Progress in Array Design, Calibration, Beamforming, and RFI Mitigation for PAFs

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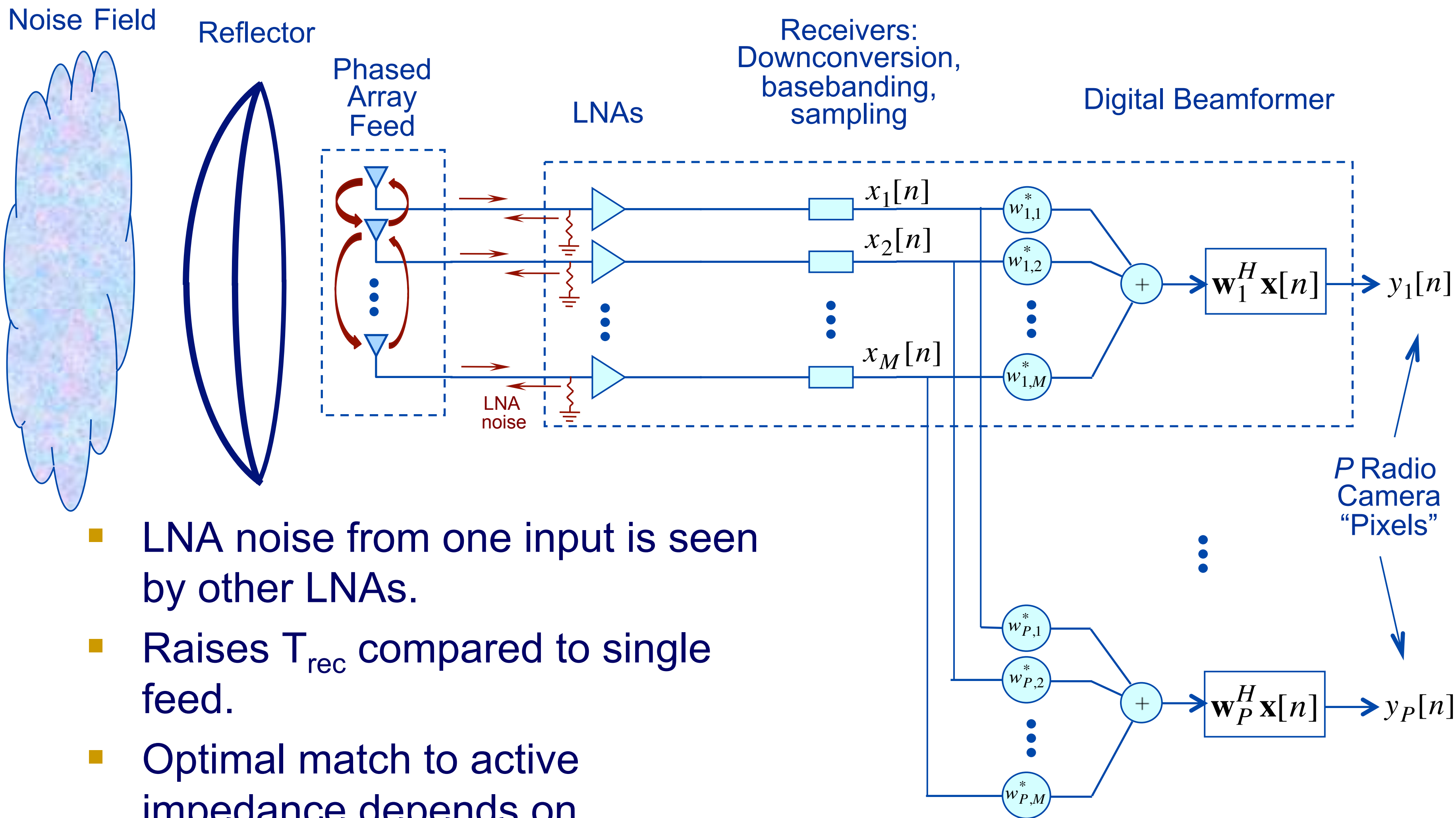
CALIM 2010, ASTRON, Dwingeloo The Netherlands
22-27 August 2010

Radio Camera System Block Diagram

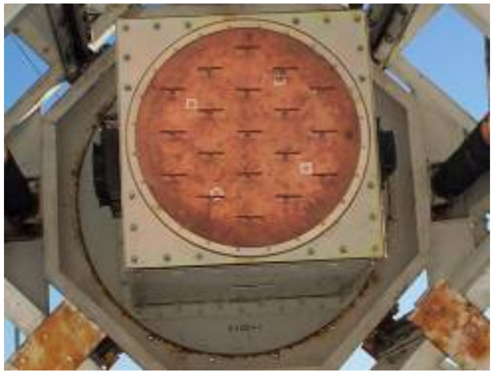


- LNA noise from one input is seen by other LNAs.
- Raises T_{rec} compared to single feed.
- Optimal match to active impedance depends on beamformer weights, $w_{p,m}$!

BYU/NRAO L-Band PAFs

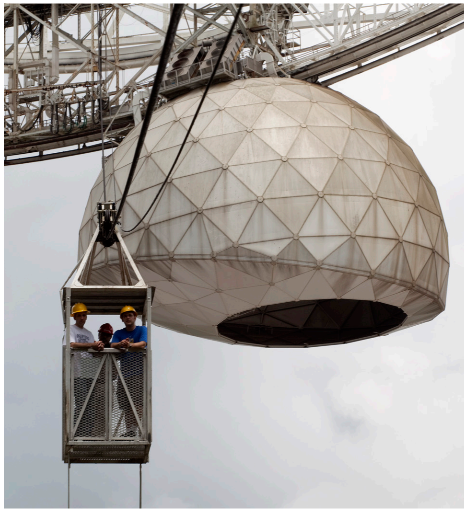
2006-2007:

- 7 element array on 3m reflector
- RFI mitigation experiments
- 19 element on Green Bank 20m
- 150 K T_{sys}



2008:

- 19 element dipole array
- 33 K LNAs (room temperature)
- 1.3 – 1.7 MHz tunable bandwidth
- *Goal:* highest possible sensitivity
- 66 K T_{sys} with room temp LNAs



2009-2010:

- Active matched low noise PAF designs
- Dual polarized 19 element array
- New 40 channel down converters and data acquisition system
- Improved beamformer methods
- Progress towards cryo-cooled array
- Deep nulling interference canceler
- AO-40 experiment on the Arecibo dish

Cornell University

National Astronomy
and Ionosphere Center

Arecibo Observatory
Phased Array feasibility Study:

AO-40, preliminary progress report

- Project director: German Cortes-Medellin
- Funded by NAIC/Cornell University
- Laying groundwork for a permanent 40 beam PAF design
- BYU 19 element array test platform mounted on the Arecibo Telescope
- Data collected June and August 2010

Some AO-40 Project Goals

- Evaluate feasibility and capability of PAF arrays for the Arecibo Telescope.
- Use observed BYU 19 element PAF data to directly estimate:
  - Achievable field of view
  - Beam sensitivity and shape
  - Number of usable independent beams
  - Required arrays size and element spacing
  - Focal surface shape
  - Optimal array placement for wide FOV
  - Gregorian optics effects on PAFs.
  - Calibration performance and stability
- Study results will inform the design of a permanent PAF instrument

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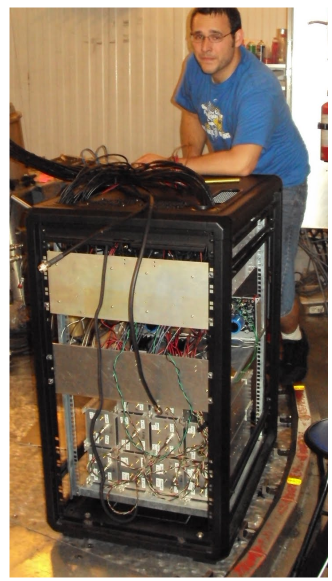
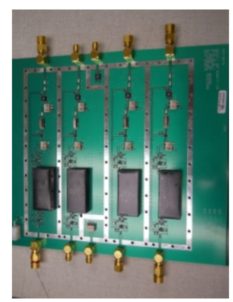
Experimental Procedure

- Room temp 19 element array
- Narrow-band (500 kHz)
- Stream data to disk for post processing analysis
- Active impedance matched low noise array
- 33K LNAs, 66K Tsys
- Dual and single pol arrays tested
- Precision positioner moves array in focal plane to simulate larger array.





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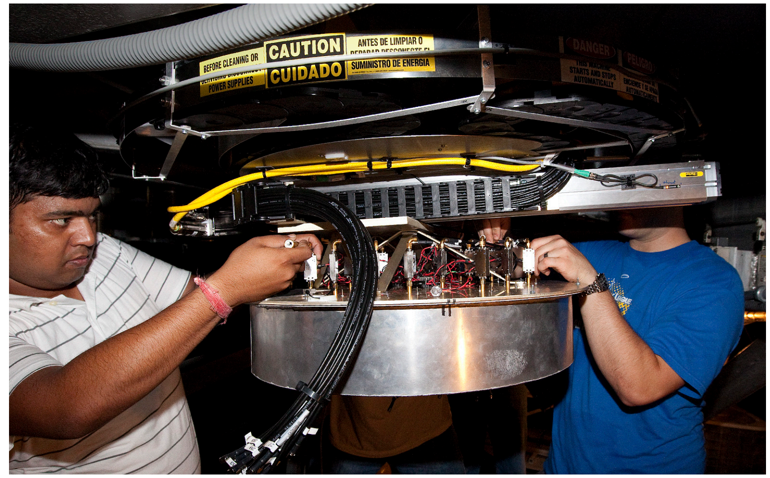

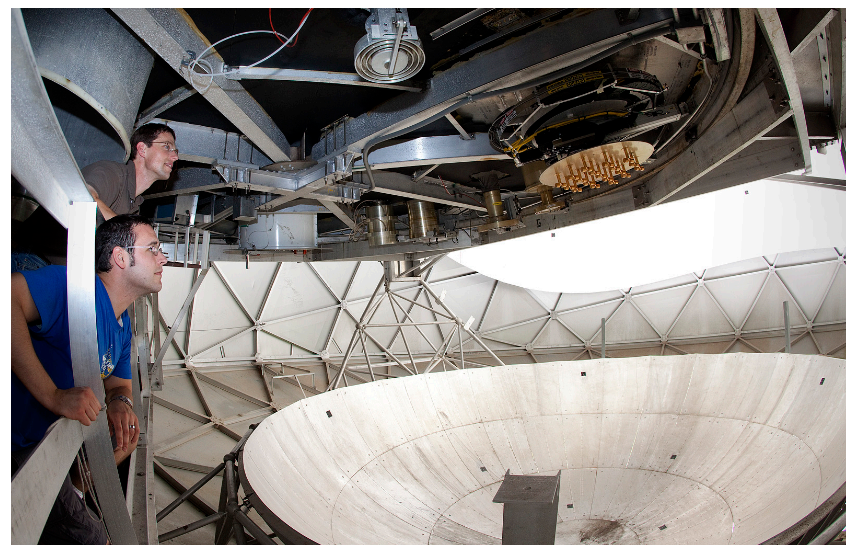

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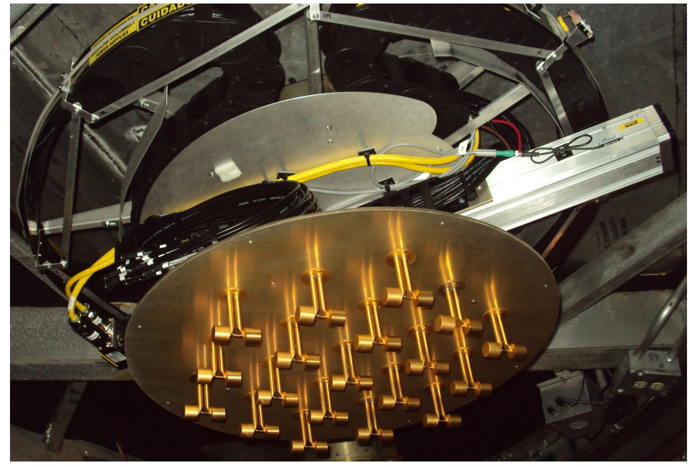

