BYU/NRAO 2007 Green Bank 20 Meter Focal Plane Array – Modeling and Experimental Results

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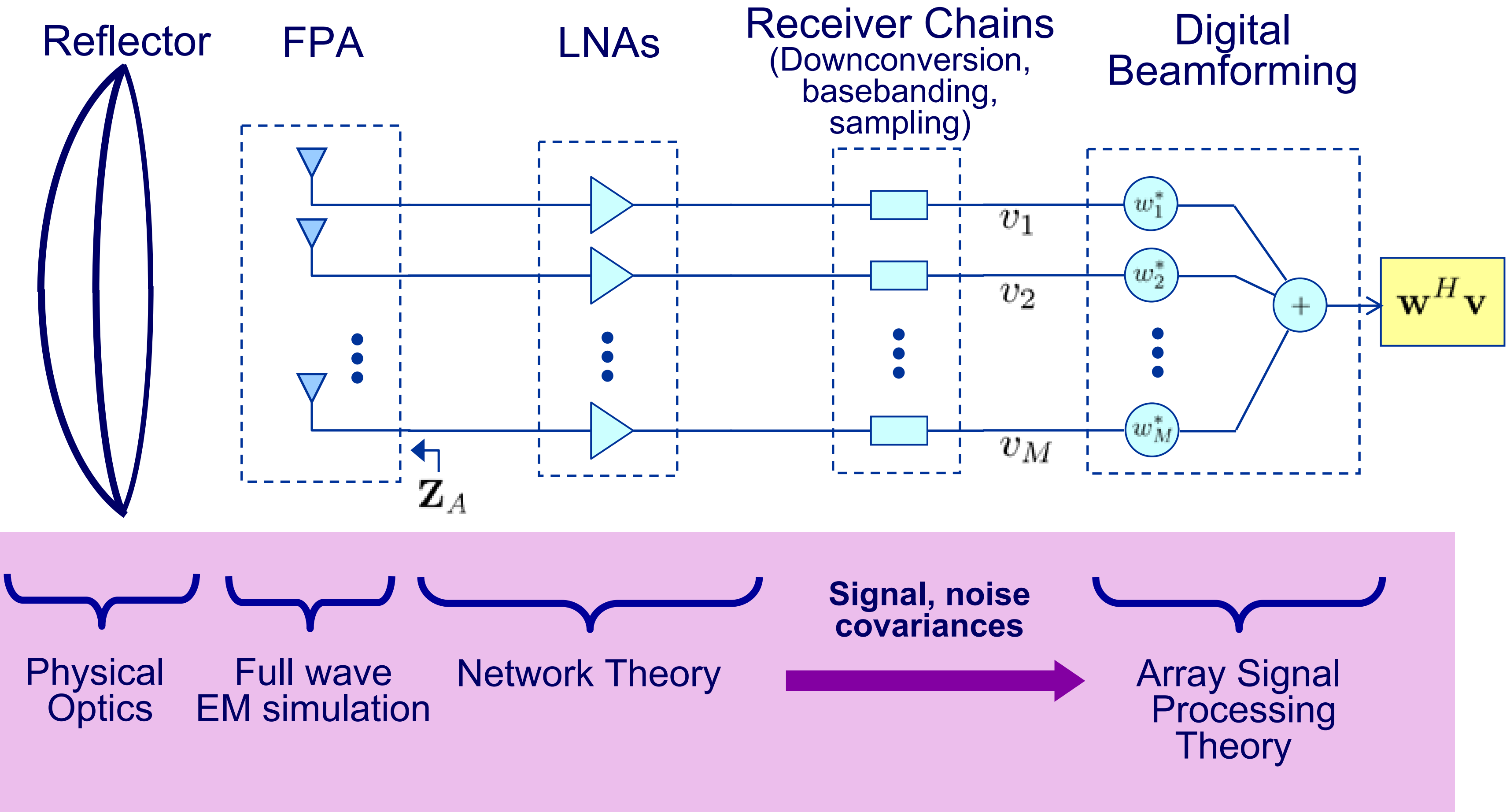
Overview

- Beamforming algorithms and calibration
- FPA simulation results
- Results from 2007 BYU/NRAO Green Bank 20 Meter Telescope 19 Element FPA Experiment

FPA System Model



Reflector

FPA

LNAs

Receiver Chains
(Downconversion,
basebanding,
sampling)

Digital
Beamforming

Physical
Optics

Full wave
EM simulation

Network Theory

Signal, noise covariances

Array Signal
Processing
Theory

Beamforming Strategies

- Fixed beamformers
  - Analog networks, subarrays, eigenbeams
- Slow adaptation (minutes)
  - Optimize sensitivity/SNR for a given reflector pointing direction
  - Calibration using bright source on/off observation
- Fast adaptation (milliseconds)
  - RFI mitigation
  - Pattern rumble must be overcome

Signal and Noise Covariance Matrices

$$\mathbf{R}_{\mathbf{v}} = \mathbf{R}_{\mathrm{sig}} + \mathbf{R}_{\mathrm{n}}$$

$\mathbf{R}_{\mathrm{sig}}$ Signal of interest

$$\left.\begin{array}{ll} \mathbf{R}_{\mathrm{sp}} & \text{Spillover noise} \\ \mathbf{R}_{\mathrm{loss}} & \text{Noise due to loss in antenna elements and feed structure} \\ \mathbf{R}_{\mathrm{rec}} & \text{Receiver noise} \\ \mathbf{R}_{\mathrm{int}} & \text{Interference} \end{array}\right\} \mathbf{R}_{\mathrm{n}}$$

$\mathbf{R}_{\mathrm{iso}}$ Covariance due to isotropic noise field

Adaptive Beamformer Calibration

Array response covariance for bright calibrator source: $\mathbf{R}_{\text{on}} = \mathbf{R}_{\text{sig}} + \mathbf{R}_{\text{n}}$

- One pointing required for each beam

Noise only: $\mathbf{R}_{\text{off}} = \mathbf{R}_{\text{n}}$

Difference approximates signal covariance - rank one matrix for point source:

$$\mathbf{R}_{\text{sig}} = \mathbf{R}_{\text{on}} - \mathbf{R}_{\text{off}} \quad (+\ \text{estimation error})$$

Dominant eigenvector: $\mathbf{d}_{\text{sig}} \rightarrow$ Signal steering vector

Classical Beamformers

$\mathbf{w} = \mathbf{d}_{\text{sig}}$ Conjugate field match (CFM)

$\mathbf{w} = \mathbf{R}_{\text{iso}}^{-1}\mathbf{d}_{\text{sig}}$ Maximum gain

$\mathbf{w} = \mathbf{R}_{\text{n}}^{-1}\mathbf{d}_{\text{sig}}$ Maximum SNR

Adaptive

$\mathbf{w} = \mathbf{R}_{\mathbf{v}}^{-1}\mathbf{d}_{\text{sig}}$ Minimum variance distortionless response (MVDR)

$\mathbf{w} = \mathbf{P}\mathbf{w}_0$ Subspace projection – adaptively update quiescent beamformer to reject RFI by placing a pattern null on the interferer

Single interferer case:

$$\mathbf{P} = \mathbf{I} - \mathbf{x}\mathbf{x}^H, \ \mathbf{x} \text{ is the dominant eigenvector of } \mathbf{R}_{\mathbf{v}}$$

$$(\text{assumes INR} \gg 1)$$

Beam Sensitivity

$$\mathrm{SNR} = \frac{P_{\mathrm{sig}}}{P_{\mathrm{n}}} = \frac{\mathbf{w}^H \mathbf{R}_{\mathrm{sig}} \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{\mathrm{n}} \mathbf{w}}$$

Beam sensitivity:

$$\frac{A_e}{T_{\mathrm{sys}}} = \frac{k_b B}{S^{\mathrm{sig}}} \mathrm{SNR}\ (\mathrm{m}^2/\mathrm{K})$$

where S^{sig} $(\mathrm{W/m}^2)$ is the signal flux density in one polarization
k_b is Boltzman's constant
B is the system noise equivalent bandwidth

Experimental measurement:

$\mathbf{R}_{\mathrm{on}}$	**Array response covariance - steered to signal source**
$\mathbf{R}_{\mathrm{off}}$	**Steered off signal source (noise only)**

$$\frac{A_e}{T_{\mathrm{sys}}} = \frac{k_b B}{S^{\mathrm{sig}}} \frac{\mathbf{w}^H \mathbf{R}_{\mathrm{on}} \mathbf{w} - \mathbf{w}^H \mathbf{R}_{\mathrm{off}} \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{\mathrm{off}} \mathbf{w}}$$

Beam Efficiencies

$$\frac{A_\mathrm{e}}{T_\mathrm{sys}} = \frac{\eta_\mathrm{rad}\eta_\mathrm{ap}A_p}{\eta_\mathrm{rad}(1-\eta_\mathrm{sp})T_\mathrm{g} + (1-\eta_\mathrm{rad})T_a + \eta_\mathrm{rad}T_\mathrm{min}/\eta_\mathrm{n}}$$

Spillover efficiency: $\eta_\mathrm{sp} = 1 - \dfrac{\mathbf{w}^H\mathbf{R}_\mathrm{sp}\mathbf{w}}{\mathbf{w}^H\mathbf{R}_\mathrm{iso}\mathbf{w}}$

Aperture efficiency: $\eta_\mathrm{ap} = \dfrac{k_bTB}{A_pS^\mathrm{sig}}\dfrac{\mathbf{w}^H\mathbf{R}_\mathrm{sig}\mathbf{w}}{\mathbf{w}^H\mathbf{R}_\mathrm{iso}\mathbf{w}}$

