold / instrumental phase calibration techniques**

Additional Information / Backup Slides

Virginia Tech's Role in LWA

- VT subcontract accounts for about 6% of ONR LWA funding (FY06-FY08)
- Current Emphasis in LWA Project:
  - Station-Level Calibration (SLC)
  - Monitoring & Control System (MCS)
  - MCS Data Recorder (MCS-DR)
- Past / Recurring Efforts
  - Systems Architecture / Systems Engineering
  - Rapid Prototyping / Equipment Loan: ARX, Digitizer, "S60" Data Recorder
  - Data Analysis, RFI Mitigation, Transient Search Software
- Faculty:
  - Steve Ellingson
  - Cameron Patterson (MCS-DR; starting Summer 2009)
- Students
  - Currently 3 Ph.D. engineering students funded by project: Harun, Liu, Wolfe
  - Recent VT engineering graduates who have done LWA-relevant work:
    Lee (Ph.D. 2008), Hasan (Ph.D. 2009), Taylor (M.S., 2006)

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LWA Long Wavelength Array

Why Can't We Do It Like…

- LOFAR:
  - Most similar to LWA in terms of array manifold issues
  - Architecturally very different from LWA – beamforming done in narrow channels as opposed to "delay and sum". Overall bandwidths much less.
  - Availability of information on their approach is sketchy
- LWDA, ETA:
  - Similar to LWA in terms of array manifold issues, but much smaller
  - Very low sensitivity and spatial resolution; crude calibration OK.
- PAPER, MWA:
  - Have simple array manifolds since elements/tiles are spaced far apart
- Clark Lake, FLIRT:
  - Elements individually had large S/N (Large conical spirals, Bays of 8 FW dipoles) and relatively simple manifold (regular spacings -> orderly coupling)
  - Superior beam sensitivity and resolution
  - In this case, relatively straightforward to get instrumental response by phasing up on strong sources

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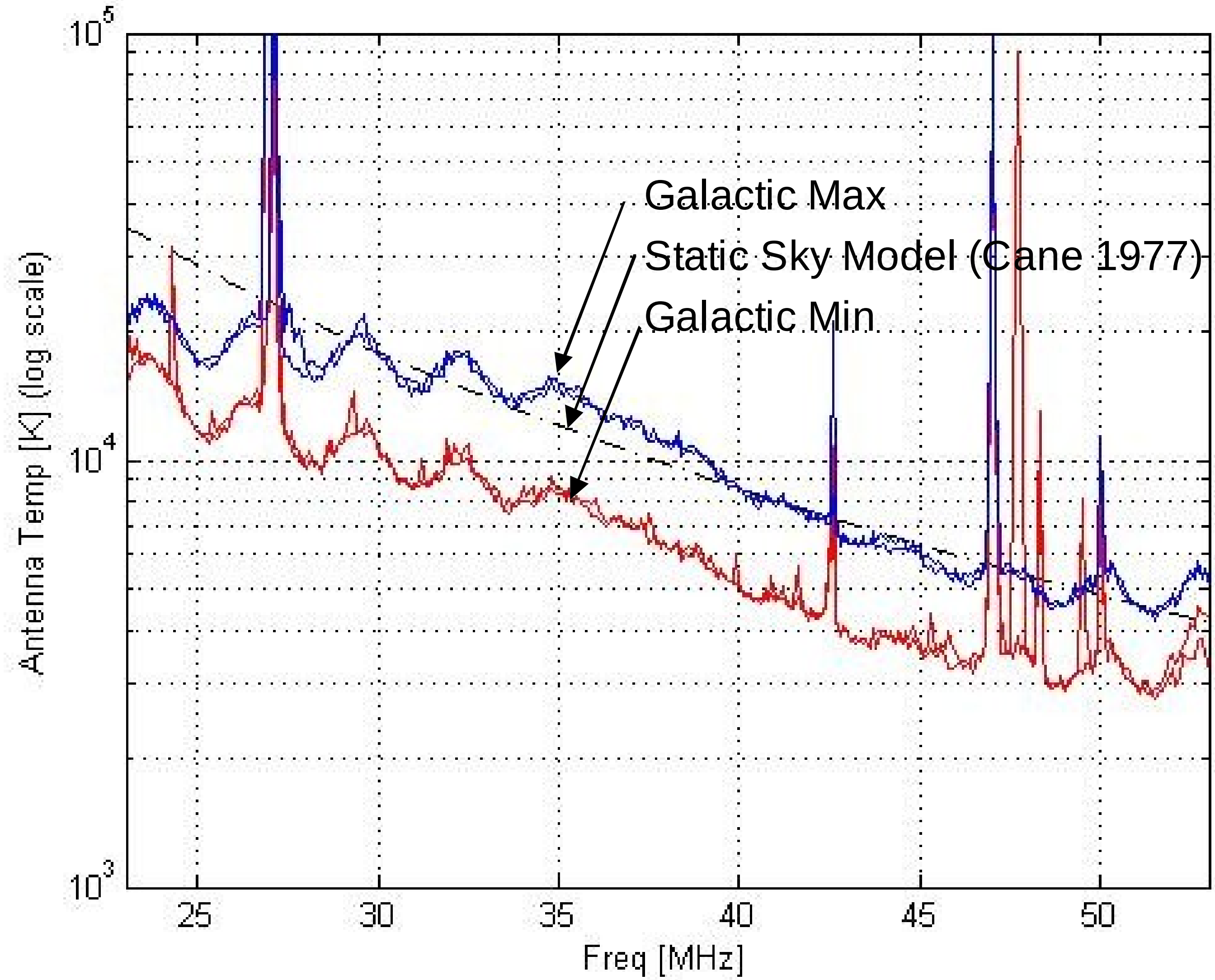
LWA Long Wavelength Array