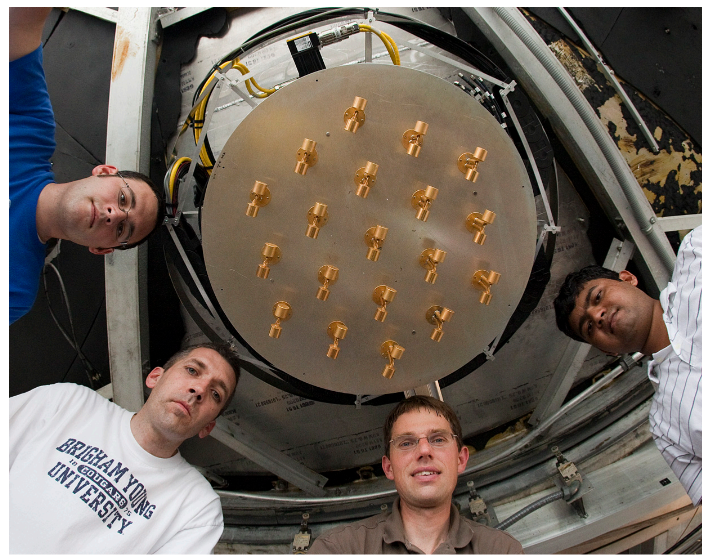

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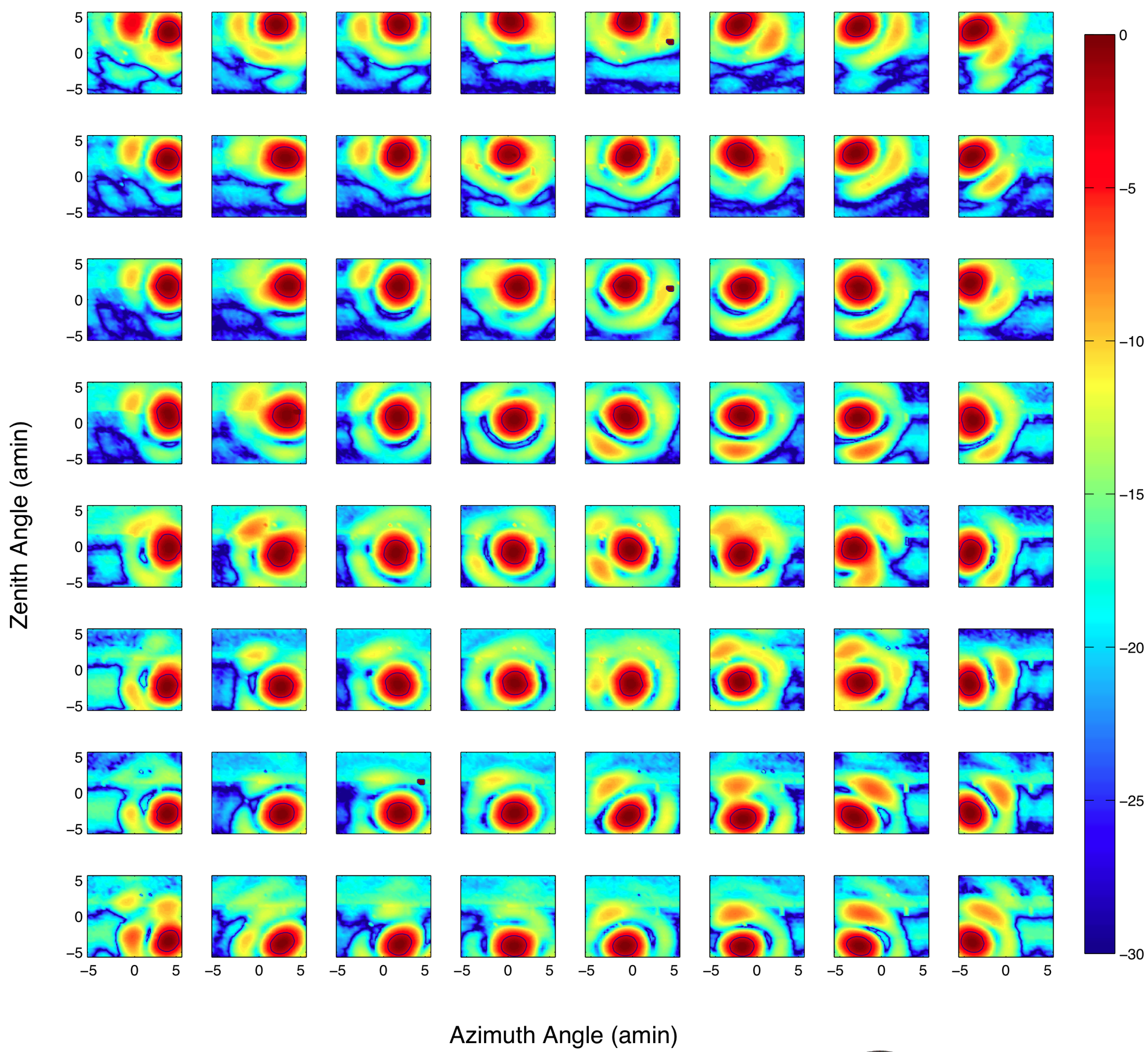
Preliminary Beamforming Results



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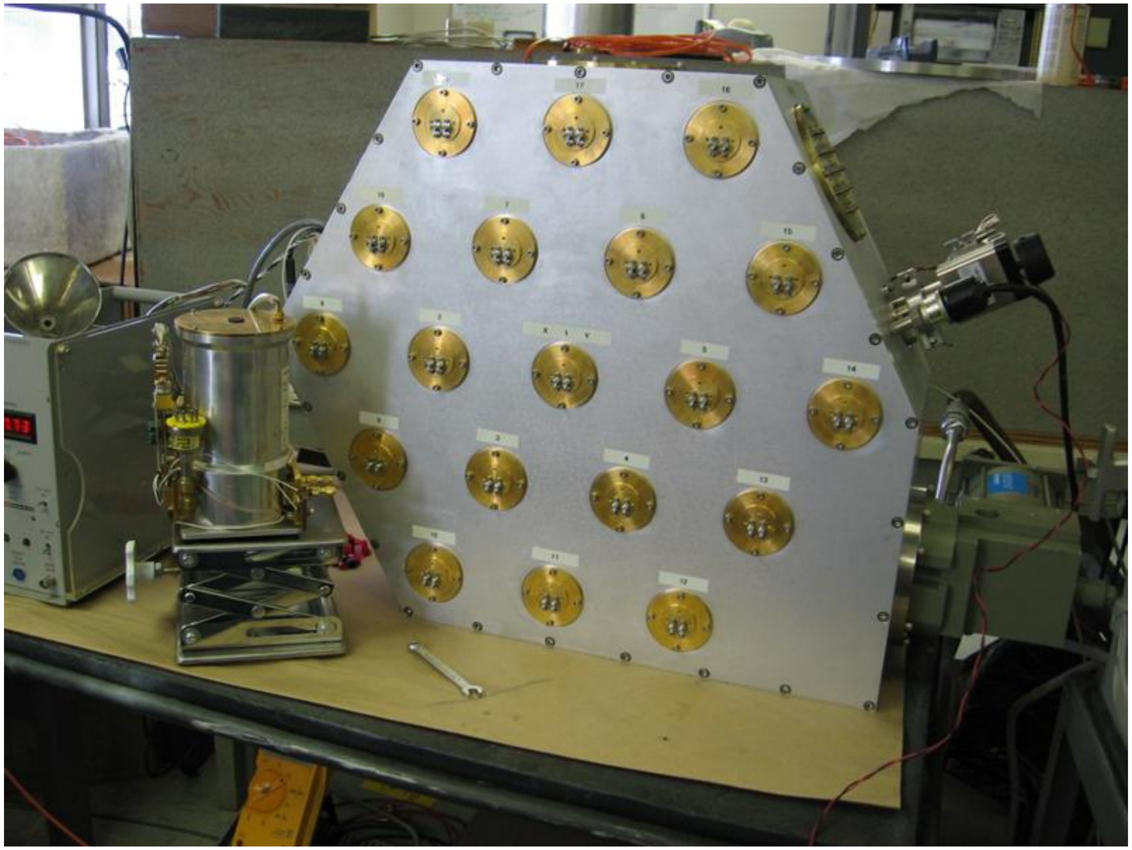
In Progress Analysis

- We are currently analyzing many Terabytes of raw voltage date to determine:
  - Beam sensitivity (A_e/T_{sys}) and sensitivity flatness
  - Active match improvement in T_{sys}
  - Effective FOV
  - Calibration longevity and dependence on elevation
  - Optimal z-axis PAF placement for widest FOV
  - Beam shape and stability
  - Other performance criteria
- Results to be presented soon with German Cortes-Medellin

NRAO Cryogenically Cooled PAF Development

Collaboration with Roger Norrod and Rick Fisher
NRAO

PAF development cryostat

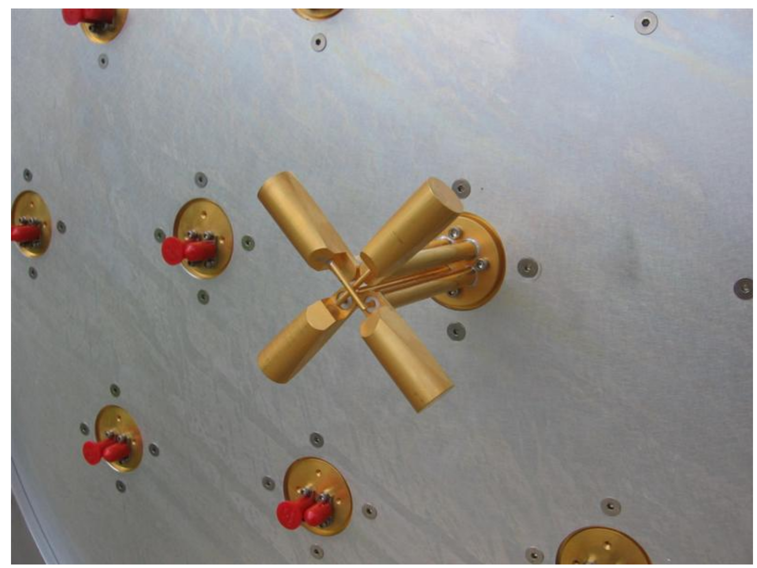


- Sander Weinreb SiGe low-noise amplifiers for 19 dual-polarized antenna elements (not installed in photo)
- Room temp antenna elements
- Closed cycle refrigerator is used to cool the LNAs to 15K.

Array Y-factor Noise Tests

Cryostat in NRAO Front-end Box

Array with ground plane and conical ground shield in sky noise test facility.