Radiation efficiency: $\eta_\mathrm{rad} = \dfrac{\mathbf{w}^H\mathbf{R}_\mathrm{iso}\mathbf{w}}{\mathbf{w}^H(\mathbf{R}_\mathrm{iso}+\mathbf{R}_\mathrm{loss})\mathbf{w}}$

Noise matching efficiency: $\eta_\mathrm{n} = \dfrac{T_\mathrm{min}}{T}\dfrac{\mathbf{w}^H\mathbf{R}_\mathrm{iso}\mathbf{w}}{\mathbf{w}^H\mathbf{R}_\mathrm{rec}\mathbf{w}}$

T_min is minimum noise temperature of one LNA

FPA Simulation Approaches

- Approximate analytical models
- Finite difference time domain (FDTD)
  - Finite Integration (CST)
  - Advantages: availability of codes, broadband
- Finite element method (FEM) – HFSS
  - Frequency domain
- Integral Equation (IE) – Feko, WIPL, Eiger
  - Frequency domain
  - Advantage: high accuracy (surface mesh)
- Time domain integral equation (TDIE)
  - Broadband and accurate, but still in research domain

Simple FPA Model

- Ground plane backed horizontal dipole array
- Embedded open circuit loaded element patterns approximated by isolated dipole pattern (minimum scattering approximation)
- Ground plane taken into account using images
- Mutual impedance matrix from overlap integrals using conservation of energy: $\mathbf{Z}_A = \frac{2}{|I_0|^2}\mathbf{A}$

  (Assumes dipoles are resonant)
- Scattered fields from reflector using physical optics (no blockage, feed supports, edge diffraction)
- *Approximate but fast, coupled, and satisfies conservation of energy*

Numerical Results

19 element, single pol, hexagonal, half-wave dipole FPA

20 meter reflector, f/D = 0.43

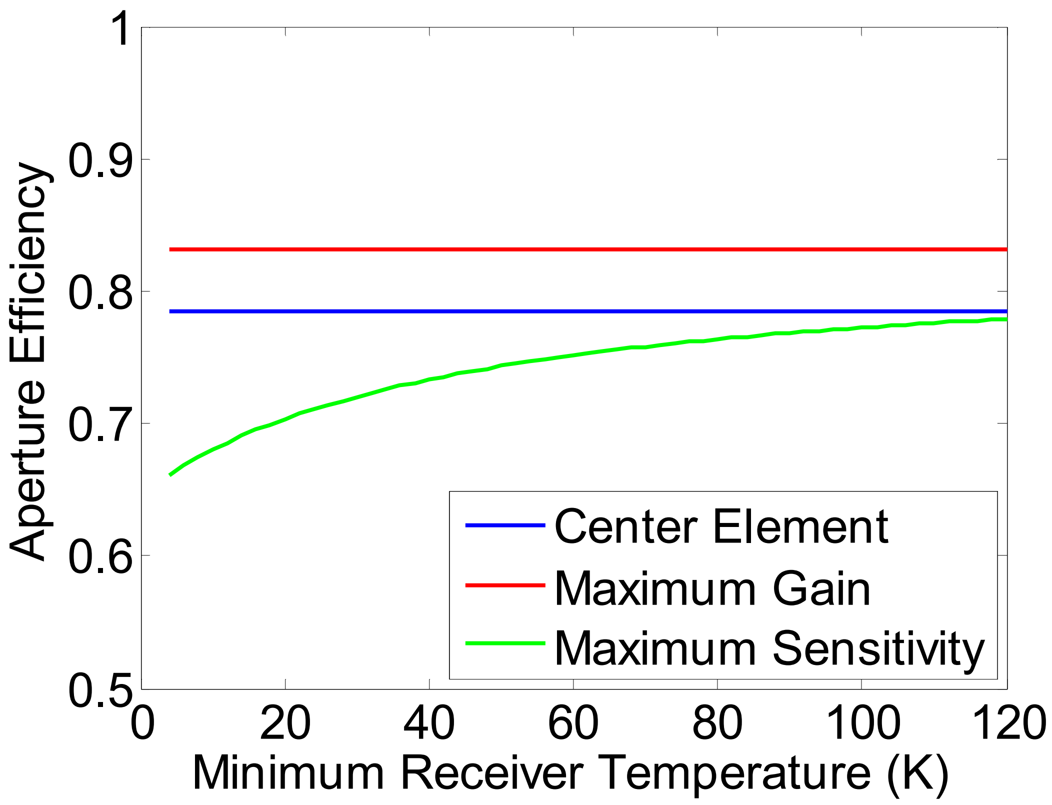
Array scattering matrix:

$$\mathbf{S}_A = \begin{bmatrix} 0.18 & -0.03 & 0.13 & 0.13 & \cdots \\ -0.03 & 0.18 & 0.13 & -0.05 & \\ 0.13 & 0.13 & 0.19 & -0.03 & \\ 0.13 & -0.05 & -0.03 & 0.19 & \\ \vdots & & & & \end{bmatrix}$$

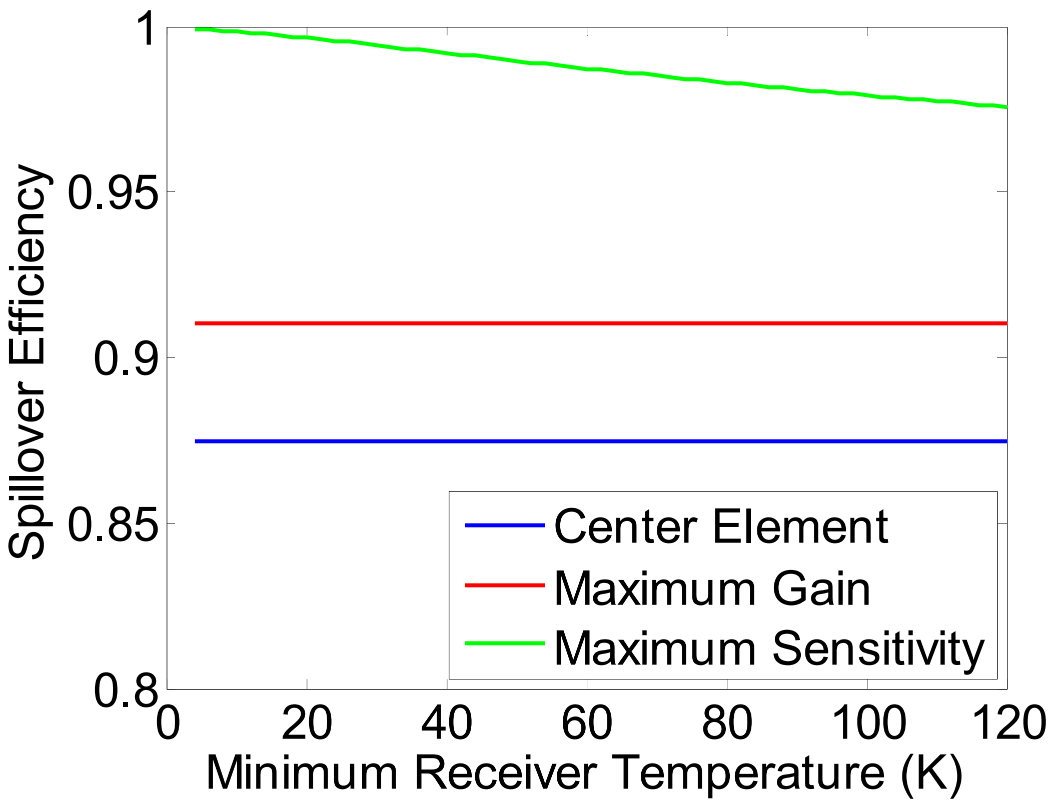
Average element efficiency: $1 - \frac{1}{M}\mathrm{tr}(\mathbf{S}_A^H \mathbf{S}_A) = 0.9$

Front end amplifiers are self-impedance matched – only coupling decreases noise matching efficiency