Stability of Instrumental Response (ETA)



Blue:
2 sets of measurements taken 24 hours apart

Red:
2 sets of measurements taken 24 hours apart

Ellingson, Simonetti, and Patterson (2007), *IEEE Trans. Ant & Prop.*, 55, 826.

Effect of Mutual Coupling on Station Beam Collecting Area

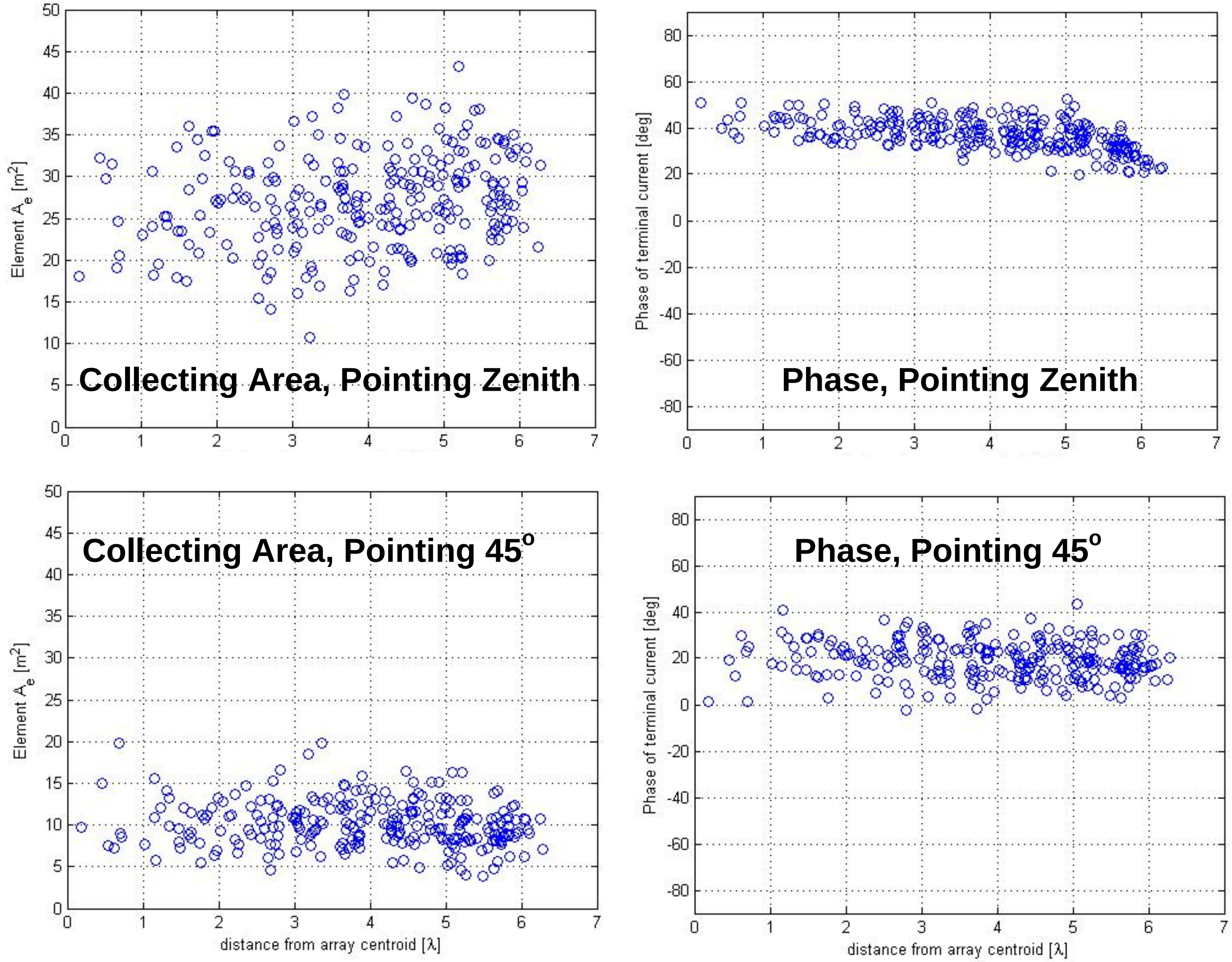
Circular 100 m dia station,
Irregular geometry,
Min. 4 m between stands
Simple dipoles, 38 MHz