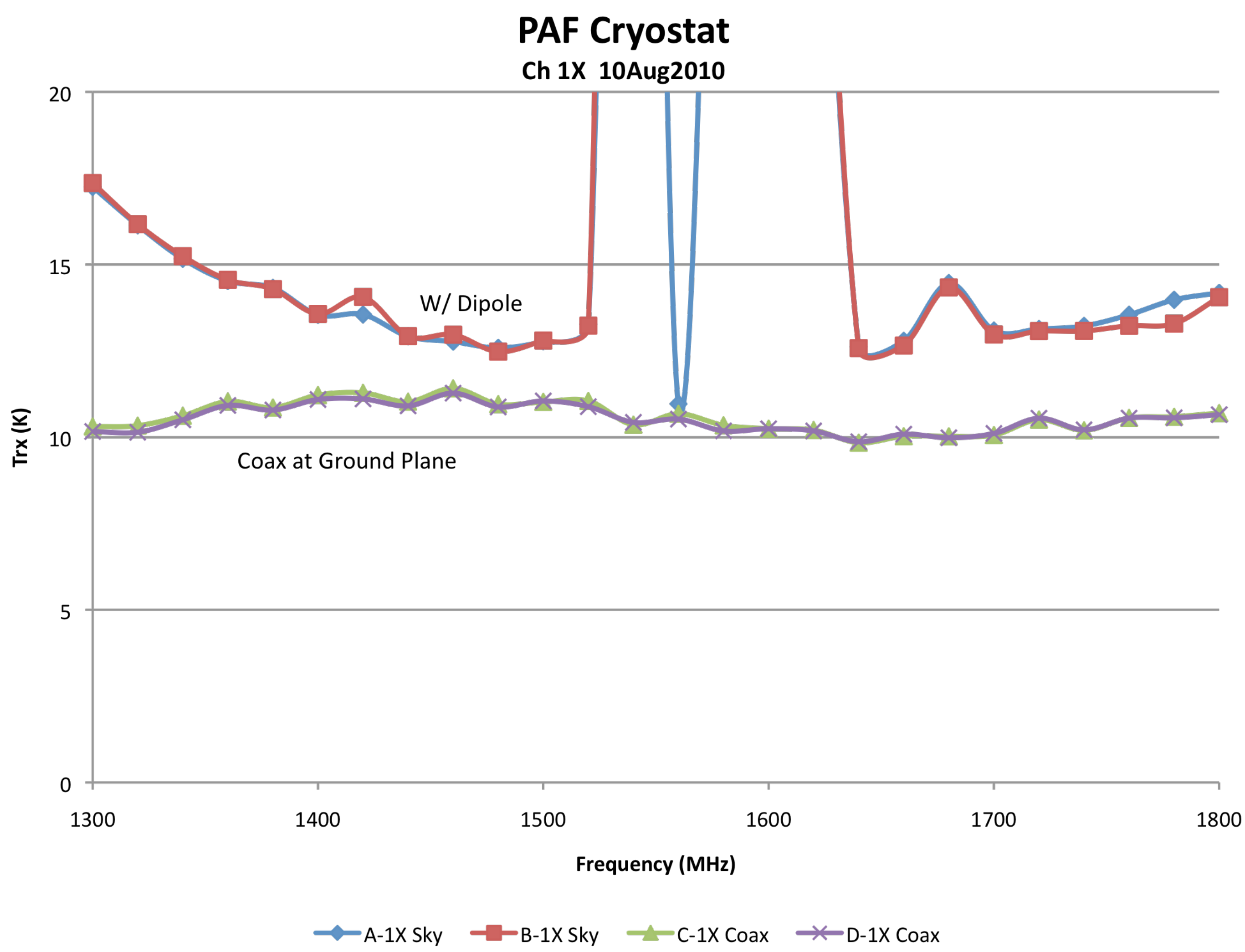
One crossed dipole on array. Other eighteen have SMA connectors.

(Continued)

Array exposed to sky for cold load.

Roof closed with ambient absorber for hot load.

Hot-Cold Sky and Coaxial Tests



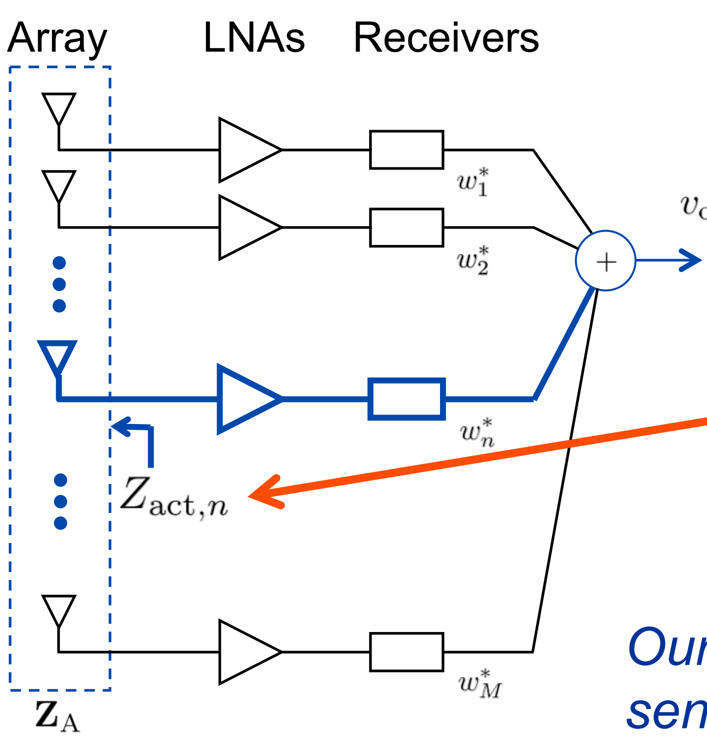
Future Plans for PAF Cryostat

- Full cooled array on Green Bank 20 meter Telescope, Fall-Winter 2010
- Dual pol active matched array element designs to be completed by BYU October 2010
- Possible GBT experiment 2011 with new 20 MHz bandwidth 64 channel data acquisition system.

First Characterization of an Active Impedance Matched Phased Array Feed

Active Impedance Matching

For a mutually coupled array antenna, front end low noise amplifiers (LNAs) see beam-dependent active impedances looking into the array ports [Woestenburg, 2005]:



$$v_{\mathrm{out}} = \sum_{m=1}^{M} w_{\mathrm{oc},m}^* v_{\mathrm{oc},m}$$

$$Z_{\mathrm{act},n} = \frac{1}{w_{\mathrm{oc},n}^*} \sum_{m=1}^{M} w_{\mathrm{oc},m}^* Z_{mn}$$

Our strategy: Design the array to maximize sensitivity (G/T)

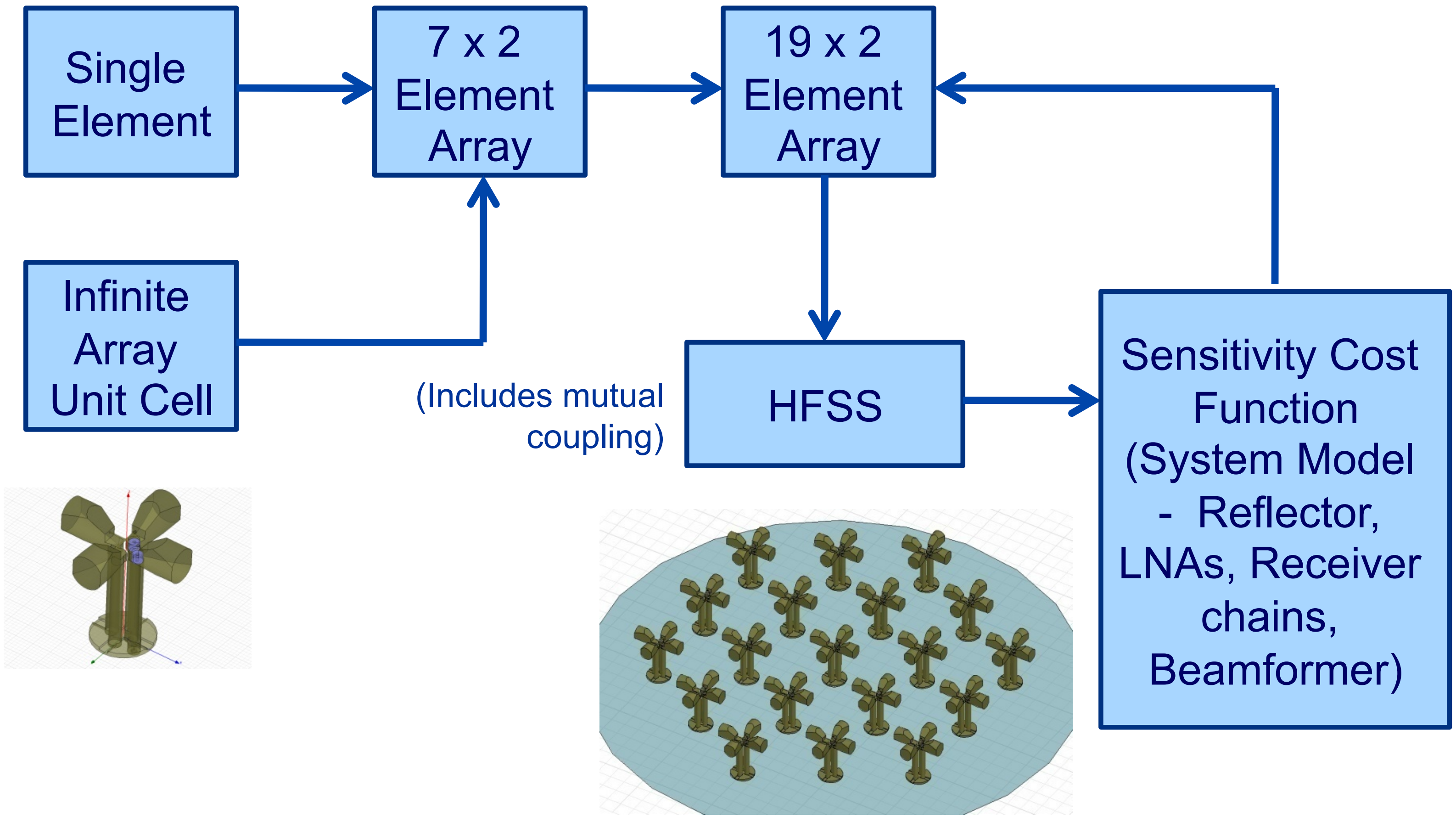
- Present active impedances as close as possible to 50Ω to the LNAs over the array field of view (low noise)
- Maximize aperture efficiency (high gain)