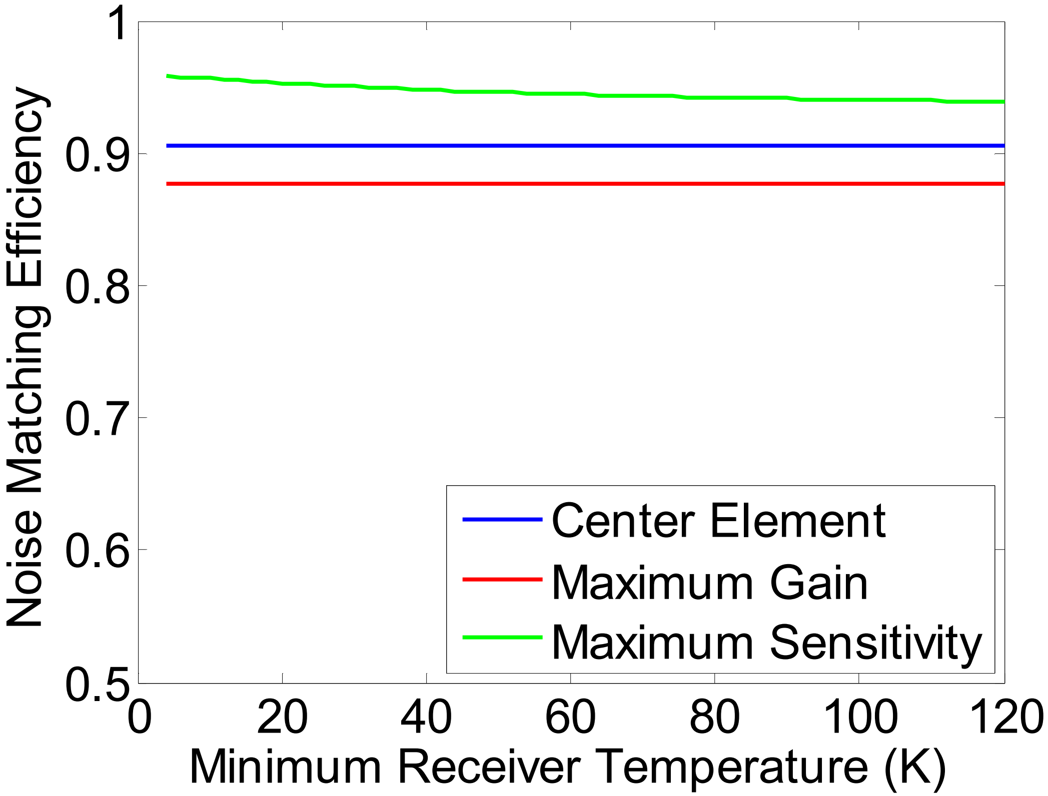
Beam Aperture Efficiency



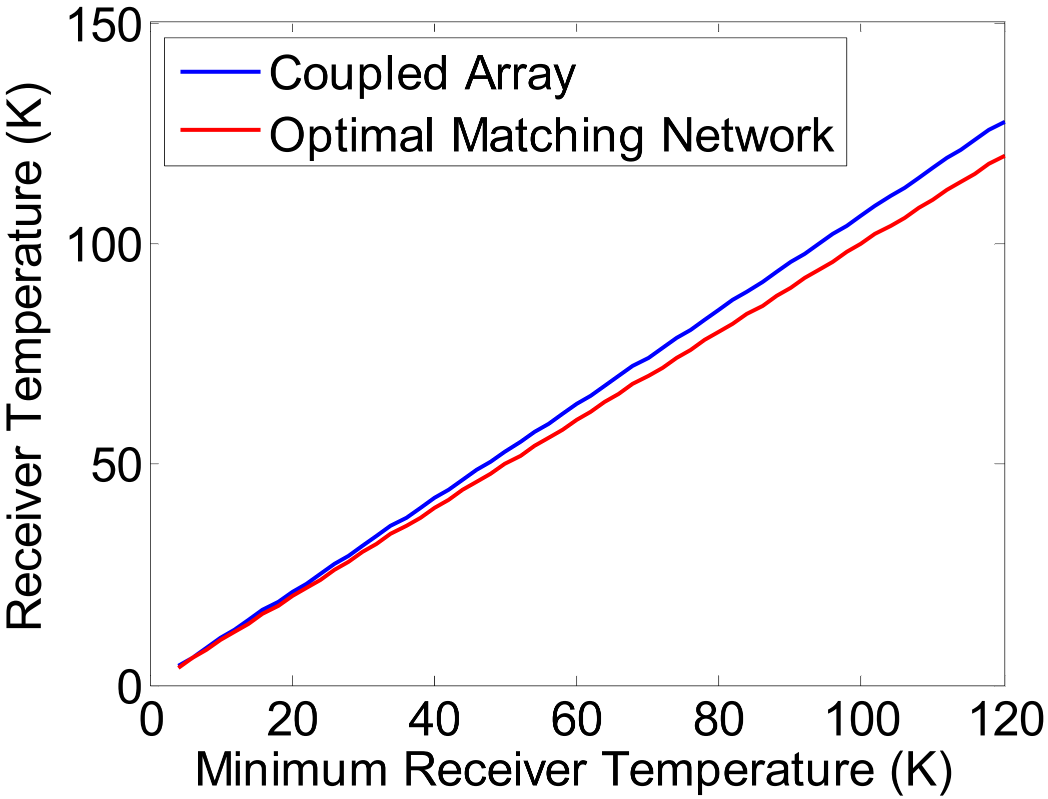
Spillover Efficiency



Noise Matching Efficiency



Mutual Coupling Noise Penalty



System Efficiency

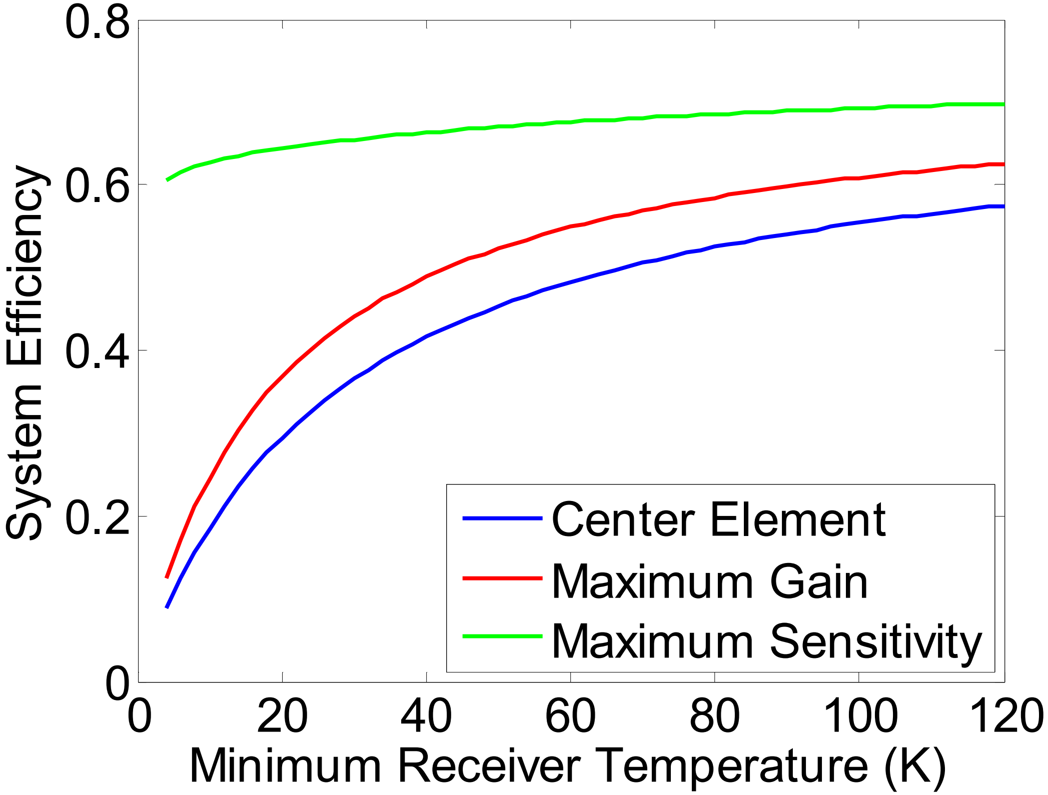
Reference sensitivity:

$$\begin{aligned} T_{\mathrm{rec}} &= T_{\mathrm{rec,min}} \\ \eta_{\mathrm{ap}} &= 1 \\ \eta_{\mathrm{sp}} &= 0 \end{aligned} \quad \longrightarrow \quad \left[\frac{A_e}{T_{\mathrm{sys}}}\right]_{\mathrm{max}} = \frac{A_p}{T_{\mathrm{rec,min}}}$$

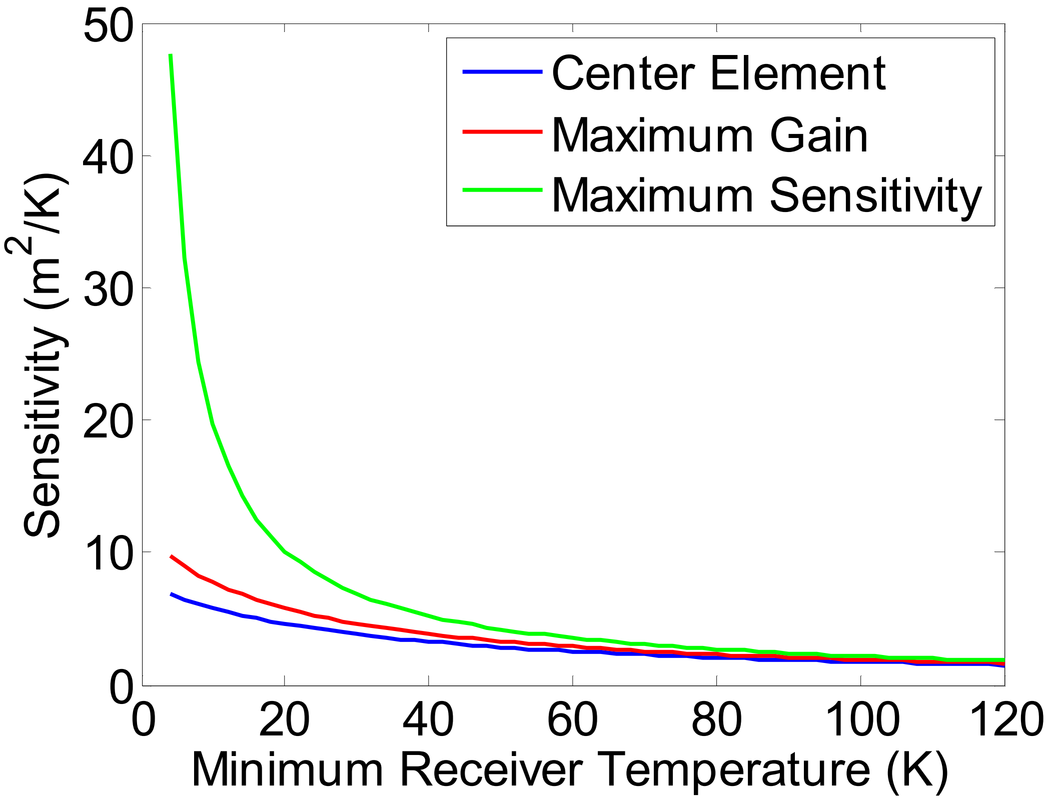
System efficiency:

$$\eta_{\mathrm{sys}} = \frac{A_e/T_{\mathrm{sys}}}{[A_e/T_{\mathrm{sys}}]_{\mathrm{max}}} = \frac{\eta_{\mathrm{ap}}}{(1-\eta_{\mathrm{sp}})T_g/T_{\mathrm{rec,min}} + 1/\eta_{\mathrm{n}}} > \eta_{\mathrm{ap}}$$

