Polarimetry with Phased-Array Feeds

Bruce Veidt

Dominion Radio Astrophysical Observatory

Herzberg Institute of Astrophysics

National Research Council of Canada

Penticton, British Columbia, Canada

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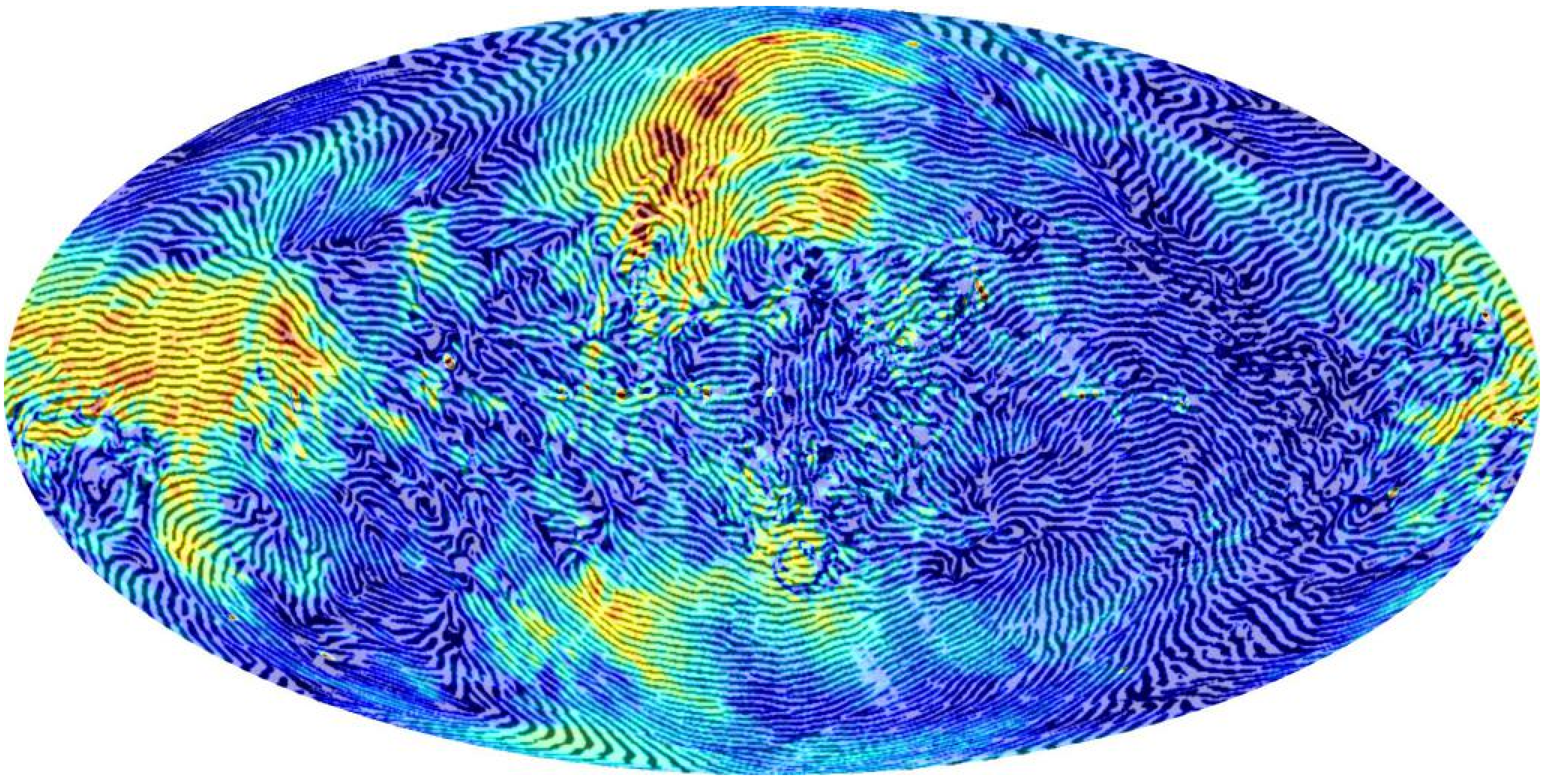
Conseil national de recherches Canada

Outline

- Radio astronomy & polarimetry
- Stokes parameters
- PHAD receiving system
- Calibration, measurements & results

All-Sky Polarization Map



Courtesy Maik Wolleben and Tom Landecker

SKA Design Reference Mission

http://www.skatelescope.org/PDF/091001_DRM_v0.4.pdf

- Cosmic Magnetism Deep Field
- Wide-Field Polarimetry
- Testing Theories of Gravity using Ultra-relativistic Binaries
- Pulsar Timing to Detect Gravitational Waves

Summary of Requirements

- frequency range: $\sim$ 0.3 – 3 GHz
- bandwidth: 0.5 GHz
- polarization purity
  - polarization surveys: 25 dB (wide field)
  - pulsar timing: 40 dB (boresight, narrow field)
- time resolution: 50 μs (100 ns for timing)
- survey time
  - deep field: 100 – 400 hours per pointing
  - wide field: 1 hour/field

Polarization — Two Worldviews

Engineers	Astronomers
highly-polarized sources	weakly-polarized sources $\lesssim$ 10%
bright sources	weak sources ($\sim$ 10 Jy)
co-pol/cross-pol/ellipticity	Stokes (un-pol/linear/circular)

Typical Calibration Sources

Source	S, Jy/pol	% pol	P_s, Jy
Cas A	1861	0.27	10
Cyg A	1589	0.5	17
3C270	17.2	7.6	2.6
3C286	14.8	9.5	2.7

(1.4 GHz)

Also regions of extended emission visible in N sky

- Question: what level of polarization purity is possible when polarized signal of calibrator is swamped by unpolarized emission?