			Single Stand [m²]			[m²] Array		
Ground	Load	θ	A_e^e	A_e^d	A_e^i	$A_e^d/256$	$\Delta\%$	e_{ap}
PEC	100Ω	0°	23.78	25.49	23.97	25.96	+2%	0.84
		45°E	8.41	8.01	7.53	10.16	+27%	0.47
		45°H	20.00	19.26	20.49	14.25	−26%	0.66

- A_e^e: **Single Dipole, Simple model**
- A_e^d: **Single Dipole, Rx-mode NEC2**
- A_e^i: **Single Dipole, Tx-mode NEC2**
- $A_e^d/256$: **Array, Rx-mode NEC2 (stand average)**
- $\Delta\%$: **Effect of mutual coupling**
- e_{ap}: **Aperture Efficiency**

LWA Memo 73

Effect of Mutual Coupling on Dipole Voltages



- **Shown here: Magnitude and phase of current induced at each feedpoint (moment method)**
- **Only a "small" effect on mail lobe shape, since phase "errors" have low bias**
- **Effect on sidelobe levels unknown, but probably significant**
- **These values "rumble" as a function of direction of arrival**

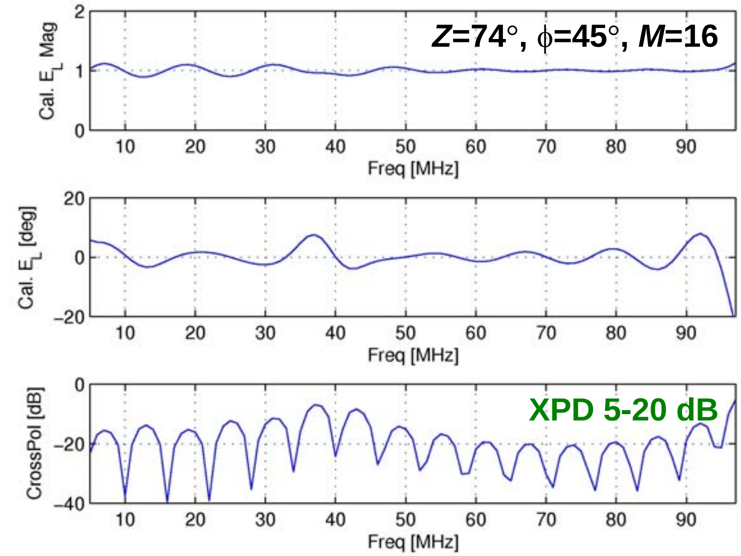
LWA Memo 67

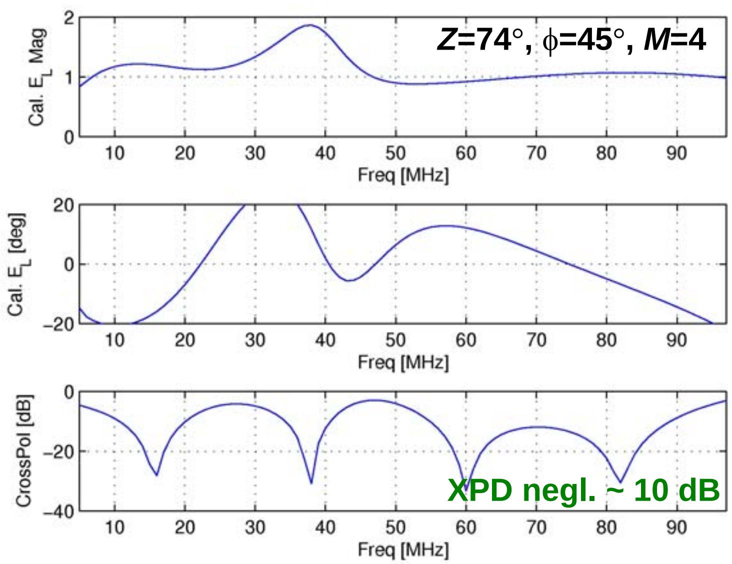