System Noise Budgets

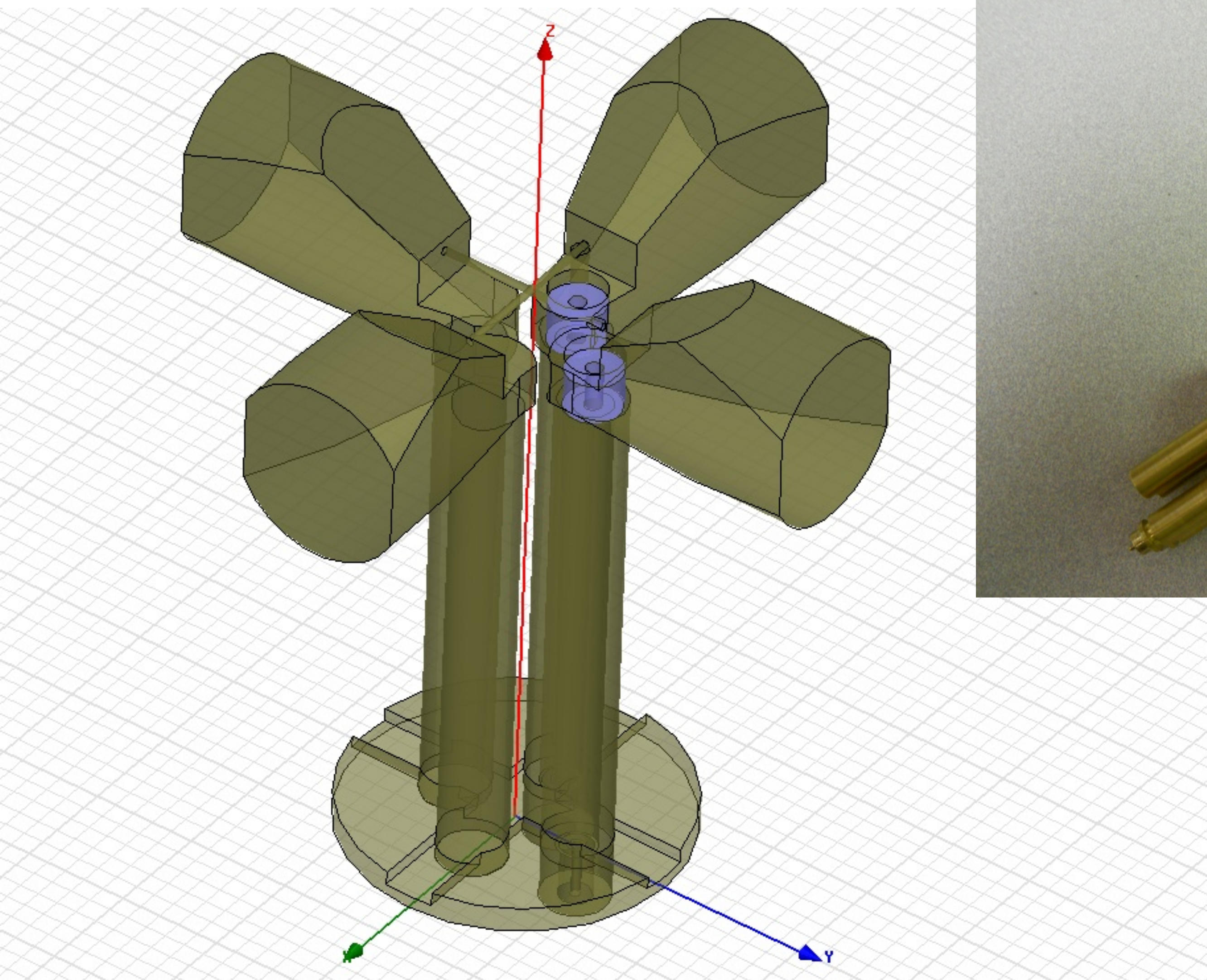
Component	2008 (Measured)	2010 (Target)	Cryogenic PAF (Target)
Sky	4	4	4
Spillover	5	5	5
Antenna Loss	4	1	5
LNA Tmin	33	33	5
Mutual Coupling	20	3	1
Total	**66 K**	**46 K**	**20 K**

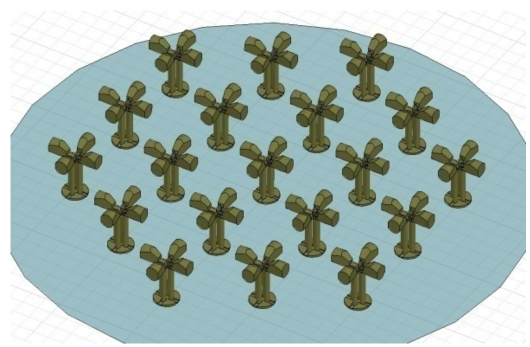
Design Optimization Process

Computationally challenging!



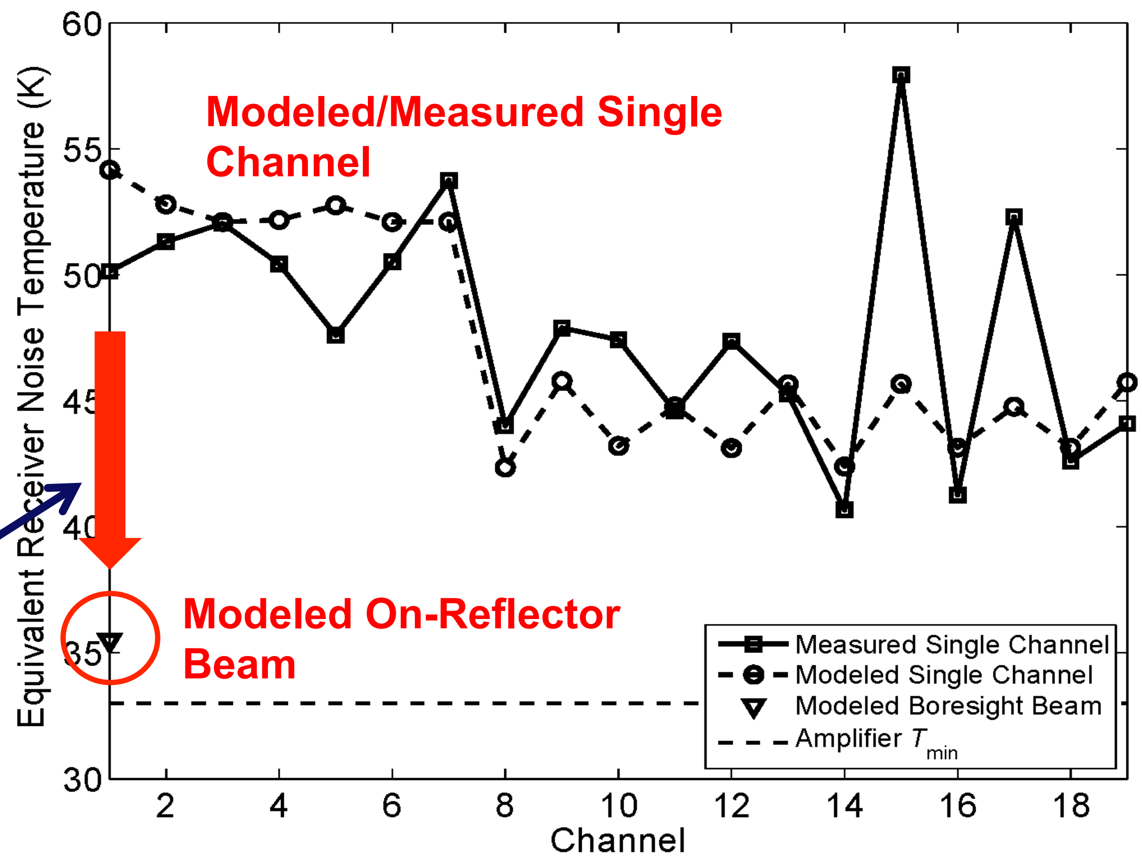
Dual Pol Element Design





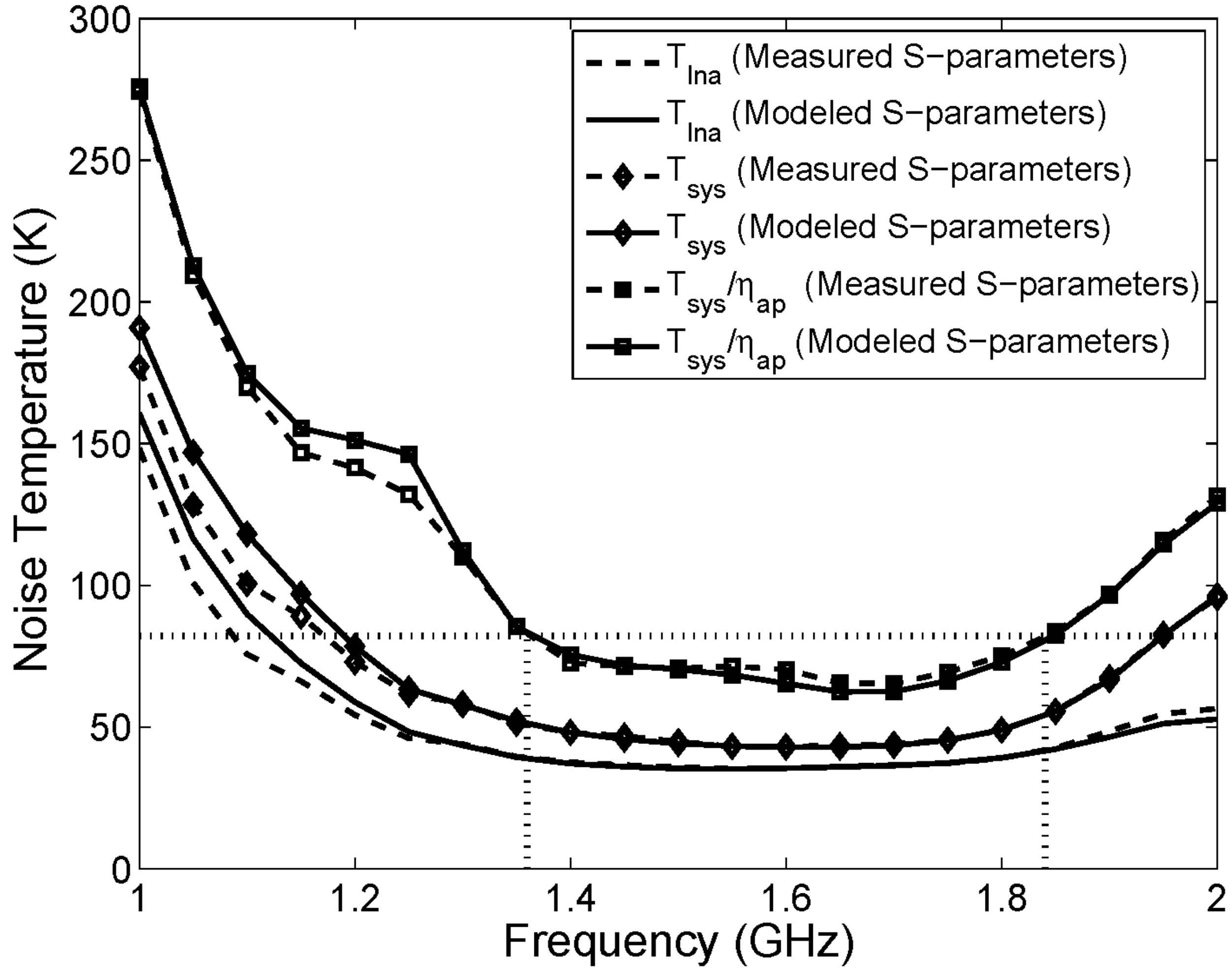
Measured Noise Performance

Expected improvement due to active impedance matched array design



Hot load (absorber) and cold load (sky) can be used to characterize single-channel array noise performance, but measuring the beam equivalent noise temperature requires that array be mounted on-reflector (calibrated beamformer coefficients are needed)