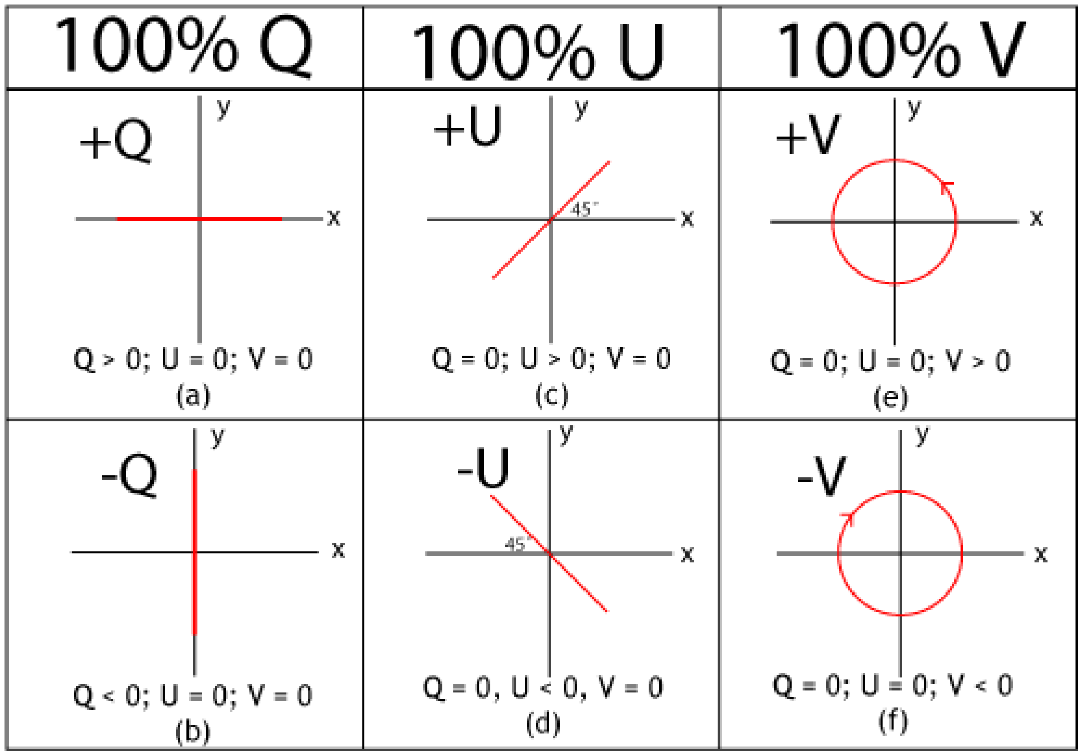
Stokes Parameters

- Stokes Parameters are a way of describing a partially-polarized radiation field

$$
\begin{aligned}
I &= \left\langle |e_x|^2 + |e_y|^2 \right\rangle \\
Q &= \left\langle |e_x|^2 - |e_y|^2 \right\rangle \\
U &= 2\,\Re \left\langle e_x \cdot e_y^* \right\rangle \\
V &= 2\,\Im \left\langle e_x \cdot e_y^* \right\rangle
\end{aligned}
$$

$$I^2 \geq Q^2 + U^2 + V^2$$

Stokes Parameters (Pictorially)



http://en.wikipedia.org/wiki/Stokes_parameters

References

- Heiles' tutorial (single dish mostly)
  - *Single-Dish Radio Astronomy: Techniques and Applications*, ASP vol. 278, 2002
  - this reference and other useful memos at http://astro.berkeley.edu/∼heiles/handouts/handouts_radio.html
- Hamaker/Sault/Bregman series of papers on polarimetry in *Astronomy and Astrophysics Supplements* (interferometry mostly)
  - search ADS
  - Johan Hamaker's web page: http://www.astron.nl/∼hamaker/