System Efficiency



Sensitivity



Efficiencies at $T_{rec,min}$ = 120K

Center element only:

- Aperture efficiency = 0.79
- Spillover efficiency = 0.88
- Noise matching efficiency = 0.91
- System efficiency = 0.58
- Sensitivity = 1.51 m^2/K

Optimal gain beamformer:

- Aperture efficiency = 0.83
- Spillover efficiency = 0.91
- Noise matching efficiency = 0.88
- System efficiency = 0.63
- Sensitivity = 1.64 m^2/K

Optimal sensitivity beamformer:

- Aperture efficiency = 0.78
- Spillover efficiency = 0.98
- Noise matching efficiency = 0.94
- System efficiency = 0.70
- Sensitivity = 1.83 m^2/K

Green Bank 20 Meter FPA Experiment

Objectives:

- Measure sensitivity and efficiencies
- Validate FPA models
- Demonstrate adaptive RFI mitigation and pattern rumble bias correction
- Gain understanding needed to develop a stable, low noise, high sensitivity FPA

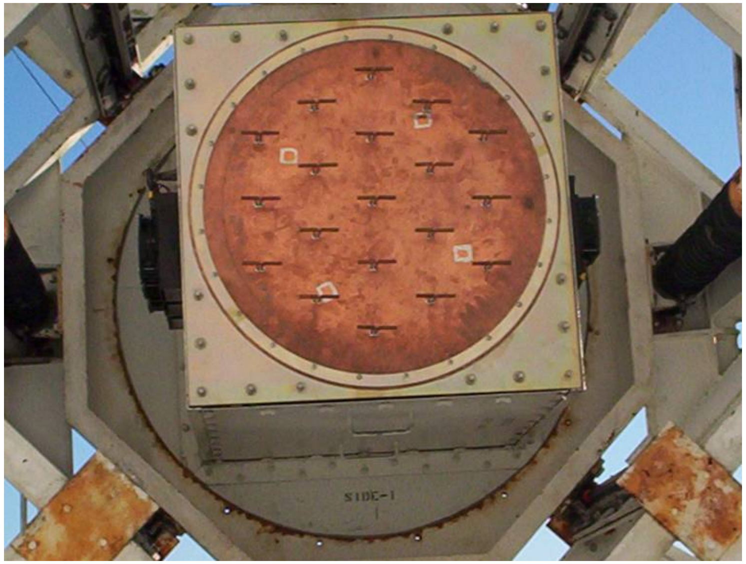
19 element L-band thickened dipole array

120 K front ends per channel

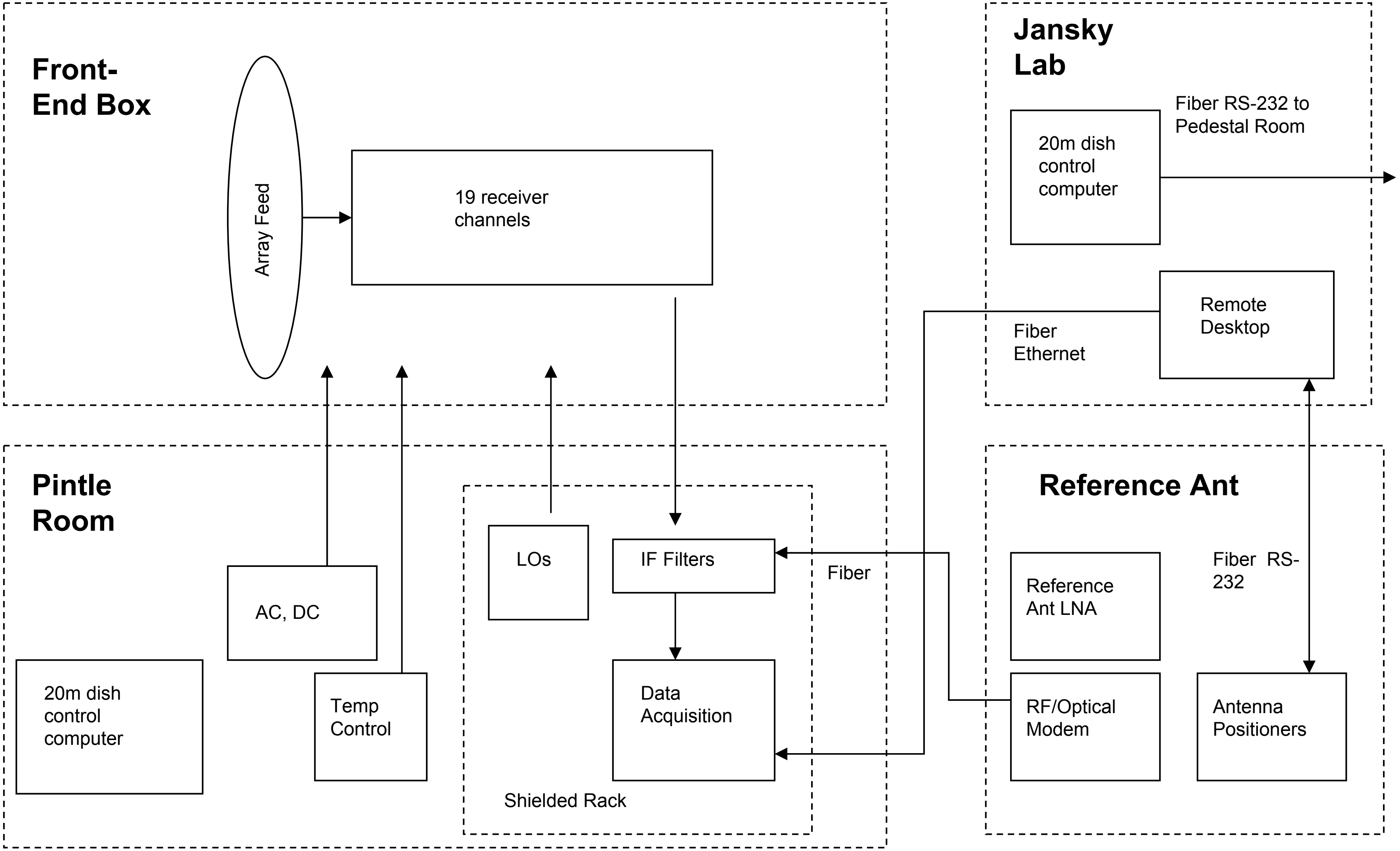
National Radio Astronomy Observatory (NRAO)