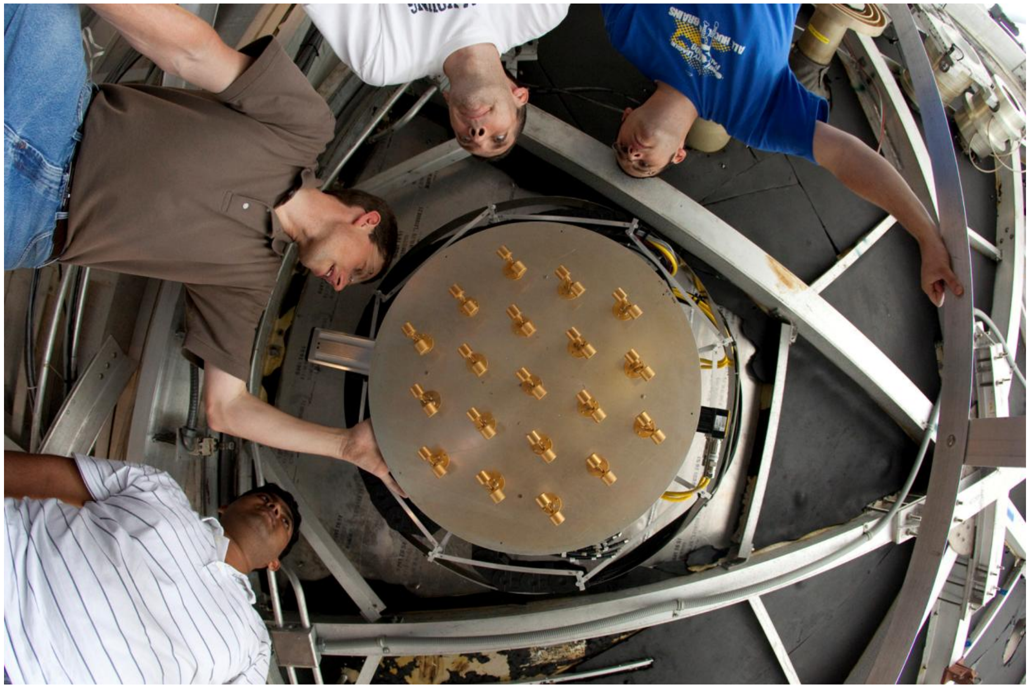
Noise Temperature and Sensitivity Figures of Merit



~500 MHz 1 dB Sensitivity Bandwidth

Observations for Active Matching

- Active impedance matching is being experimentally demonstrated
- Significant hurdle for high sensitivity phased arrays overcome
- Best phased array noise performance ever reported (<50 K at L band)



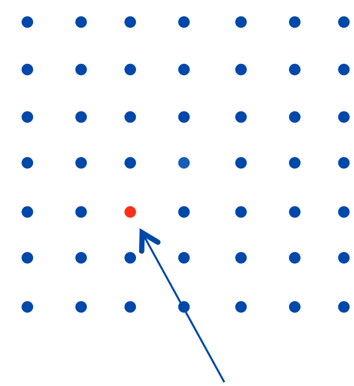
Improvements in PAF Beamformer Design Methodologies

Hybrid beamformer combines direct pattern control with sensitivity maximization

Improved Array Calibration Procedure

Array output voltage correlation matrix: $\mathbf{R}_{\text{on}} = E\{\mathbf{x}[n]\mathbf{x}^H[n]\} = \mathbf{R}_{\text{sig}} + \underbrace{\mathbf{R}_{\text{sp}} + \mathbf{R}_{\text{rec}} + \mathbf{R}_{\text{sky}} + \mathbf{R}_{\text{loss}}}_{\mathbf{R}_{\text{off}}}$

- 31×31 raster grid of reflector steering directions:
  - Each direction places calibrator source (e.g. Cas) on a different grid point.
  - 10 sec integration time per pointing.
  - Acquire array covariance matrices $\mathbf{R}_{\text{on},j}$.



Calibrator Source position for *j*th pointing

- One off-pointing per cross elevation row (2-5 degrees away) to estimate $\mathbf{R}_{\text{off}}$, noise covariance .
- Array response calibration vector $\mathbf{v}_j$ is estimated as:

$$\mathbf{v}_j = \mathbf{R}_{\text{off}}\mathbf{u}_j$$

where $\mathbf{u}_j$ is solution to pre-whitened (generalized) eigenvector problem

$$\mathbf{R}_{\text{on},j}\mathbf{u}_j = \lambda_{\max}\mathbf{R}_{\text{off}}\mathbf{u}_j$$

- Lower bias and error variance than old method: $(\mathbf{R}_{\text{on},j} - \mathbf{R}_{\text{off}})\mathbf{v}_j = \lambda_{\max}\mathbf{v}_j$

Maximum Sensitivity Beamformer

- Statistical optimization of SNR at output

$$\mathbf{w}_{\mathrm{SNR}} = \arg\max_{\mathbf{w}} \frac{\mathbf{w}^H \mathbf{R}_{\mathrm{sig}} \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{\mathrm{off}} \mathbf{w}}, \quad \mathbf{R}_{\mathrm{sig}} \approx \mathbf{R}_{\mathrm{on}} - \mathbf{R}_{\mathrm{off}}$$

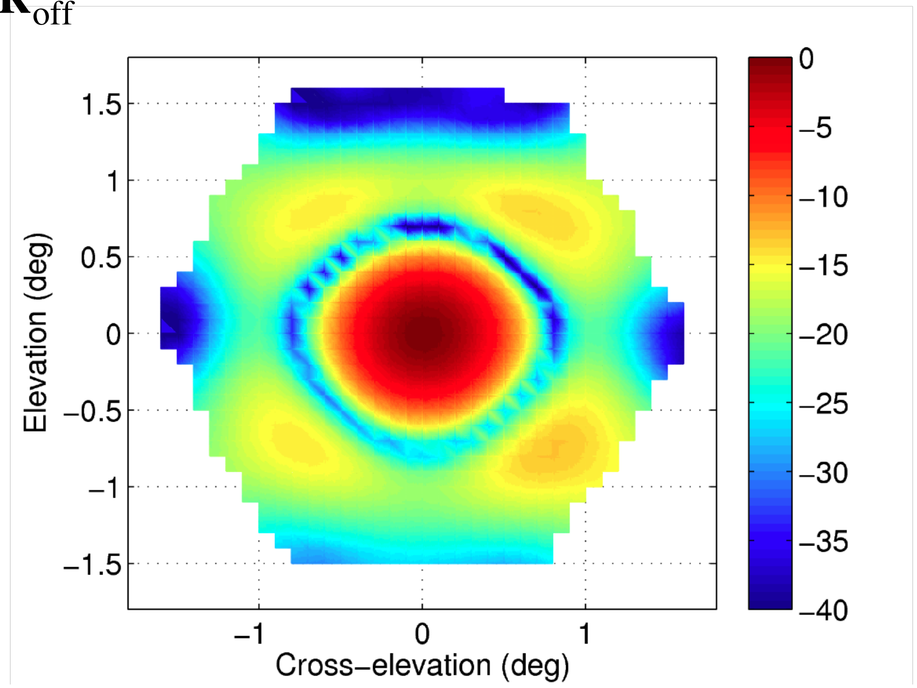
- Solution for Arbitrary SOI structure

$$\mathbf{R}_{\mathrm{sig},j} \mathbf{w}_{\mathrm{SNR},j} = \lambda_{\max} \mathbf{R}_{\mathrm{off}} \mathbf{w}_{\mathrm{SNR},j}$$

- Solution for point source SOI

$$\mathbf{w}_{\mathrm{SNR},j} = \mathbf{R}_{\mathrm{off}}^{-1} \mathbf{v}_j$$

- Problem: No direct control of beamshape
  - Possible coma, mainlobe distortion
  - Possible high sidelobe peaks.
  - Happens due to spatially correlated noise, $\mathbf{R}_{\mathrm{off}}$ non diagonal



Equiripple Sidelobe Beamformer

- Deterministic design method
- Minimizes maximum level for near sidelobes

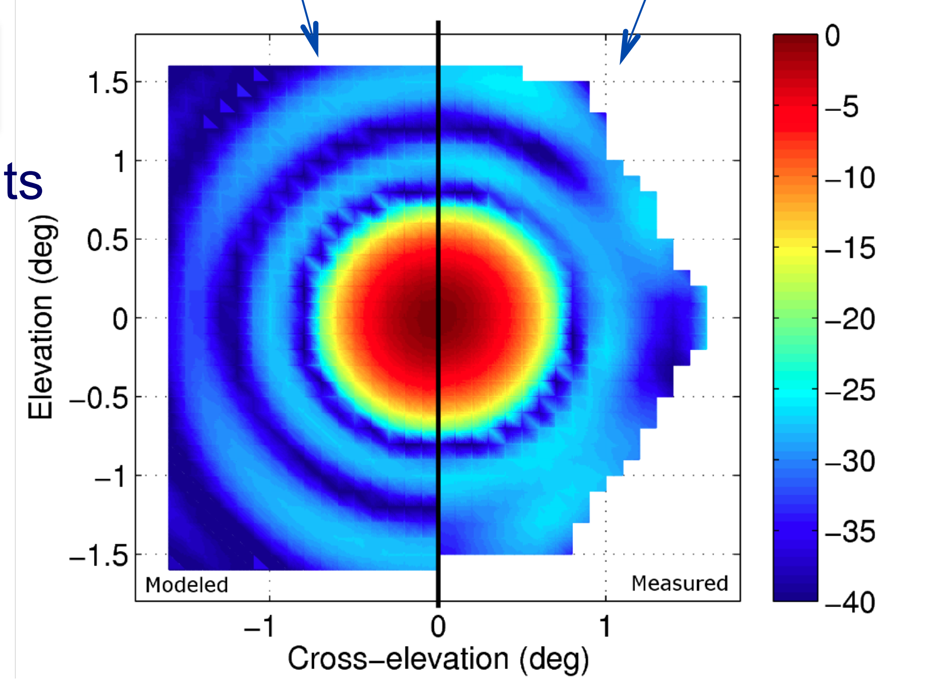
$$\mathbf{w}_{\mathrm{er}} = \arg\min_{\mathbf{w}} \left|\mathbf{V}_{\mathrm{side}}^{H}\mathbf{w}\right|_{\infty} \quad \text{subject to} \quad \left|\mathbf{V}^{H}(\Omega_k)\mathbf{w}\right|_{2} = c_k, \ \forall k$$

columns are calibration vectors over dense grid over sidelobe region

steering angle to mainlobe equality constraint point ck

Using simulated calibration vectors

Using measured calibration vectors



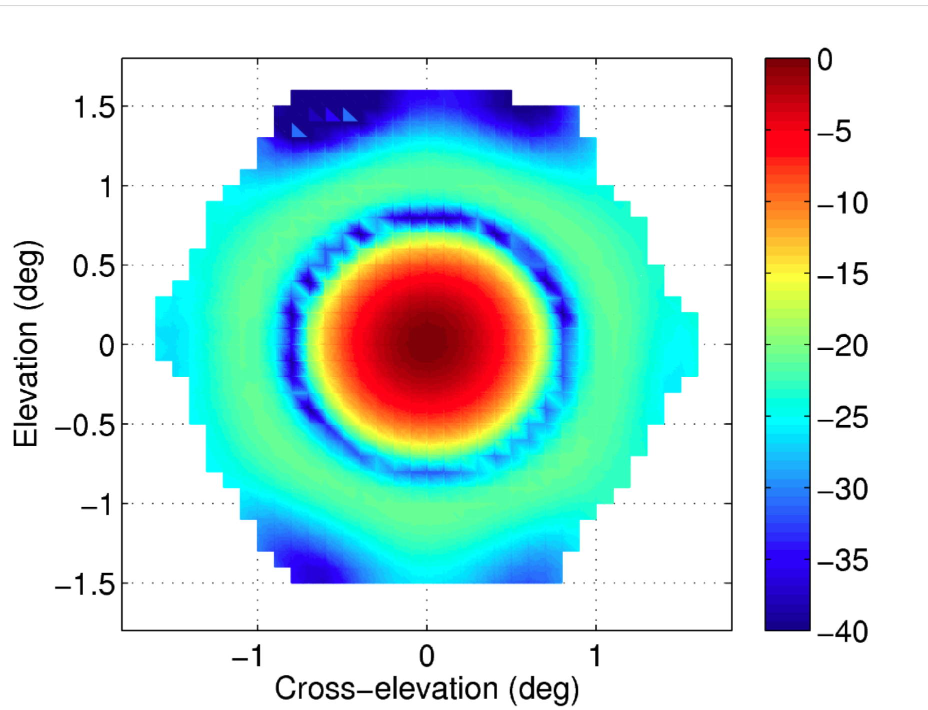
- Direct mainlobe shape constraints
- Sacrifices sensitivity (SNR) for beampattern control
- Solved with general purpose numeric optimizer code in MATLAB

Hybrid Beamformer

- Best of both deterministic and statistically optimal worlds.
- Minimizes hybrid function of max sideobel level and inverse SNR

$$\mathbf{w}_{\text{hy}} = \arg\min_{\mathbf{w}} \gamma \frac{\mathbf{w}^H \mathbf{R}_{\text{off}} \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{\text{sig}} \mathbf{w}} + (1-\gamma) \left| \mathbf{V}_{\text{side}}^H \mathbf{w} \right|_\infty \quad \text{subject to} \left| \left| \mathbf{V}^H(\Omega_k) \mathbf{w} \right|_2 - c_k \right|_2 \leq \gamma b_k \;, \; \forall k$$

- $0 \leq \gamma \leq 1, \quad \gamma = 0 \rightarrow \mathbf{w}_{\text{hy}} = \mathbf{w}_{\text{er}}, \quad \gamma = 1 \rightarrow \mathbf{w}_{\text{hy}} = \mathbf{w}_{\text{SNR}}$



Which Beamformer Design Method?