Polarization & Dispersion Calibration

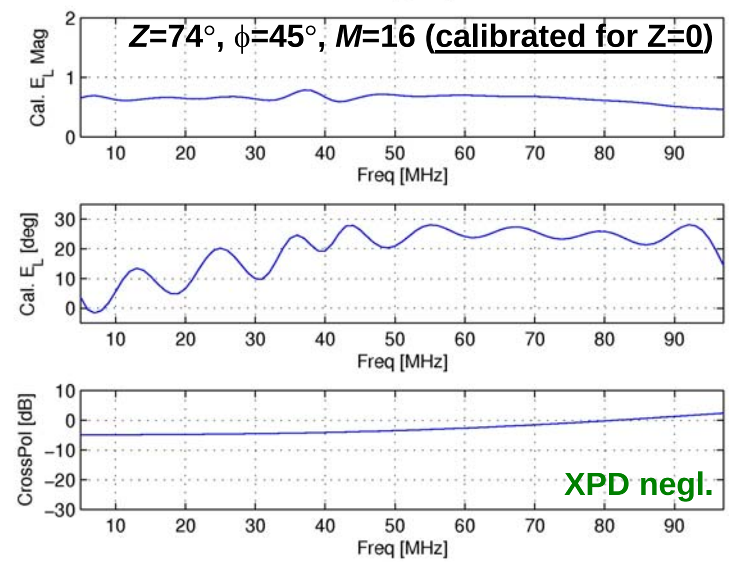
- **Beams should be not only "full bandwidth" (78 MHz) and fully independent, but also well calibrated. Xpol!**
- **"Perfect" calibration possible, but only for a single frequency and beam pointing, or if FIR filters of infinite length are available**
- **Cable dispersion further complicates this:**

$$\tau_d = (4.78\ \text{ns}) \left(\frac{l}{100\ \text{m}}\right) \left(\frac{f}{10\ \text{MHz}}\right)^{-1/2}$$

- **"Reasonable" performance seems possible with *M*=16 (@ 98 MSPS) FIR filters**







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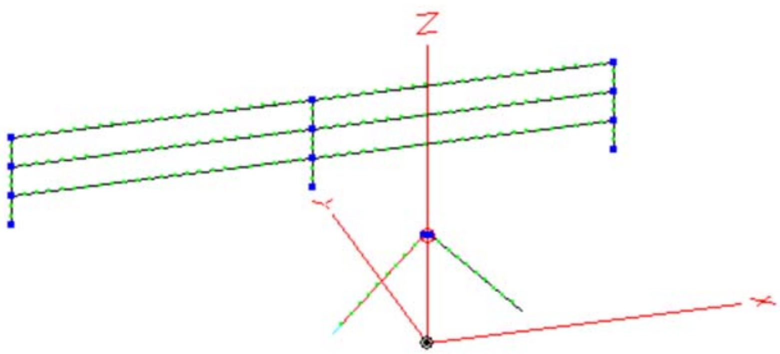
Effect of Fence



- Security fence required around array – effect?
- Biggest impact is for H-plane pattern, when collinear (as shown in these moment method simulations)
- < 1 dB gain variation, but oscillates
- Effect depends on ground type