Green Bank, West Virginia, USA

Oct. 31 – Nov. 8, 2007



System Overview



Front-End Box

Array Feed

19 receiver channels

Jansky Lab

20m dish control computer

Fiber RS-232 to Pedestal Room

Remote Desktop

Fiber Ethernet

Pintle Room

AC, DC

20m dish control computer

Temp Control

LOs

IF Filters

Data Acquisition

Shielded Rack

Fiber

Reference Ant

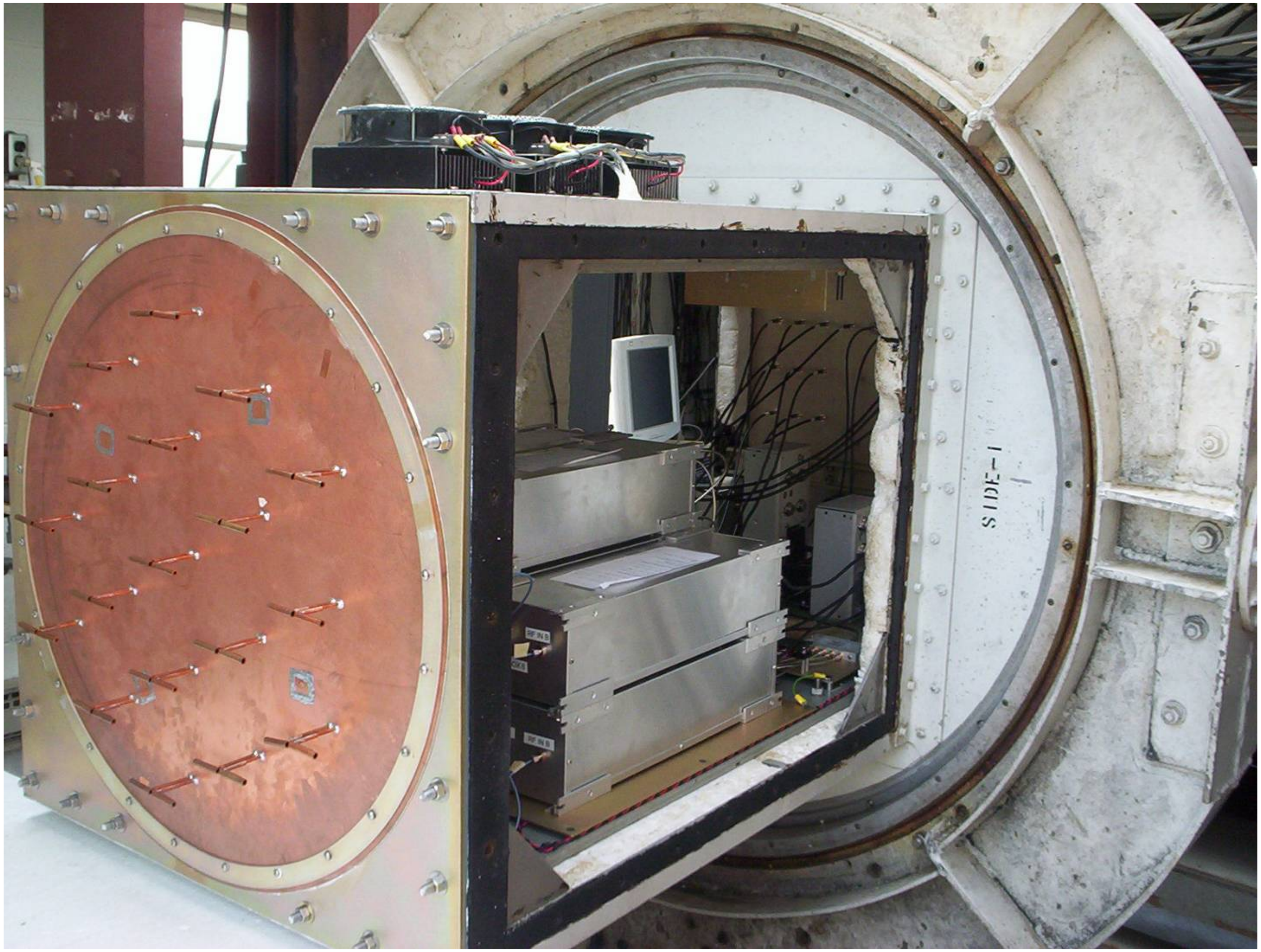
Reference Ant LNA

Fiber RS-232

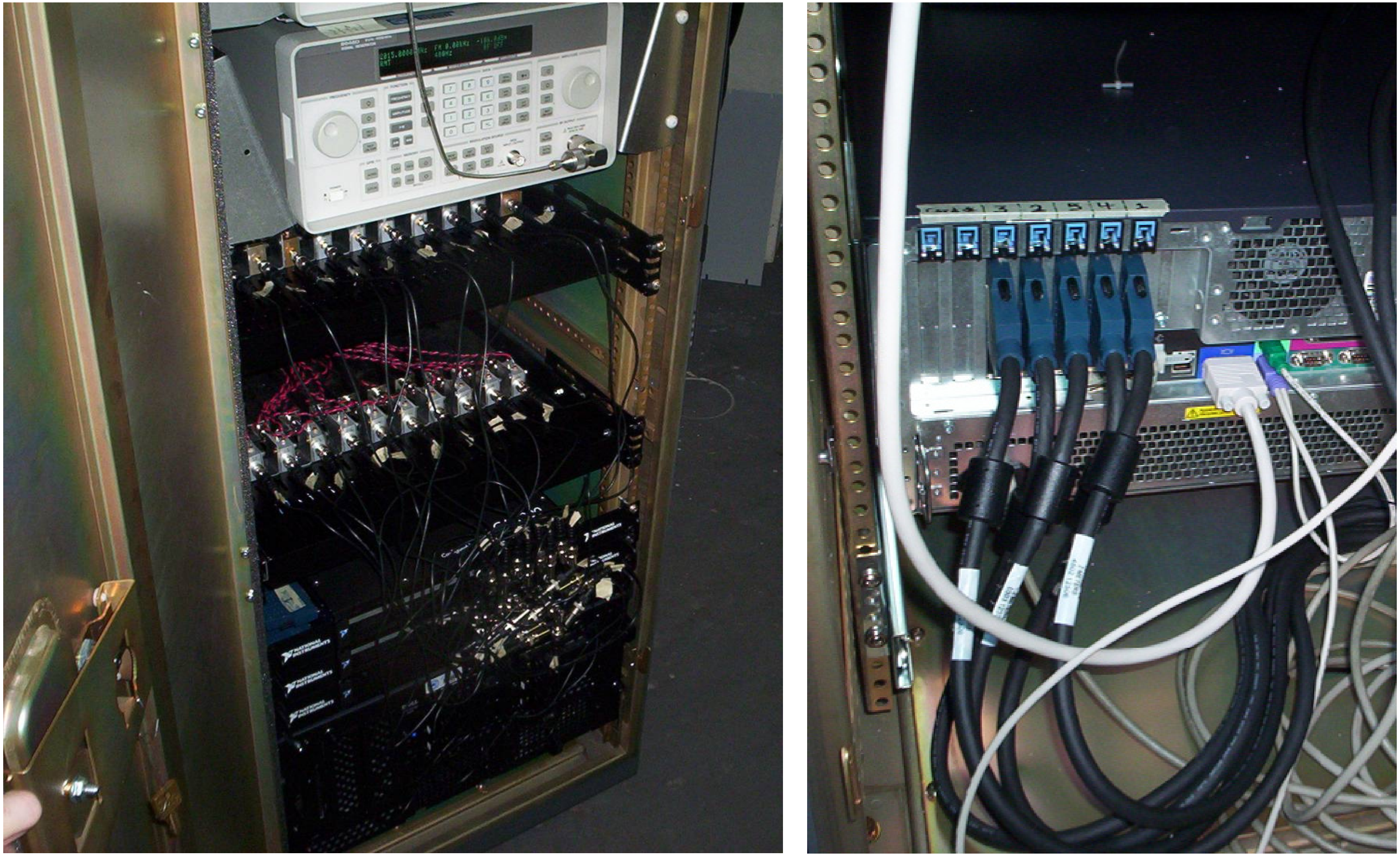
RF/Optical Modem

Antenna Positioners

FPA in NRAO Front End Box



Data Acquisition

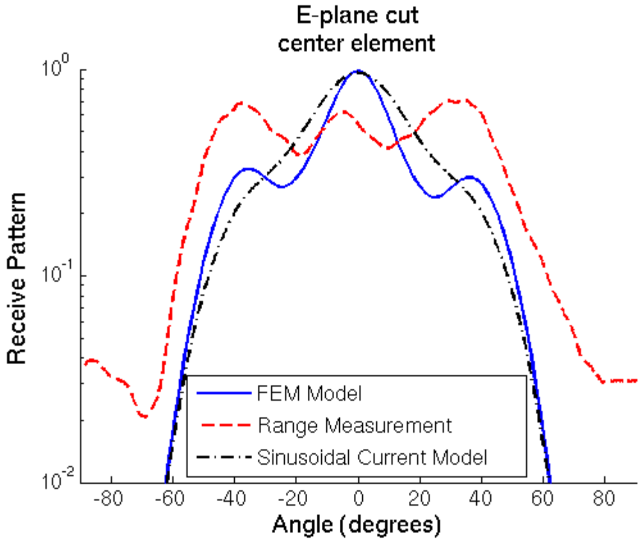


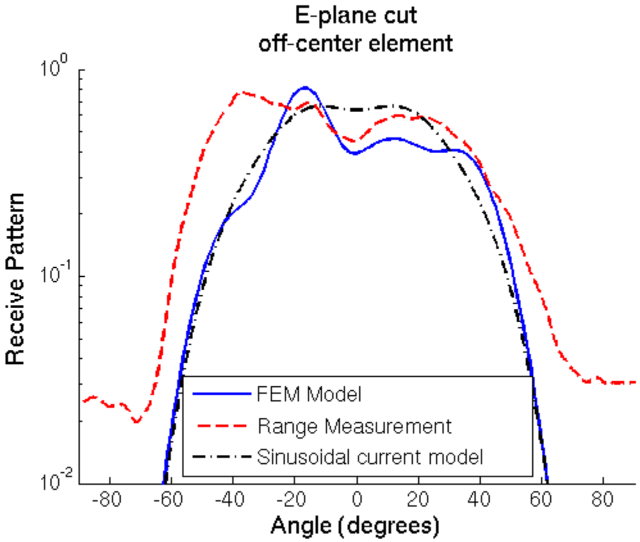