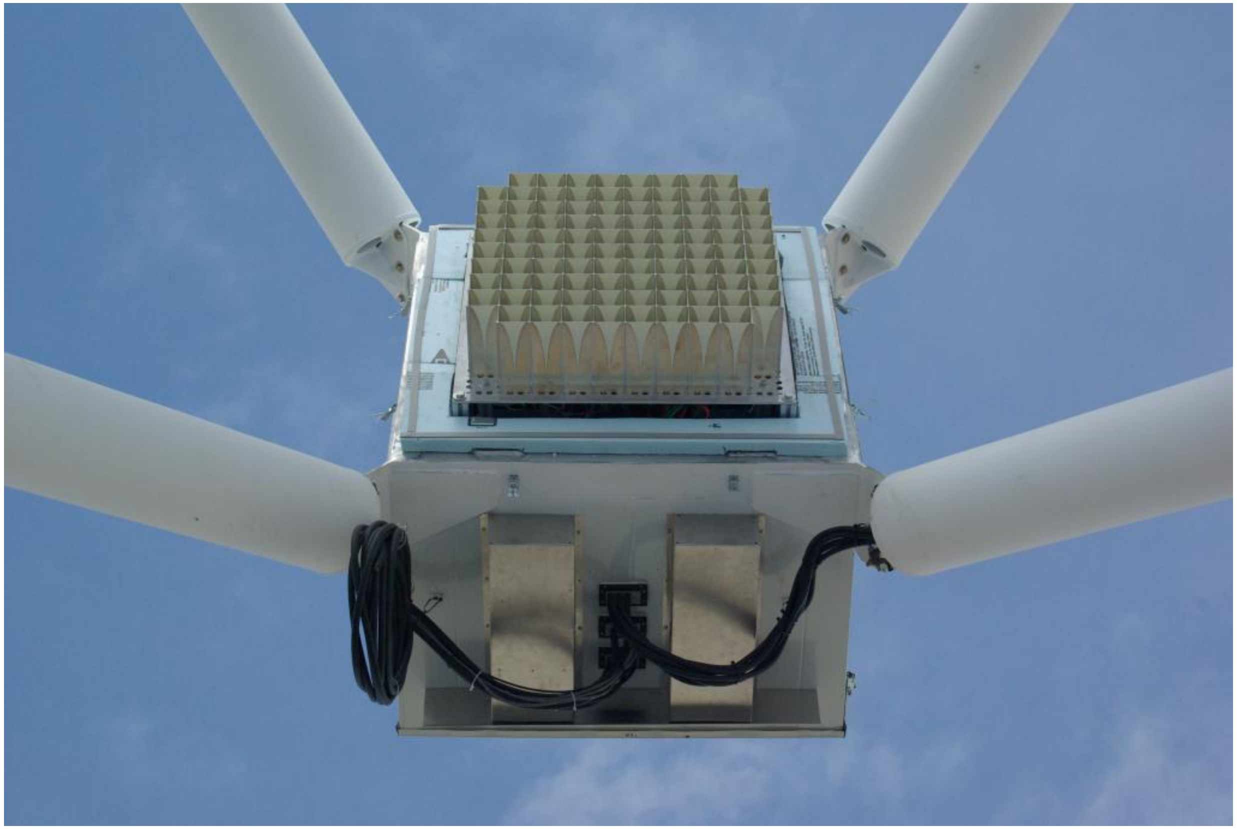
PHAD receiving system

- Phased-Array Feed Demonstrator = PHAD
- *Engineering* demonstrator
- Vivaldi-element based array (dual polarization)
- 84 active elements ($6 \times 7 = 42$ per polarization)
- Data store $\longrightarrow$ off-line beamforming

PHAD Specifications

Frequency range	1–2 GHz
Array size	0.76 m $\times$ 0.76 m
Number of elements	$9 \times 10 \times 2$ polarizations $= 180$
Active elements	42×2 polarizations $= 84$
Element spacing	$\lambda_{min}/2 = 76$ mm
Receiver architecture	direct conversion (complex)
Bandwidth	4 MHz/sideband
Sample rate	10 MHz
Sample precision	14 bits
Memory depth	16 MB/element