- Choose your beamformer design tool to meet your needs!

COMPARISON OF BEAMFORMER TECHNIQUES.

Beamformer	Beamwidth	Peak side lobes	Sensitivity
max-SNR	1.6°	-13.03 dB	$2.973\ \mathrm{m}^2/\mathrm{K}$
equiripple	1.6°	-26.40 dB	$1.839\ \mathrm{m}^2/\mathrm{K}$
hybrid ($\gamma = 0.5$)	1.6°	-17.70 dB	$2.860\ \mathrm{m}^2/\mathrm{K}$
hybrid ($\gamma = 0.25$)	1.6°	-21.02 dB	$2.545\ \mathrm{m}^2/\mathrm{K}$

Deep Nulling Adaptive Interference Canceler for Phased Array Feeds

Polynomial model-based method provides better performance for low INR cases

Conventional Subspace Projection (SSP)

- This zero-forcing method can place deeper nulls than max SNR, LCMV, MVDR, Weiner filter, and other array cancellers
- At *k*th STI, form an orthogonal projection matrix for the interferer(s):
  - Sample STI covariance estimate:

$$\hat{\mathbf{R}}_k = \frac{1}{N}\sum_{n=0}^{N-1} \mathbf{x}[n+kN]\mathbf{x}^H[n+kN] \quad \text{for } k\text{th STI of length } N$$

  - Partition eigenspace. Largest eigenvalues(s) correspond to interference.

$$\hat{\mathbf{R}}_k[\mathbf{U}_{\text{int}} \mid \mathbf{U}_{\text{sig+noise}}] = [\mathbf{U}_{\text{int}} \mid \mathbf{U}_{\text{sig+noise}}]\Lambda$$

  - Form projection matrix:

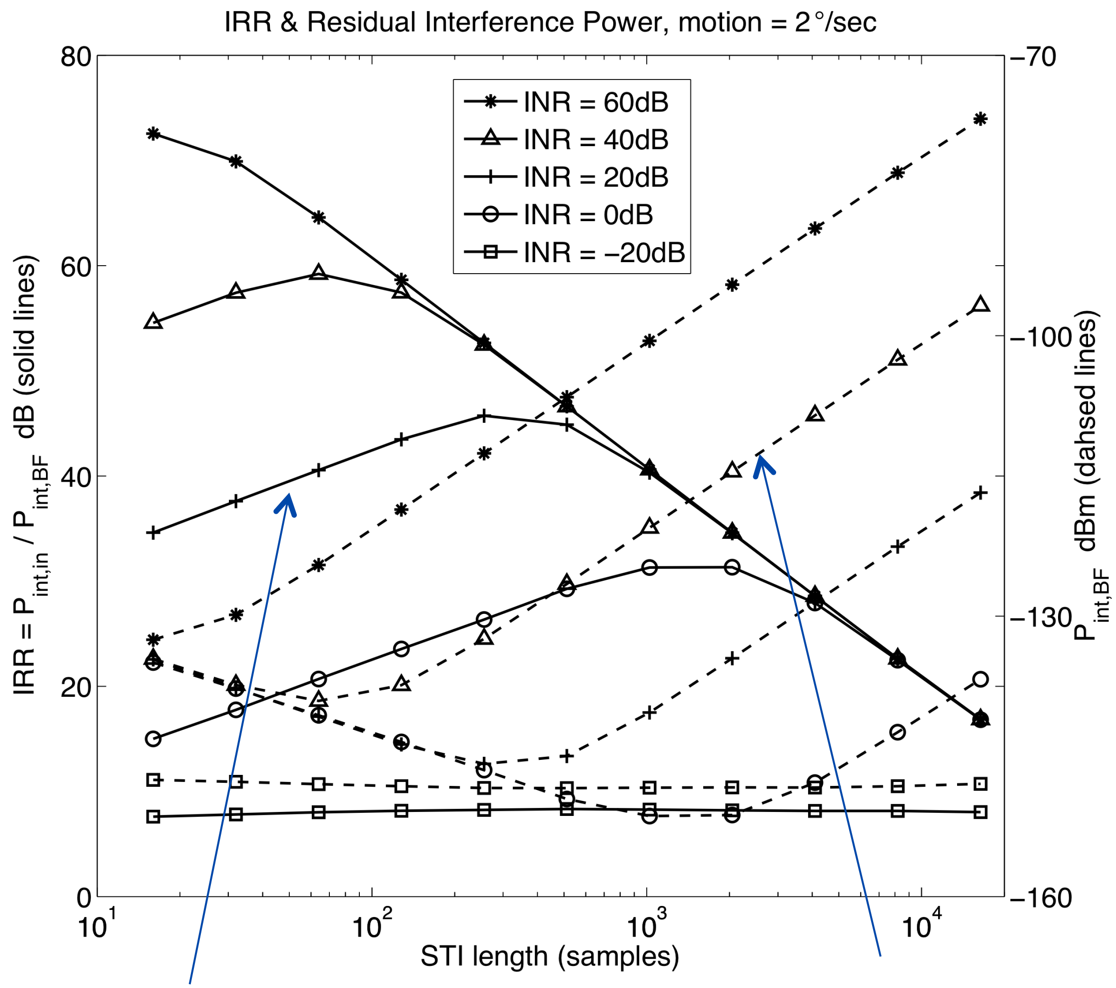
$$\mathbf{P}_k = \mathbf{I} - \mathbf{U}_{\text{int}}\mathbf{U}_{\text{int}}^H$$

- Compute weights and beamform:

$$\mathbf{w}_{\text{SSP},k} = \mathbf{P}_k \mathbf{w}_{\text{nominal}}, \quad y[n] = \mathbf{w}_{\text{SSP},k}^H \mathbf{v}[n], \quad k = \left\lfloor \frac{n}{N} \right\rfloor$$

Conventional SSP Limitations

- Detailed simulation
- 19-element PAF on 20m reflector, 0.43f/D
- Correlated spillover noise, mutual coupling, modeled 33K Ciao Wireless LNAs.
- Measured array element radiation patterns.
- Physical Optics, full 2D integration over reflector.



Subspace estimation error due to sample noise from short STI

Subspace smearing error due to motion, i.e. null depth with no sample estimation error.

Low-order Parametric Model SSP

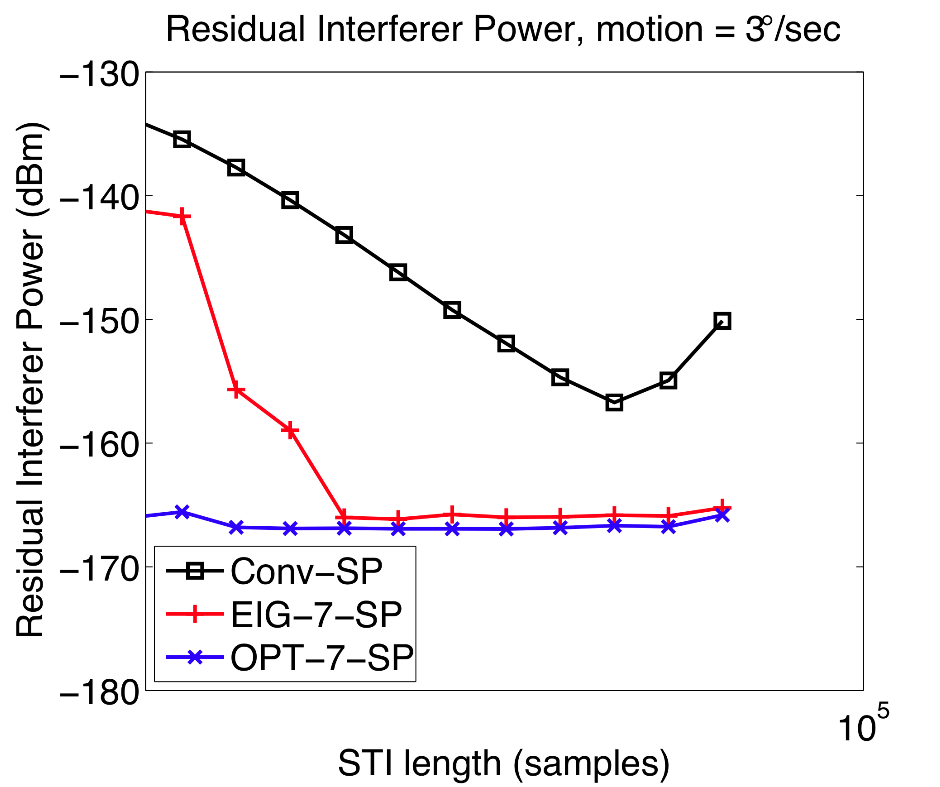
- Fit a series of STI covariances $\mathbf{R}_{\text{int}}[n]$ to a polynomial that can be evaluated at arbitrary timescale
  - Beamformer weights can be updated at every time sample, not just once per STI.
  - Use entire data window to fit polynomial yields less sample estimation error.