Antenna Range Measurements

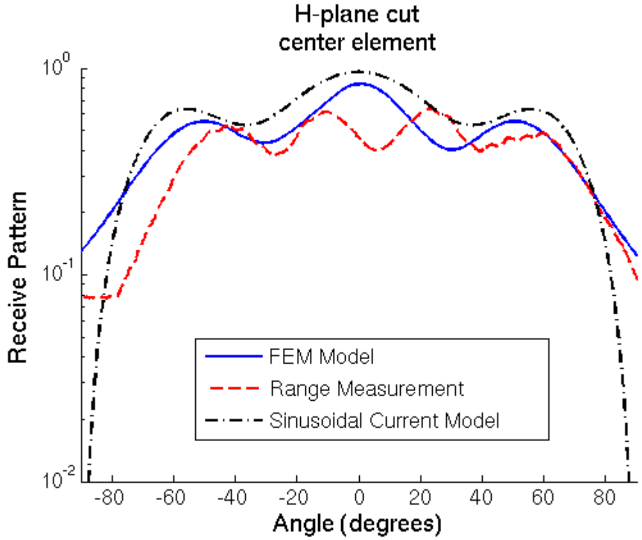
NRAO Green Bank outdoor range

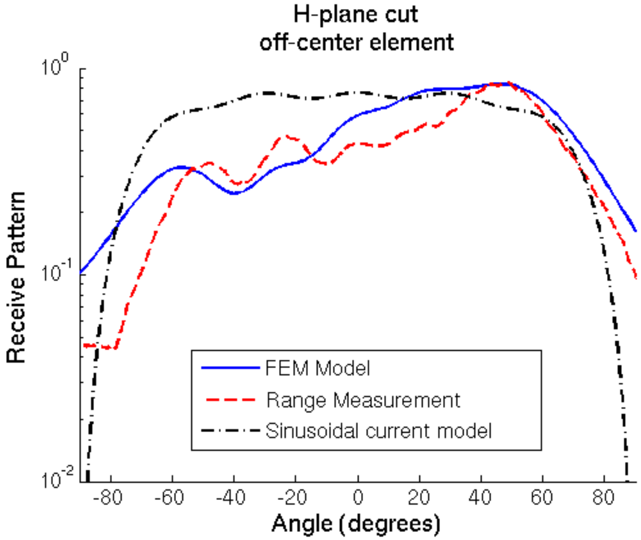
FEB on 20 Meter Reflector

Embedded Element Patterns









Cygnus A

Telescope steering:

24 arcmin steps (half beamwidth)

20 seconds per pointing

Beamformer:

Maximum SNR

Calibrated using Cygnus A

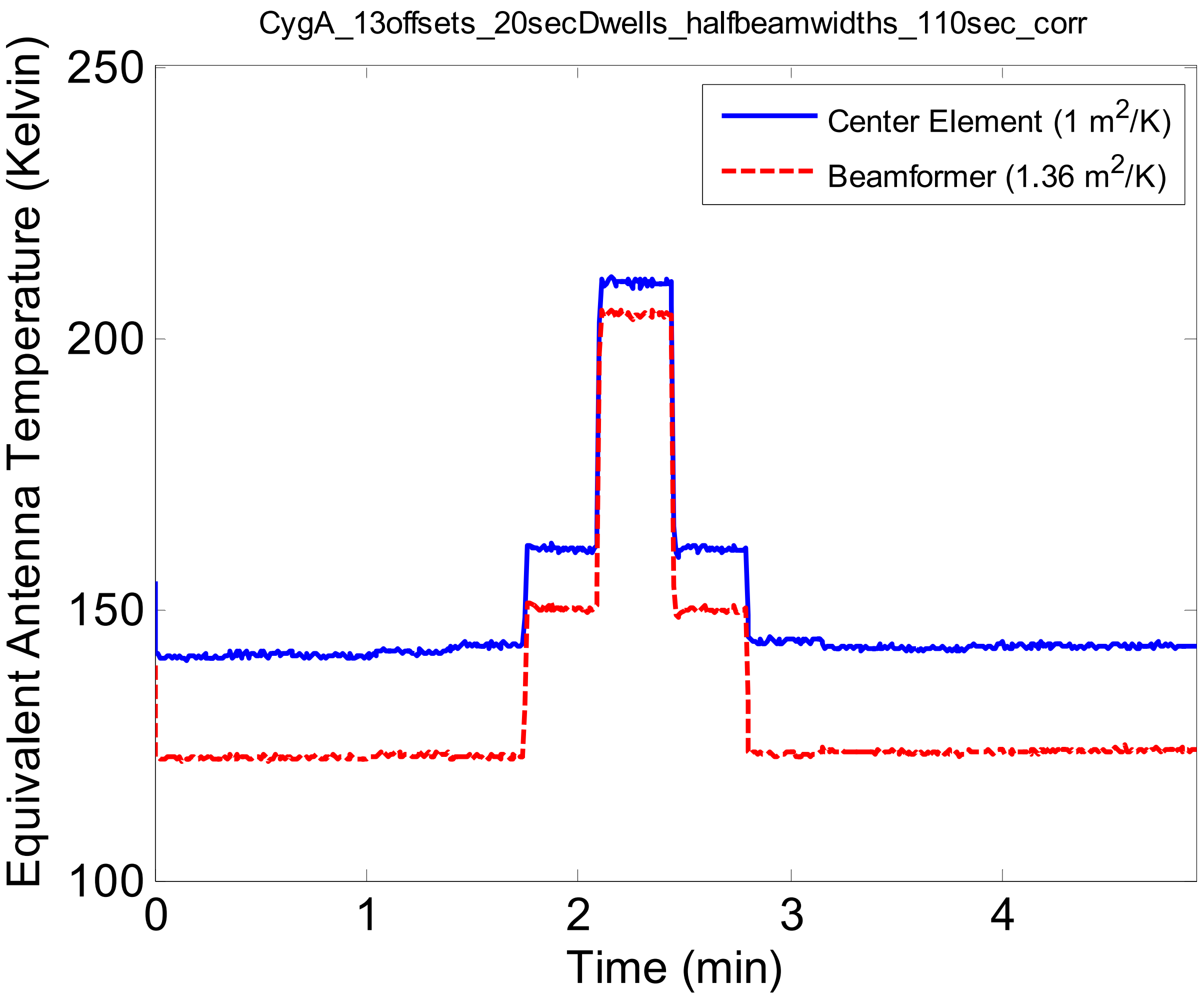
Source flux density: 1380 Jy

Using preliminary T_{sys} calibration:

Gain: 0.06 ± 0.005 K/Jy

Aperture efficiency: 53% ± 5%

Signal processing sensitivity improvement: 36%



Virgo A

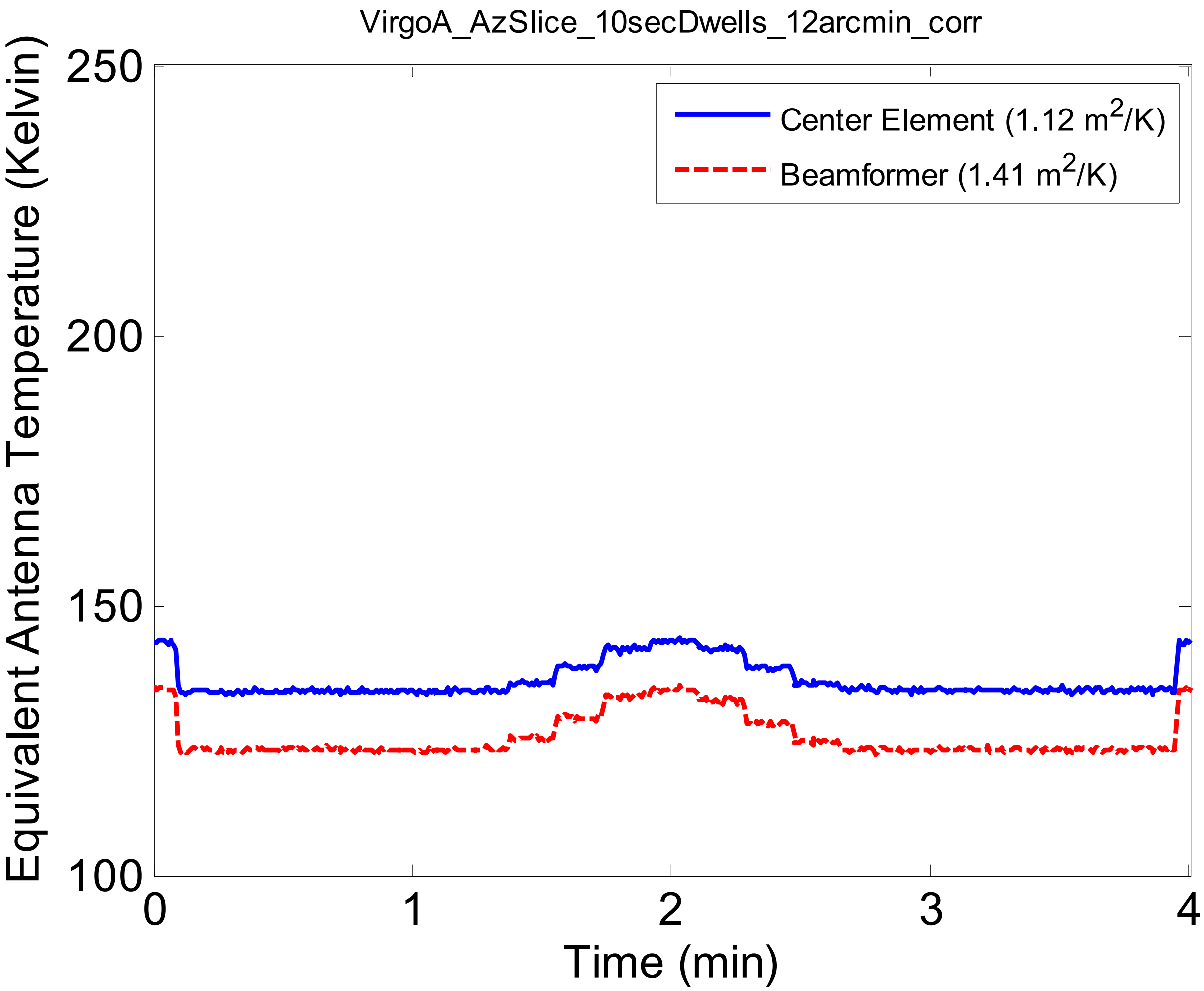
Telescope steering:

12 arcmin steps
10 seconds per pointing

Beamformer:

Maximum SNR
Calibrated using Cygnus A

Source flux density: 200 Jy

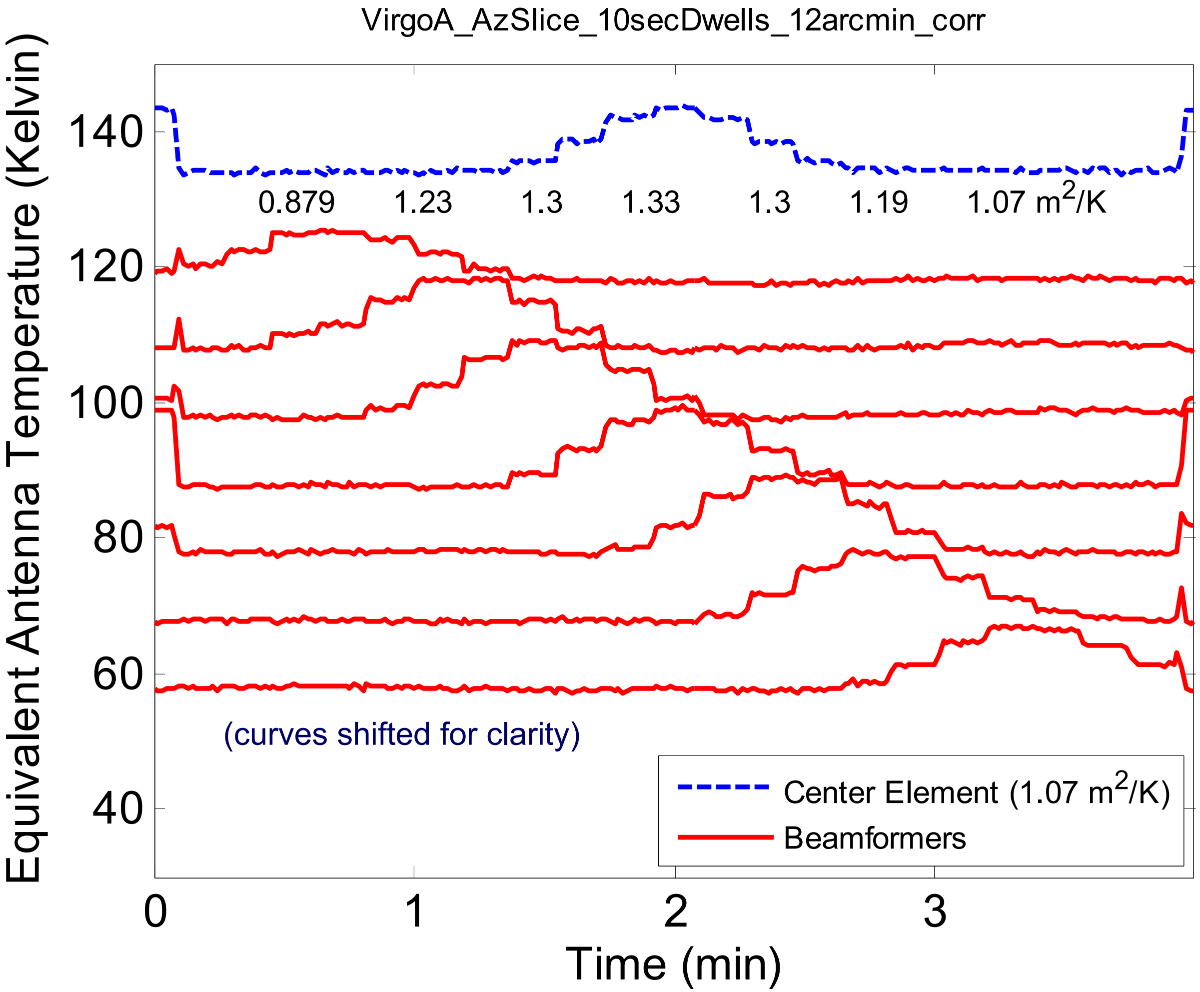


Multiple Beam Formation

Beamformer:

  Maximum SNR
  Calibrated using Cygnus A
  Multiple pointings

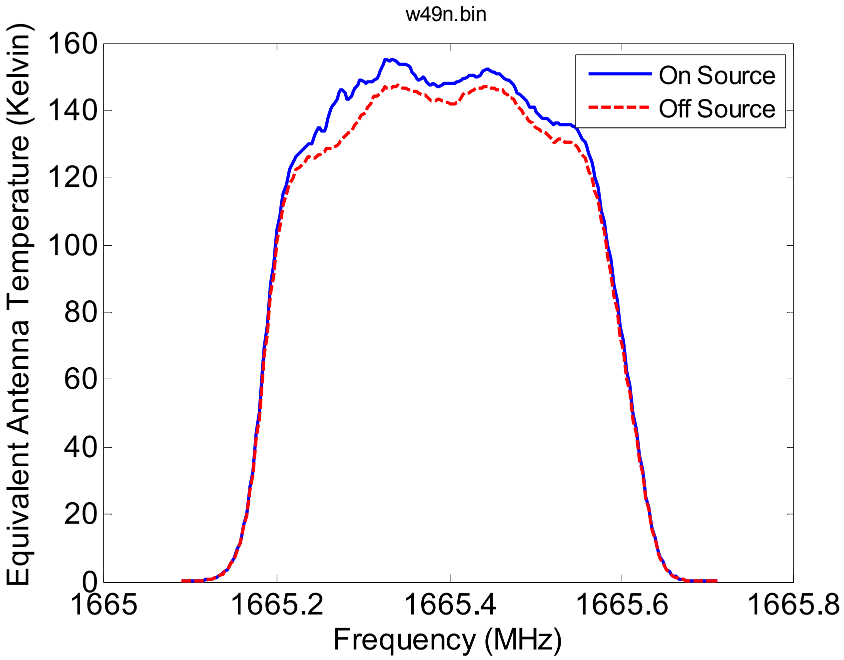
Decrease in sensitivity evident for large steering angles

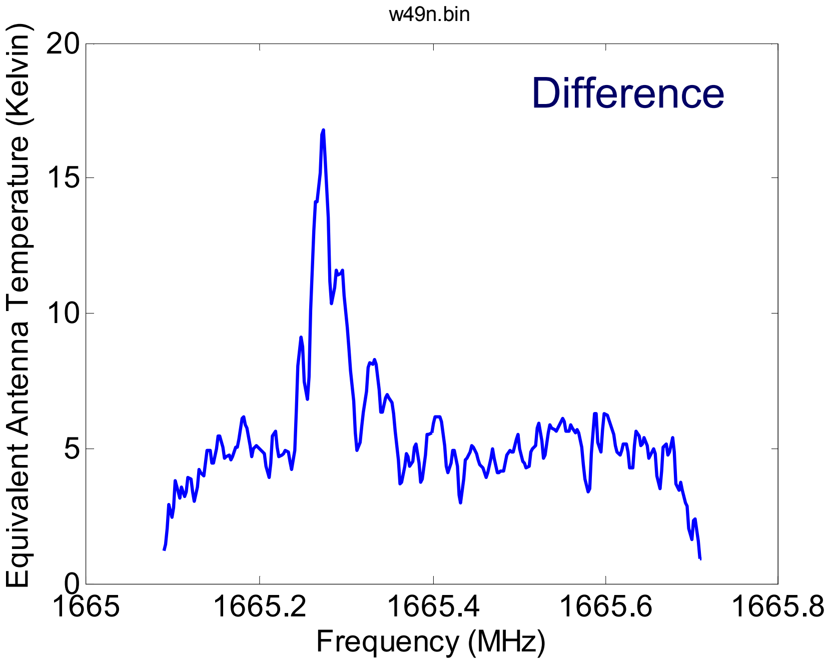


Spectral Line Source

OH Maser (W49N)

- Largest peak is roughly 200 Jy over 10 KHz
- Continuum component





Adaptive RFI Mitigation

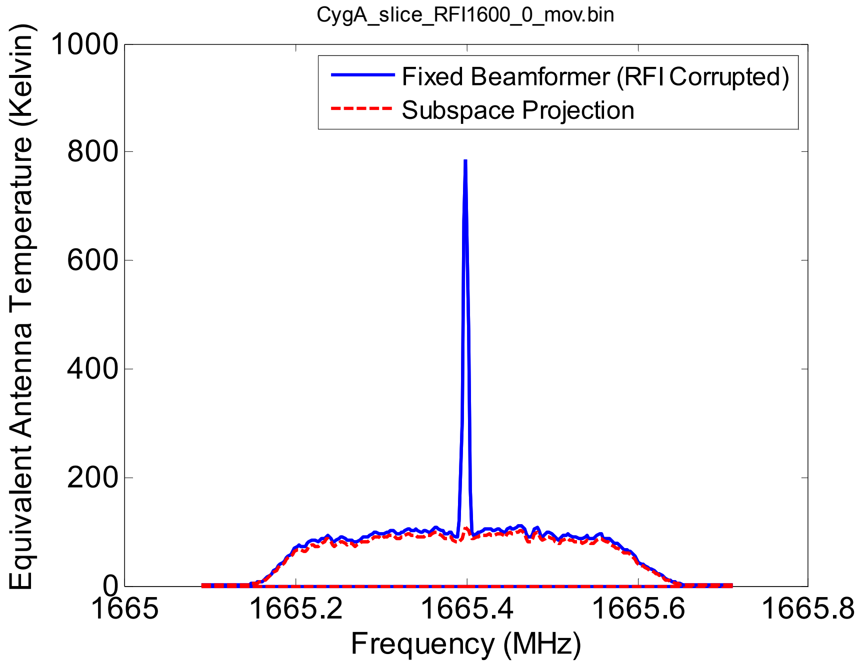
- Beamformer updated in short term integration (STI) windows (on the order of 1 ms)
- Interferer tracked using subspace identification
- Spatial null on RFI source(s)
- Beam pattern changes with time
  - FPA sidelobe perturbation causes spillover noise fluctuations
  - Noise floor variance increases and radiometric sensitivity decreases