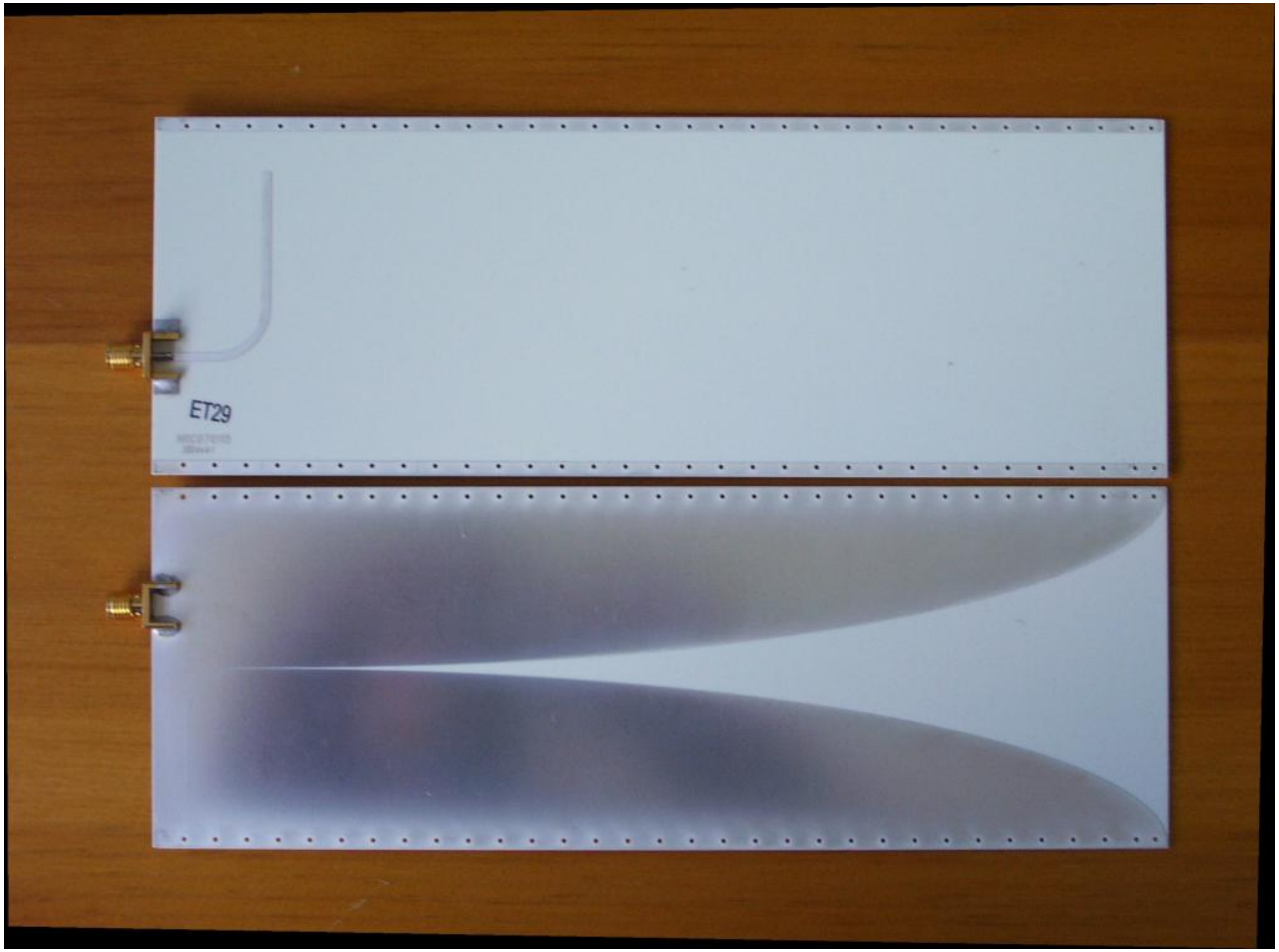
PHAD Array



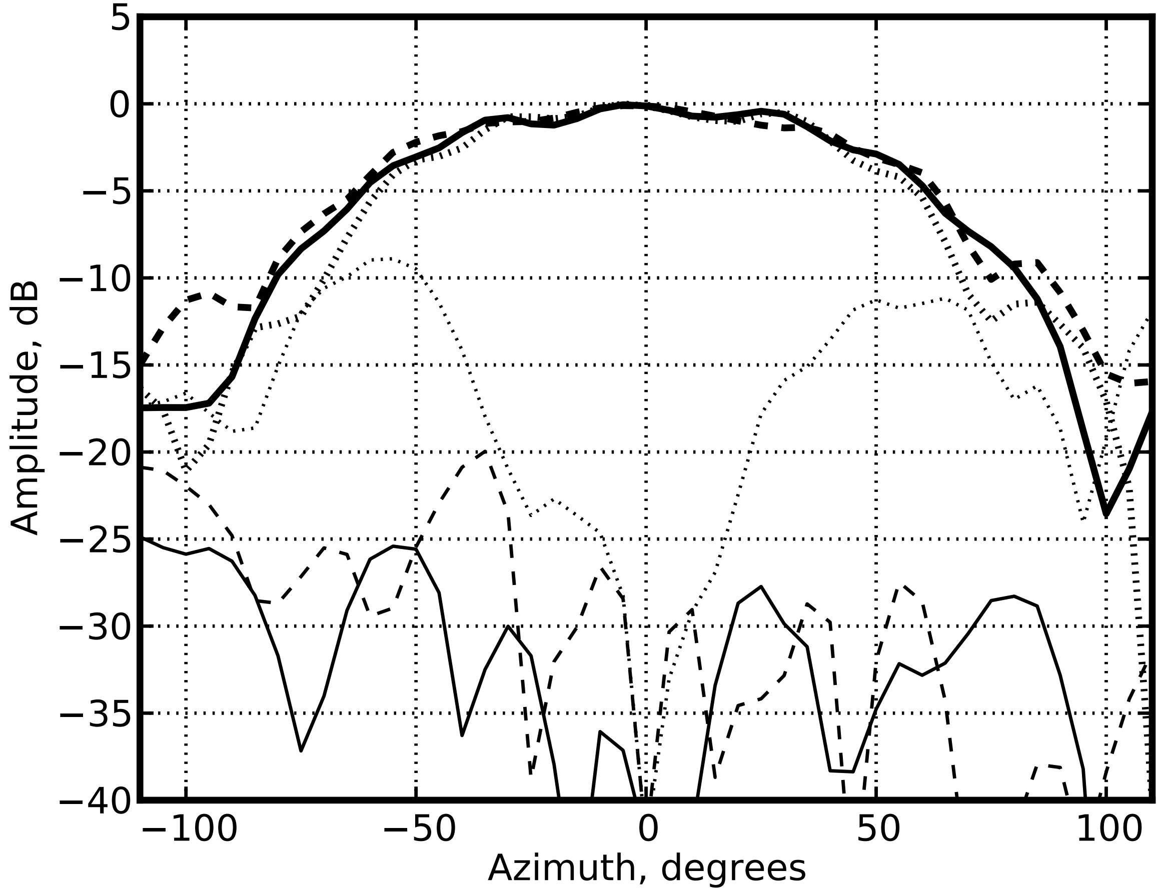
PHAD on CART Dish

- 10-metre diameter
- $f/D = 0.45 \Rightarrow \theta_{half} = 58^\circ$
- RMS surface error 1.2 mm
- composite construction