- Minimize the squared error between STI sample covariances and the polynomial model $\mathbf{C}_{\text{LS}}$:

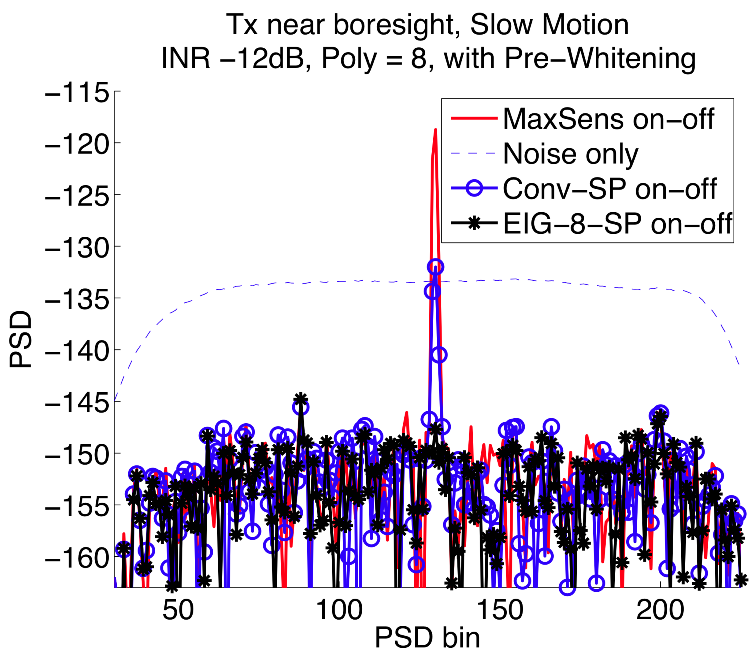
$$\mathbf{C}_{\text{LS}} = \arg\min_{\mathbf{C}} \sum_{k=1}^{K} \left\| \hat{\mathbf{R}}_k - \tilde{\mathbf{R}}_{\text{int}}(t_k, \mathbf{C}) \right\|_F^2 ,$$

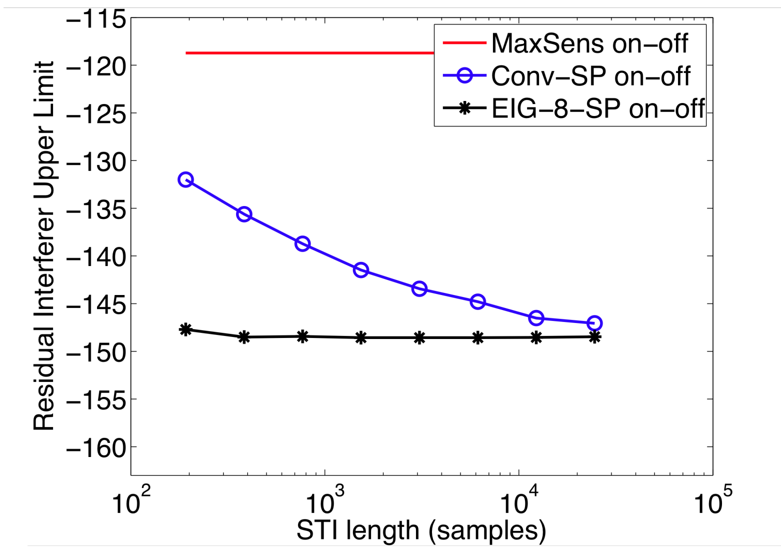
where $t_k = kNT_s$

- Use $\tilde{\mathbf{R}}_{\text{int}}(t, \mathbf{C}_{\text{LS}})$ to calculate SSP beamformer weights at any n



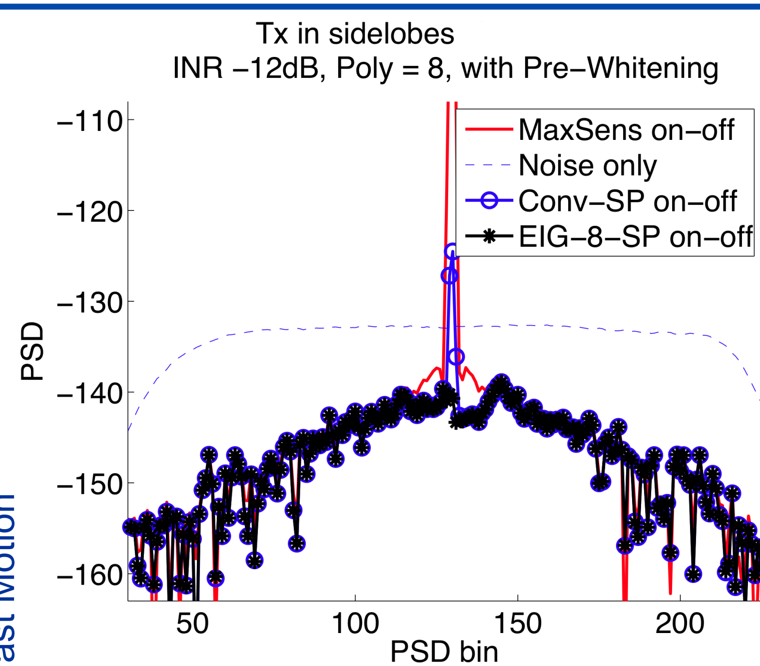
Real Data Cancelation Results

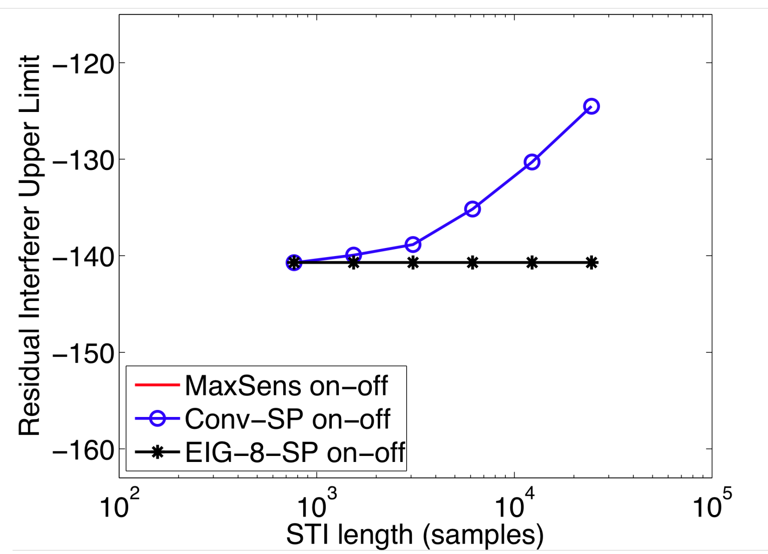




Slow Motion

Fast Motion





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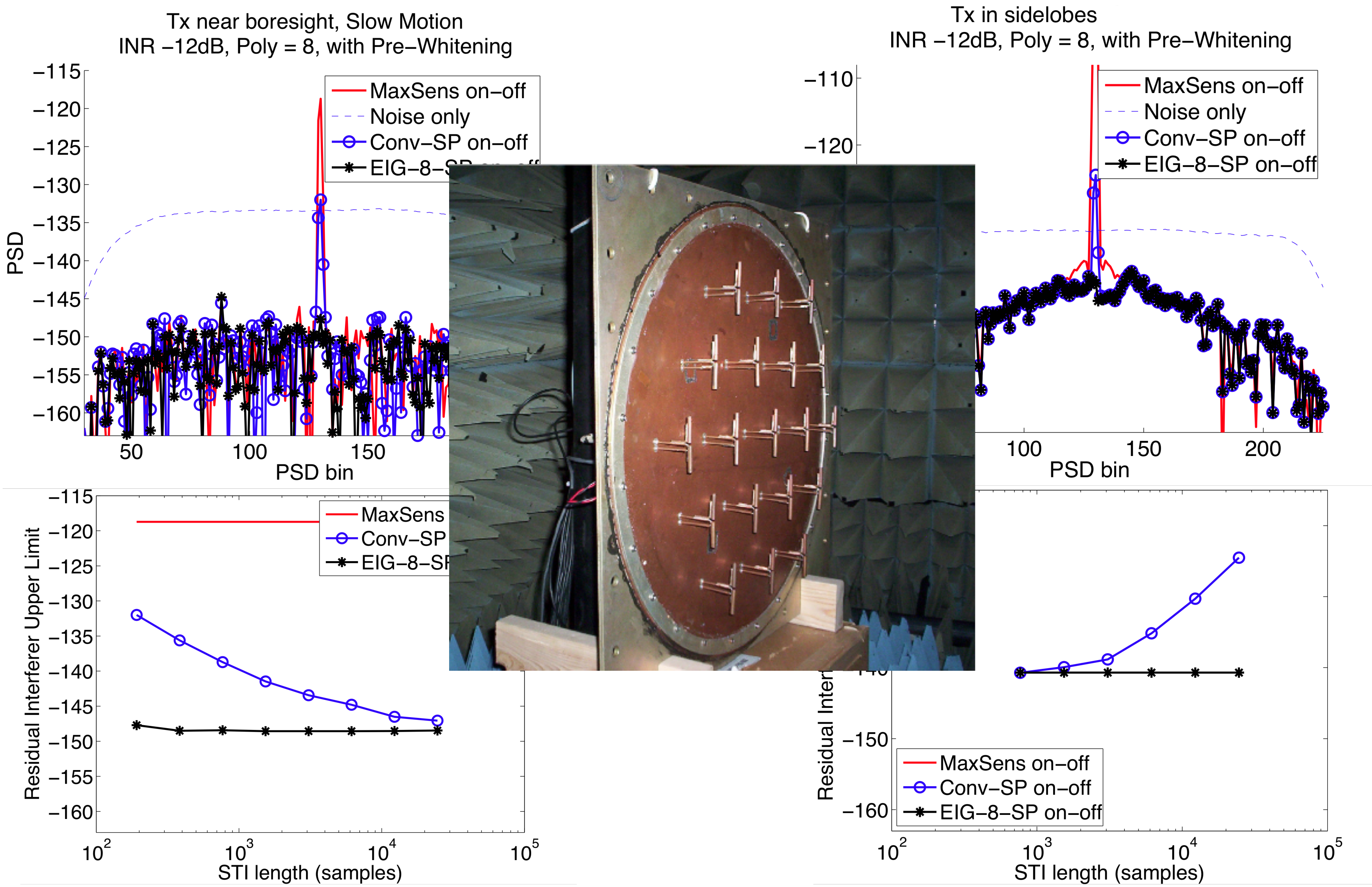
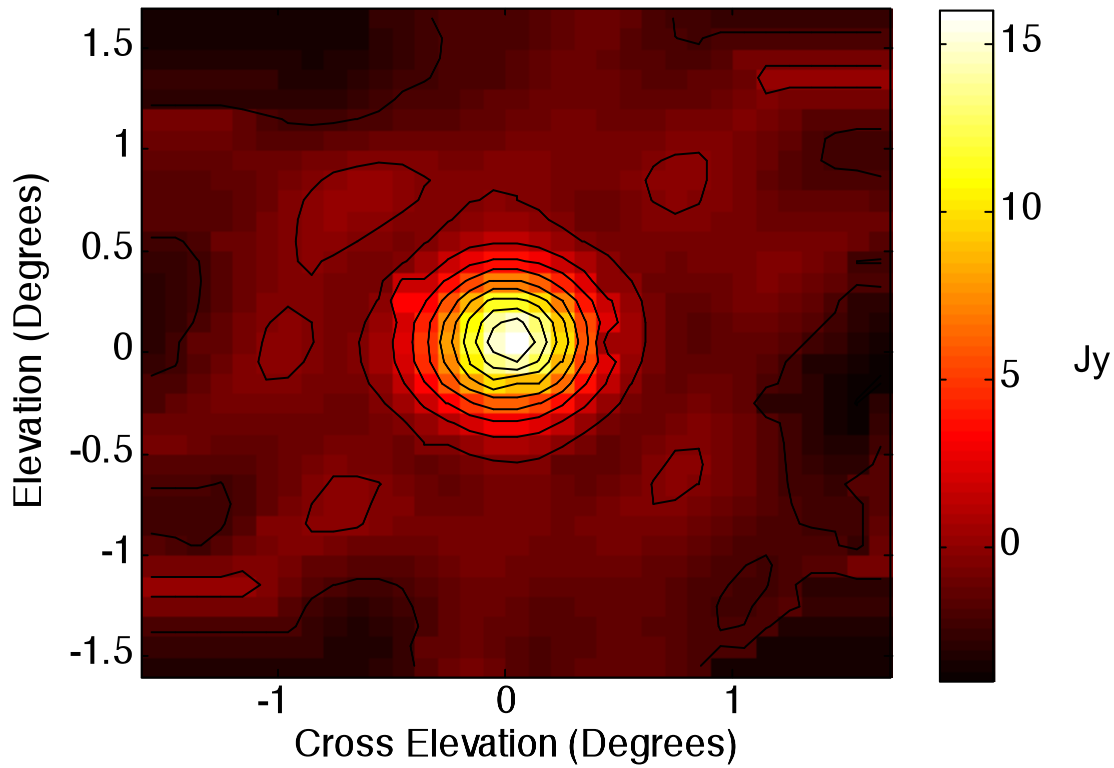