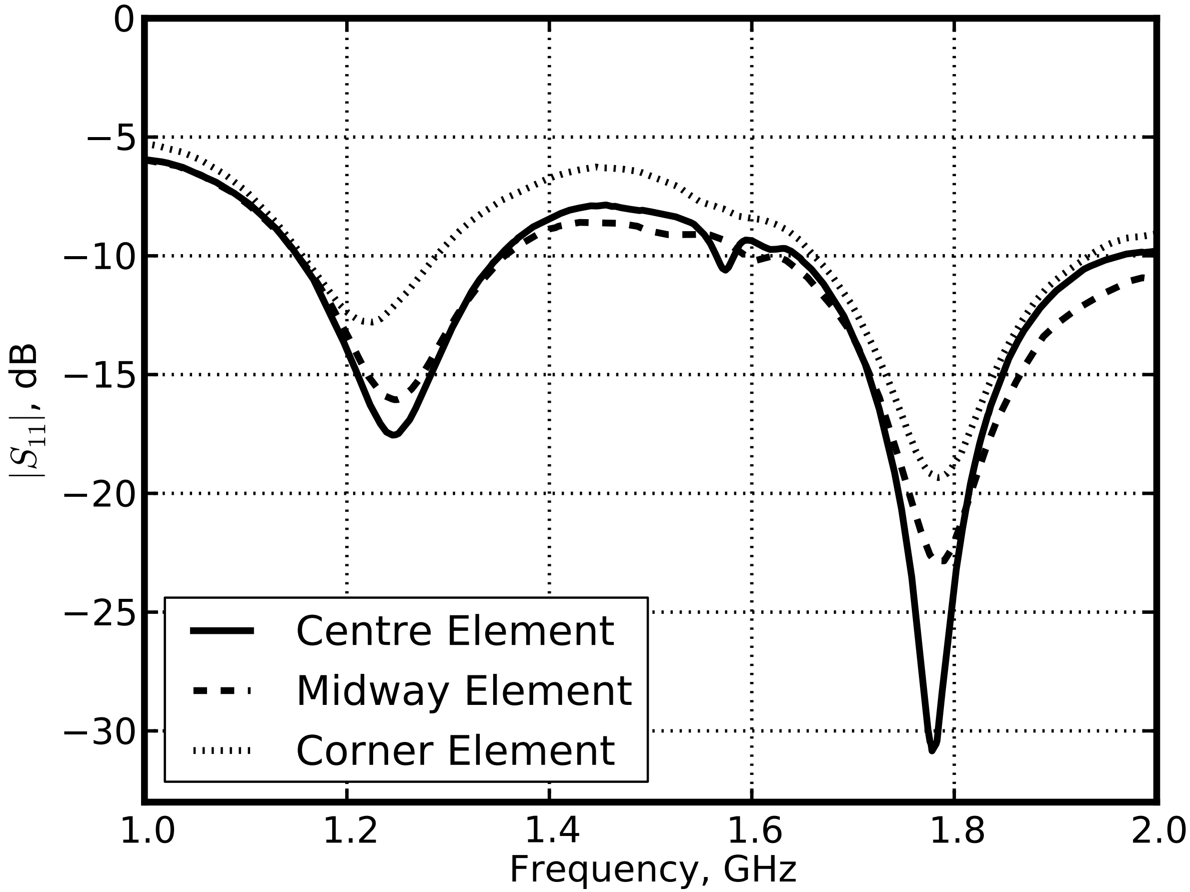
Vivaldi Element Layout



Typical Element Patterns



Typical Element S_{11} (Passive)

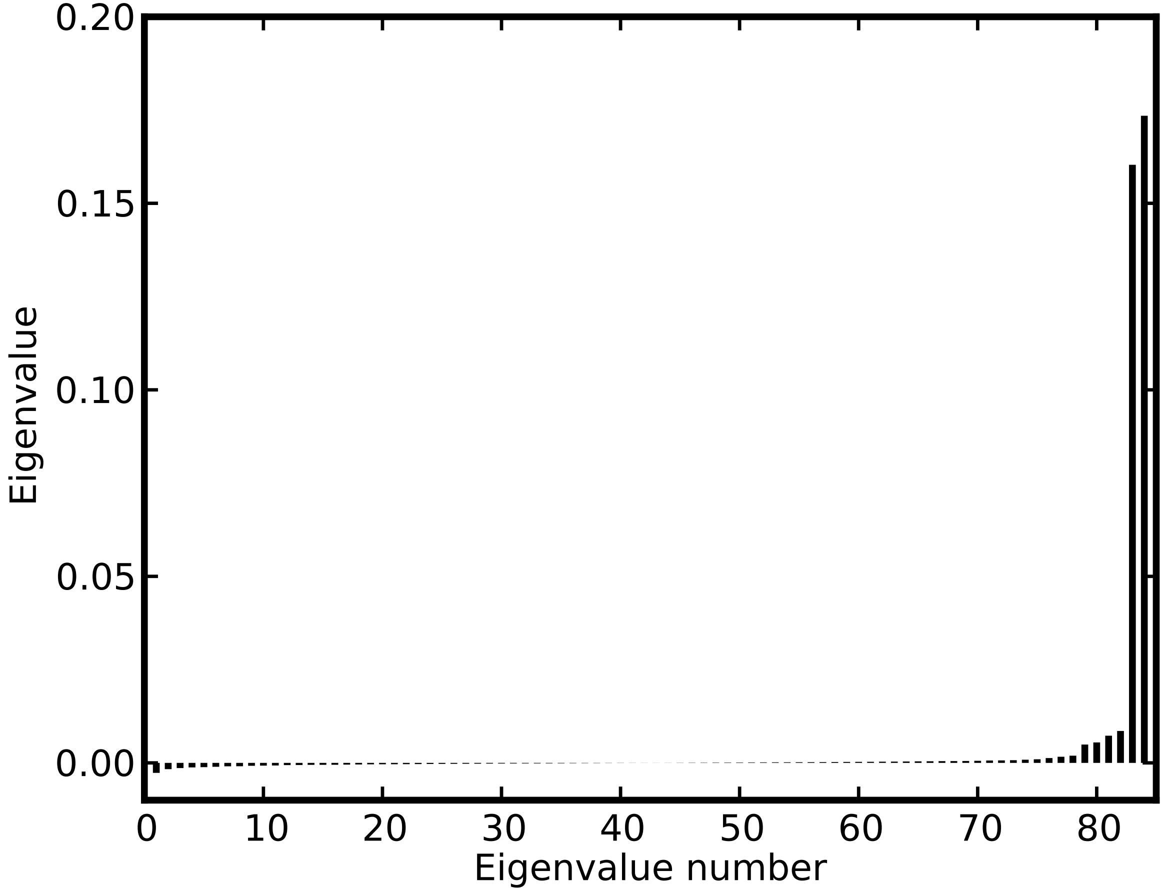


Beamformer Calibration

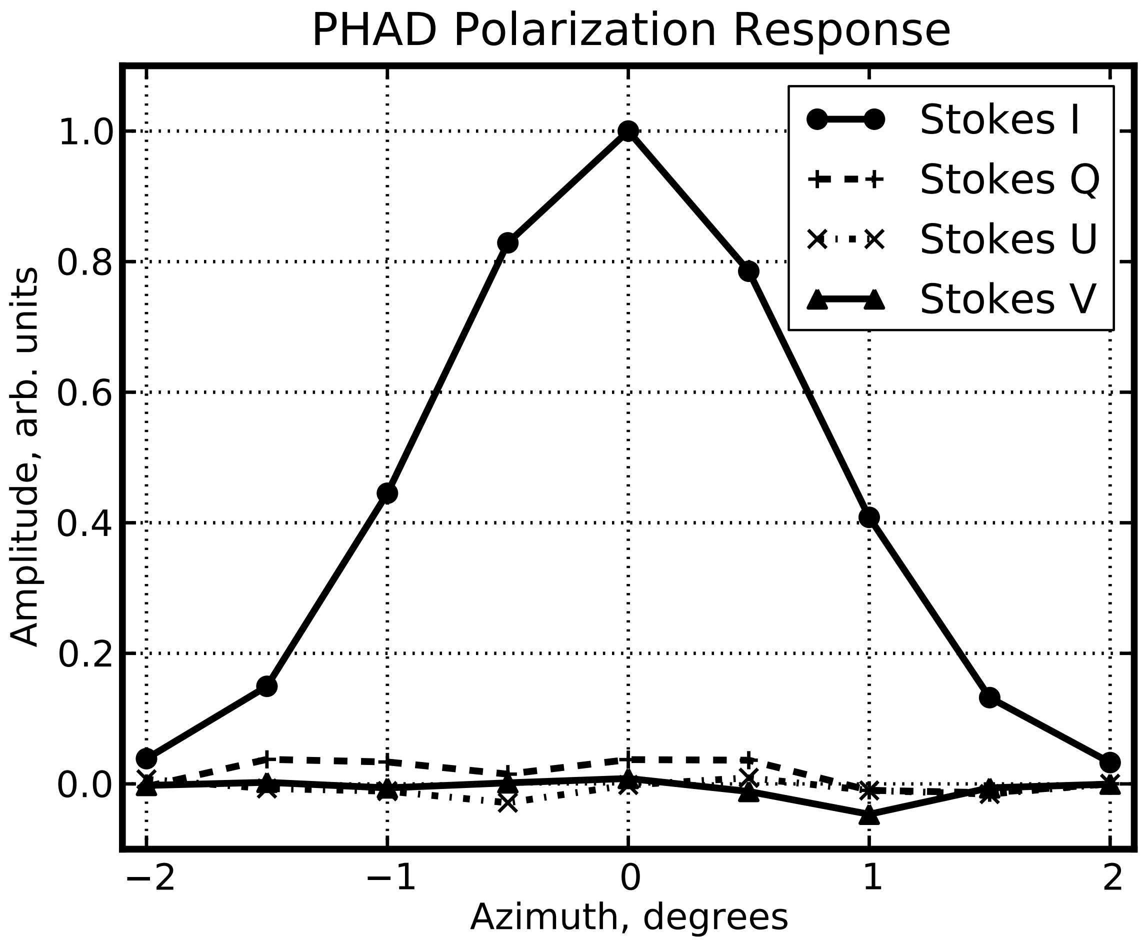
Use Conjugate Field Matching (CFM) for two polarizations

1. Observe unpolarized calibration source and calculate covariance $\Rightarrow \mathbf{R}_{on}$
2. Observe dark sky and calculate covariance $\Rightarrow \mathbf{R}_{off}$
3. Calculate difference $\mathbf{R}_{on} - \mathbf{R}_{off}$ and calculate eigenvectors
4. Select two dominant eigenvectors
5. Conjugate of eigenvectors are weights for the two polarizations

Eigenvalue Spectrum



Synthesized Stokes Beams



Summary of Instrumental Polarization

parameter		with cross-pol		no cross-pol	
Q/I	$\leftrightarrow$	0.062	-12 dB	0.055	-13 dB
U/I	$\swarrow\!\!\nearrow$	0.006	-22 dB	0.027	-16 dB
V/I	$\circlearrowleft$	0.007	-22 dB	0.021	-17 dB