Radio camera results

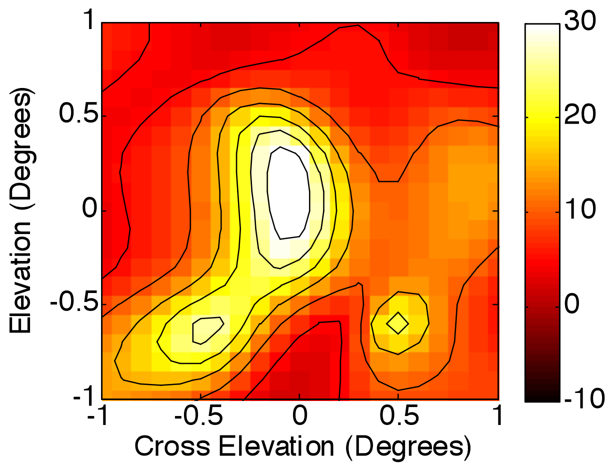
Demonstration of PAF image mosaicing on the Green Bank 20 meter Telescope, July 2008

Single Pointing Image - 3C295

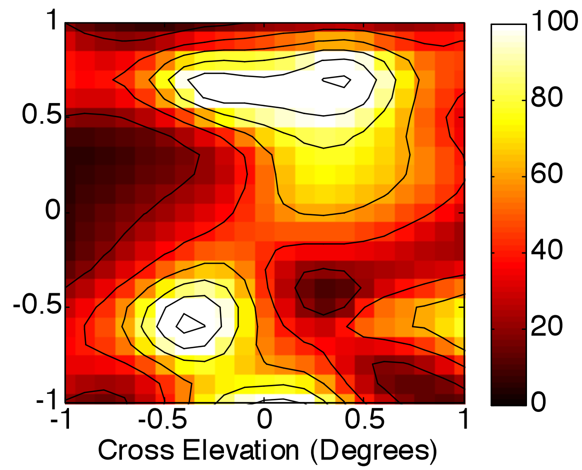
Source: 3C295
Flux density: 21 Jy at 1400 MHz
Observation freq. 1612 MHz
Integration time: 60 sec



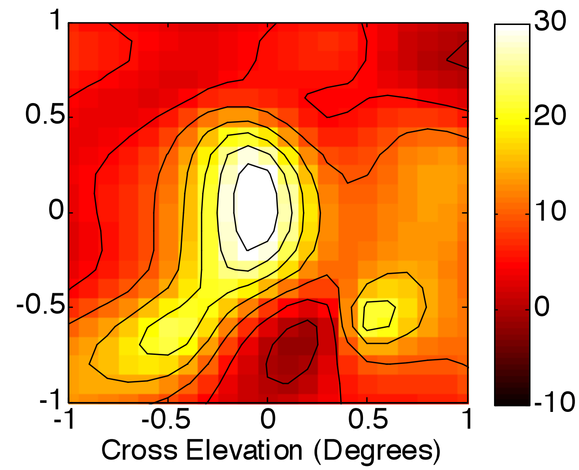
Adaptive RFI Mitigation



W3OH, no RFI

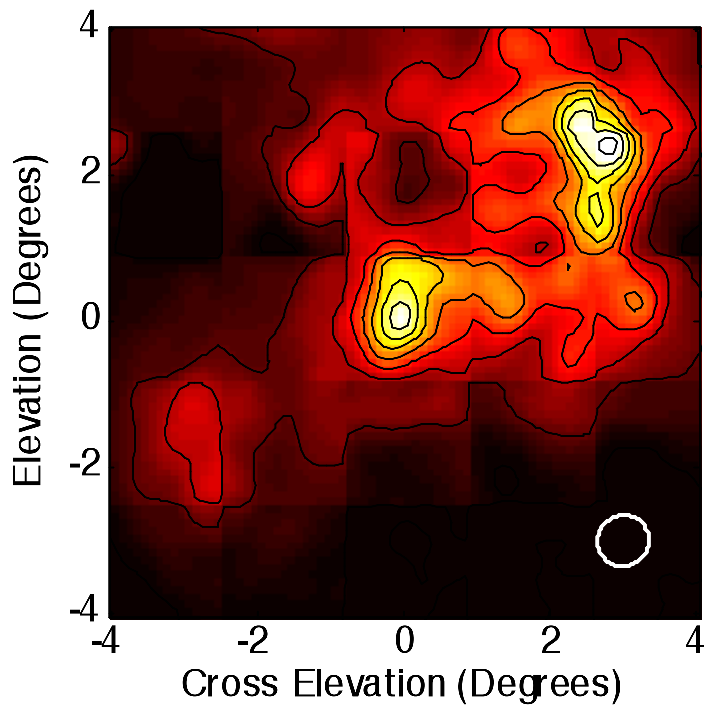


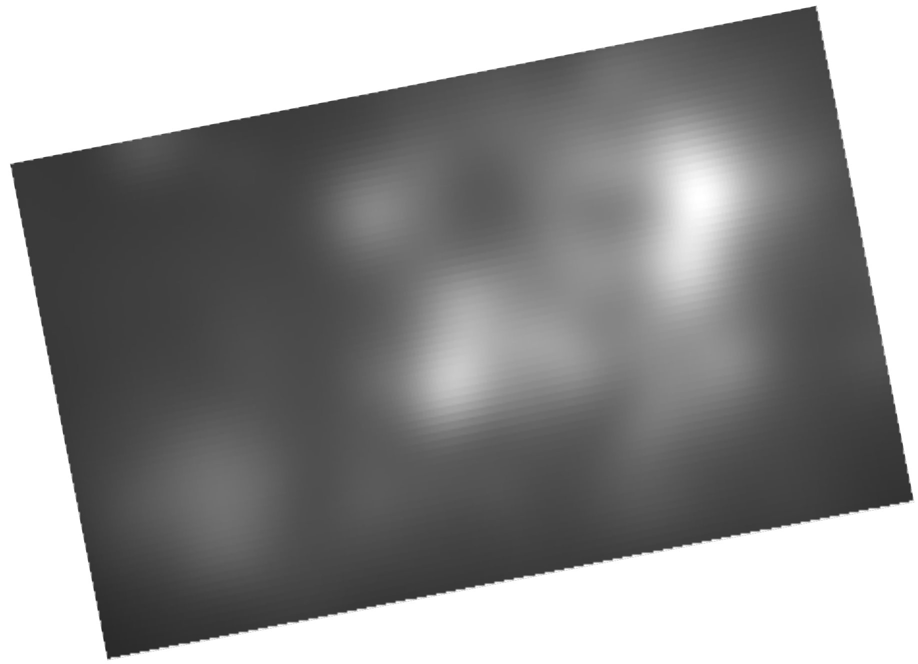
RFI corrupted image
(moving function generator
and antenna on the ground)



Adaptive spatial filtering
Subspace projection algorithm

Cygnus X Region at 1600 MHz





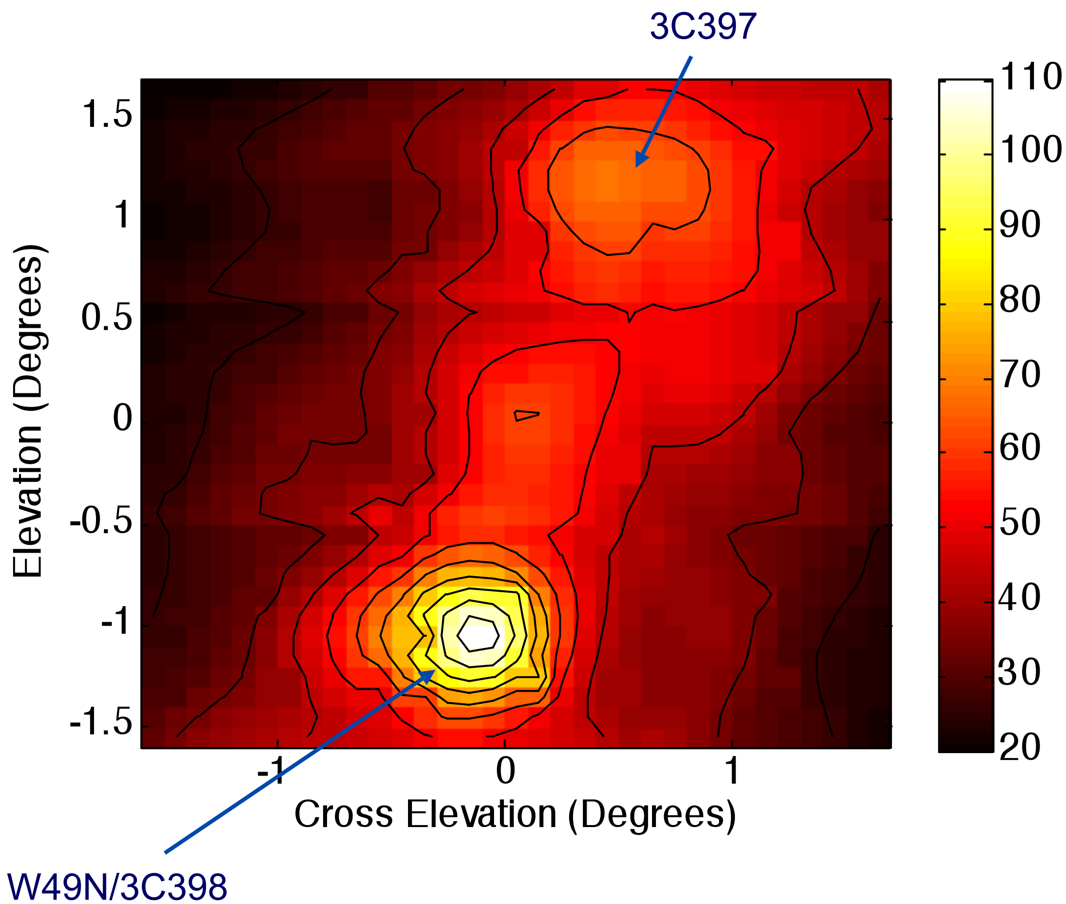
5 x 5 mosaic of PAF pointings
Circle indicates half power beamwidth
Required antenna pointings:

Single-pixel feed: ~600
PAF: 25
Imaging speedup: 24x

Canadian Galactic Plane Survey
Convolved to 20-Meter beamwidth

Image Mosaic - W49 Region

1612 MHz
3 x 3 = 9 pointings



Conclusions and Future Work

- First demonstration of high sensitivity observation with a PAF on a large instrument.
- Practical calibration and beamforming methods.
- Demonstration of active match low-noise PAF
- Significant progress towards a truly usable adaptive PAF canceller.
- Future work:
  - Dual pol, 37 element array.
  - Real time data acquisition and beamfomer, 20 MHz instantaneous BW.
  - Cryo-cooled front end demonstration.
  - Science-ready PAFs for Green Bank Telescope, Arecibo, SKA.
  - Apply polynomial assisted SSP to real observation data sets