$$\frac{I_{x-pol}}{I_{no-x-pol}} = 1.04\ (0.17\,\mathrm{dB})$$

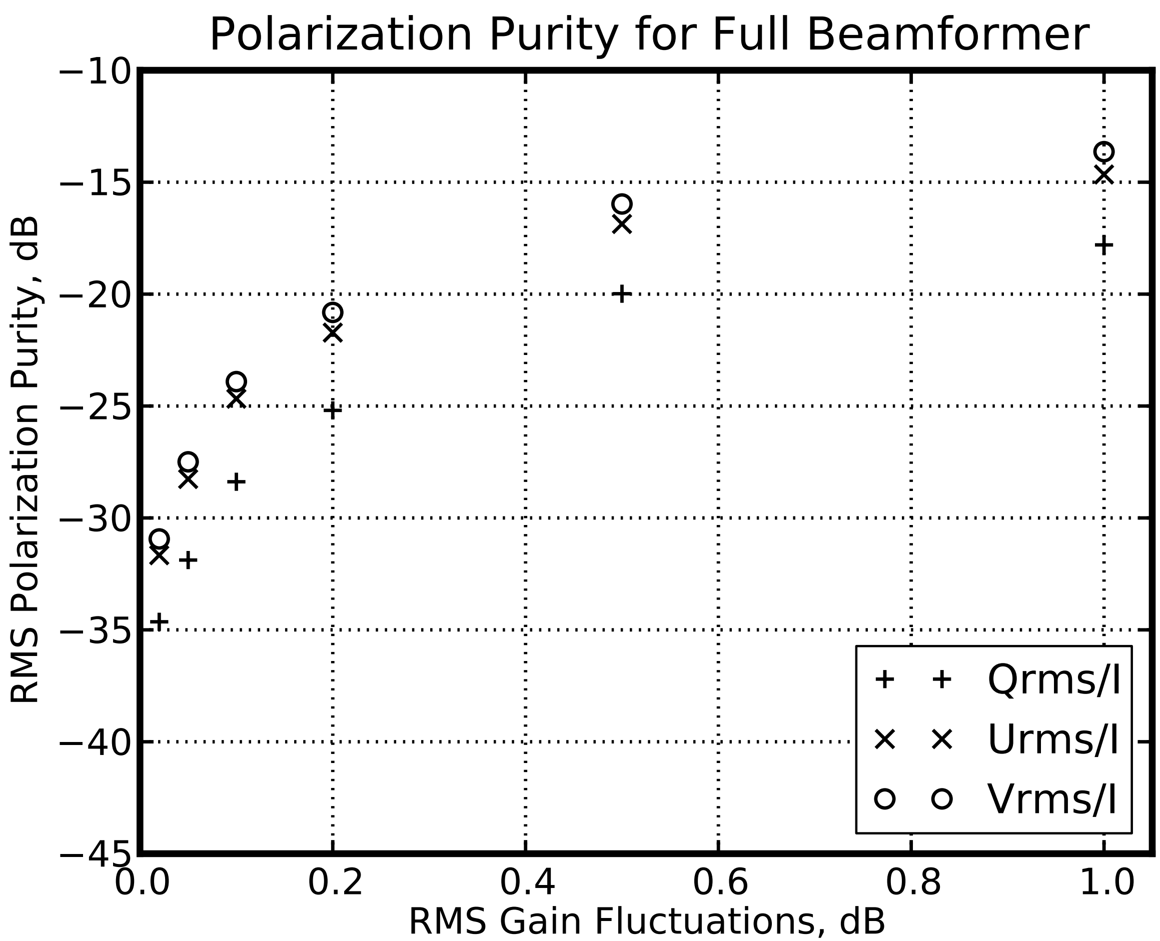
Is This Calibration Complete?

- We have two orthogonal beams
- We have not established polarization angle
  - CFM solutions for different beams will have different rotational angles
  - observe astronomical calibrator with known polarization angle
  - or on-dish calibration source (watch out for reflections)
  - or cross-correlation with reference antenna in an interferometer
- Do not have "handedness" of U and V (phase between e_x and e_y)
  - requires another observation with a polarized source
- *But*, at this point calibration is similar to what is done for conventional horn feeds

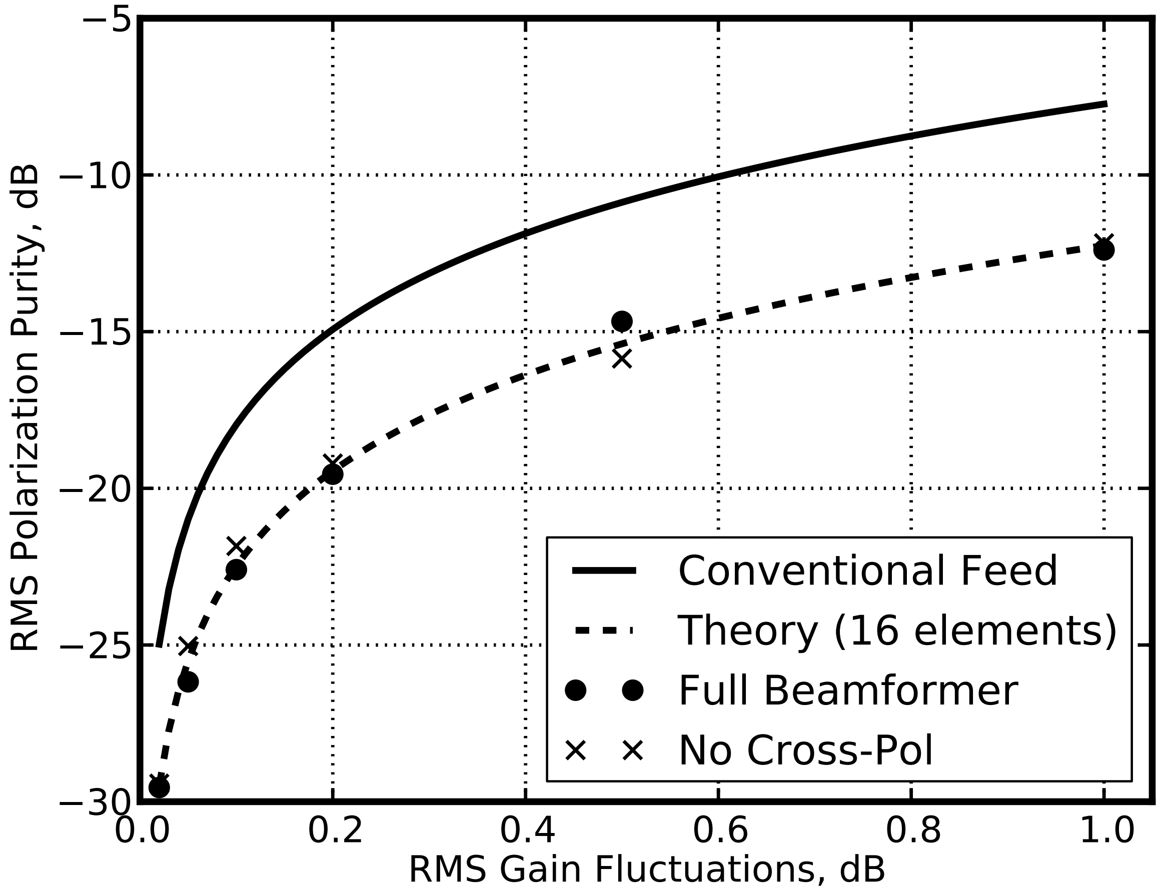
Electronic Gain Stability

- As long as Stokes beams are stable, instrumental polarization can be corrected
- How stable?
- Simulate by introducing random gain errors into recorded data streams and reprocessing
- Compare with a simple model: $e = \sum_{i=1}^{n} (1 + \Delta g \, \rho \, (i))$

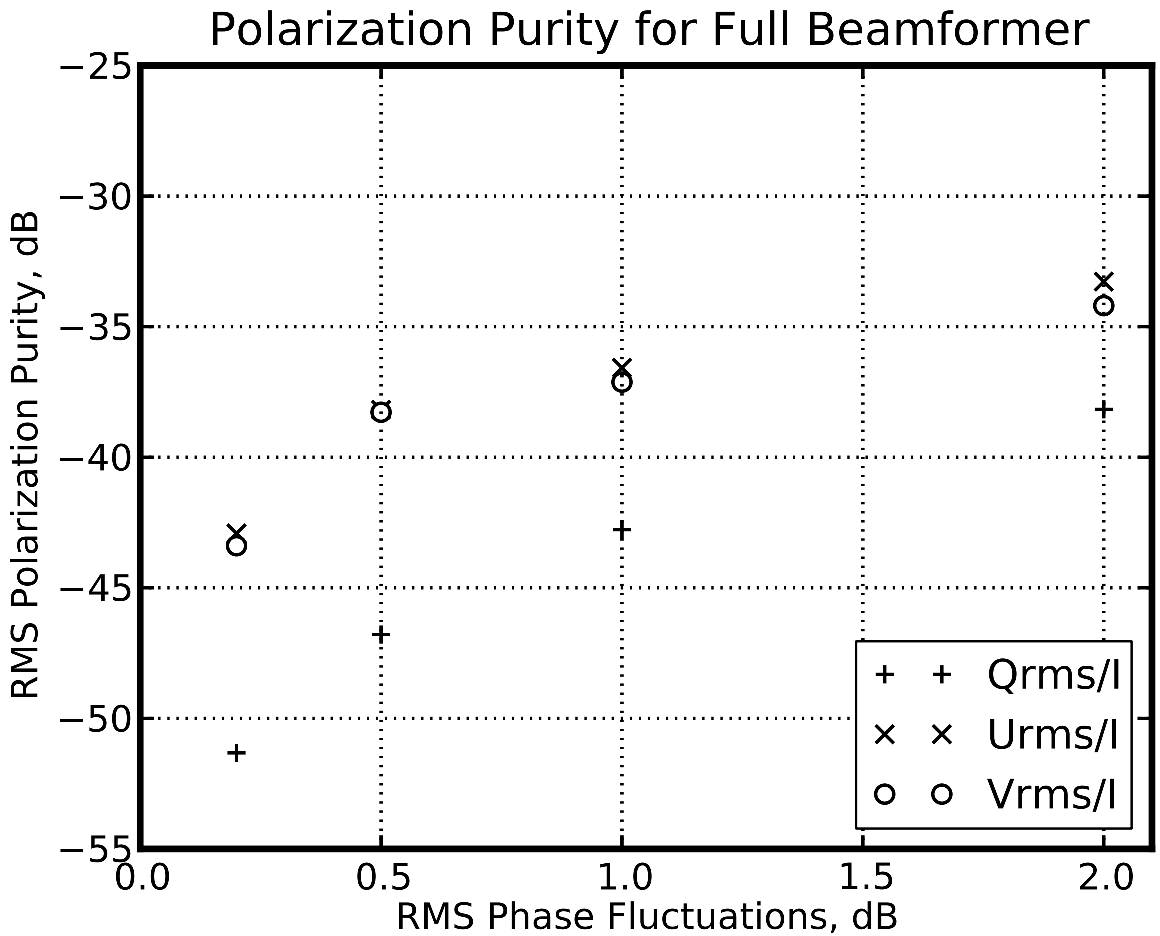
Polarization Purity with Gain Fluctuations



Polarization Purity with Gain Fluctuations (II)



Polarization Purity with Phase Fluctuations



Discussion on Stability Specification

- Gain stability more stringent than phase stability
  - to meet 40 dB spec need gain stability of 0.0018 dB
  - ATA measures 0.0009 dB over 1–3 minutes (Memo 76)
  - phase stability of $\sim 0.2^\circ$
- Cross-coupling between Stokes parameters for PAFs more complicated than horn feeds
  - gain fluctuations *are* seen in U and V
  - stability will be an issue with wide-band single-pixel feeds too

Discussion on Calibration System

- Calibration system crucial for PAFs
  - {monitor/correct} {gain/phase} fluctuations in receivers
  - provide coordinate system references
  - dish with very good polarization properties to act as a polarization reference in an interferometer?
- Sidelobes are highly polarized so spillover can introduce a contaminating signal

Acknowledgments

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The End