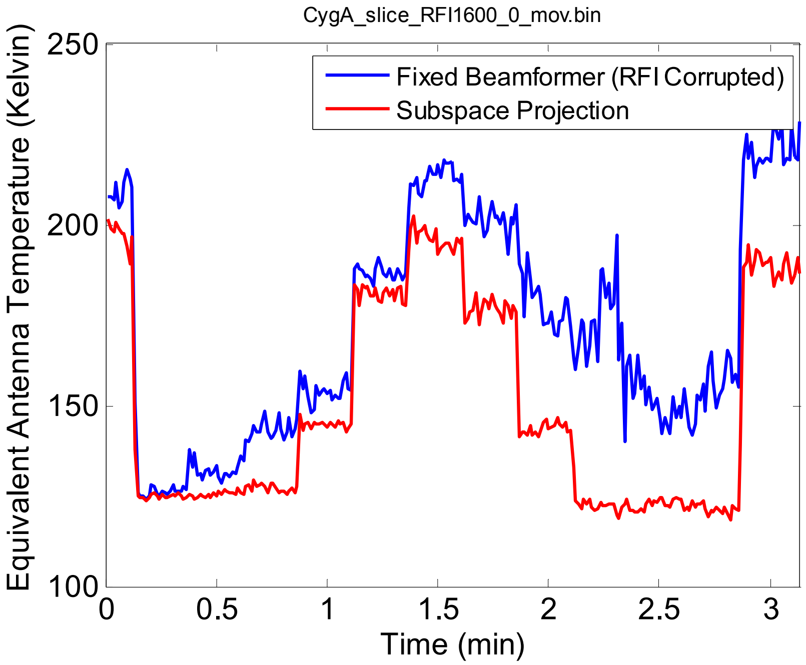
Experimental Results

RFI Source: Artificial CW Tone, moving ground-based transmitter
Significant multipath (simulates terrestrial source)

Quiescent beamformer: Maximum SNR

RFI Mitigation: Subspace Projection
Projection operator nulls RFI subspace identified using dominant eigenvector of array response covariance
4.9 ms short term integration (STI) time



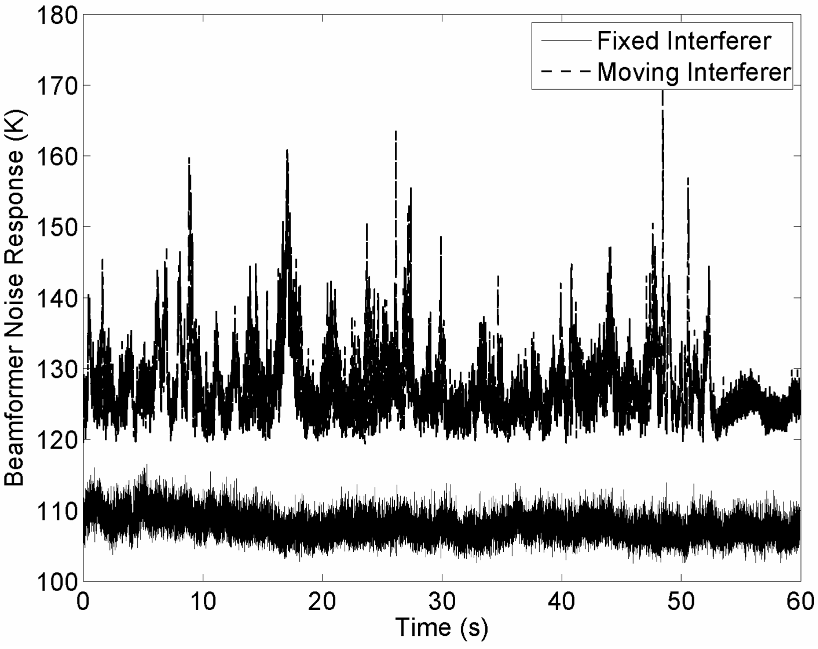


Pattern Rumble

19 element FPA on 3 meter reflector

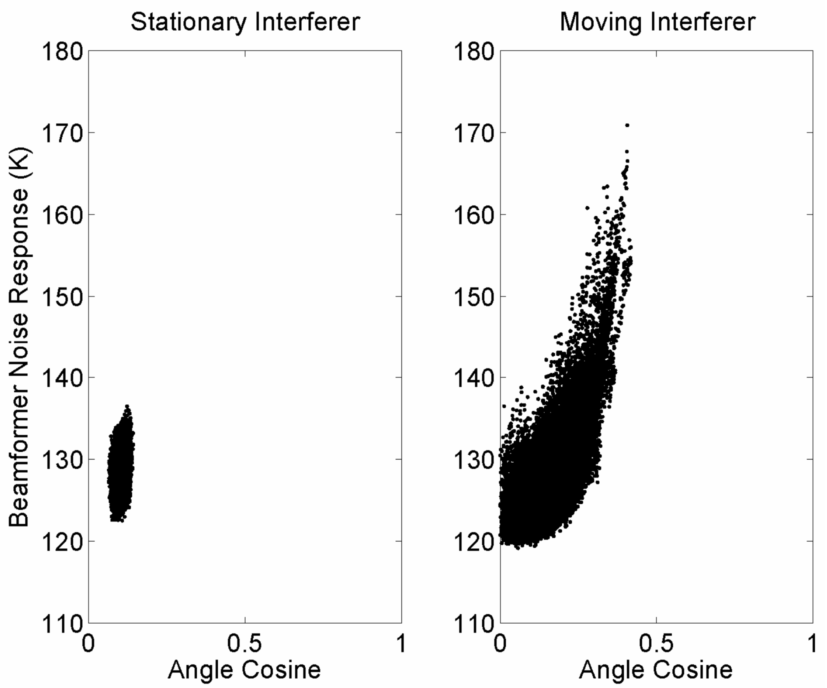
Fixed and moving artificial RFI sources

Adaptive RFI mitigation



Noise response (with constrained signal gain) fluctuates due to beamformer adaptation

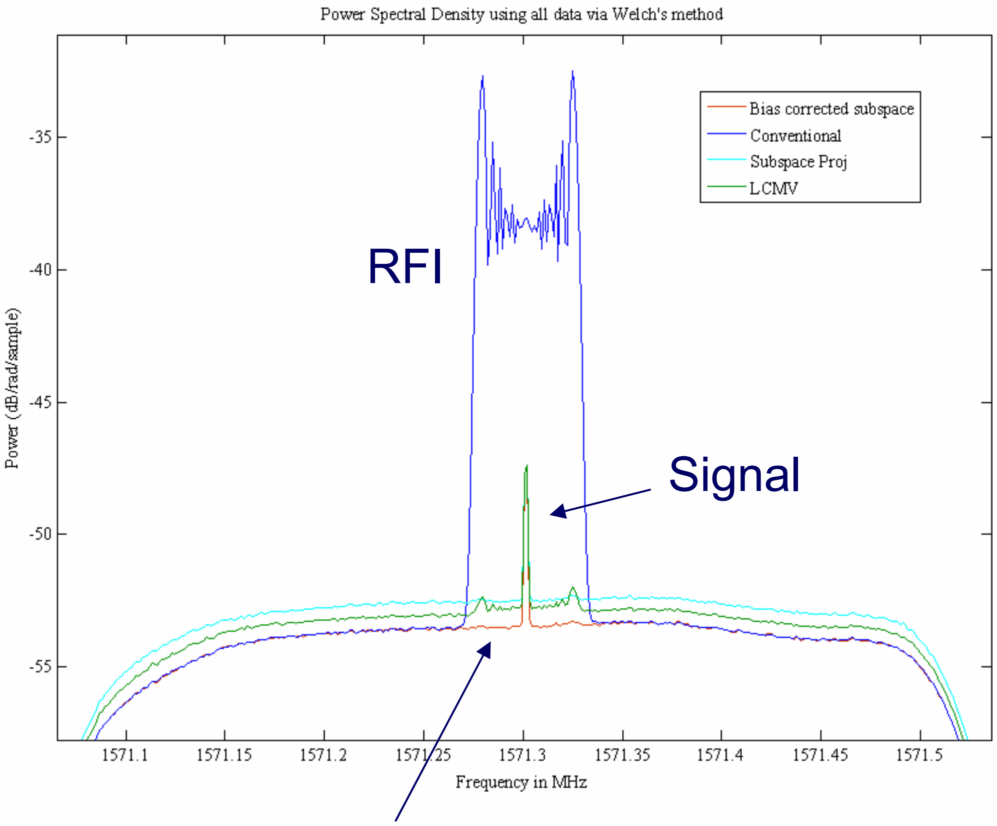
Angle cosine of interferer response vector and signal steering vector



Pattern deviation from quiescent is largest when signal and interferer array responses are similar

Bias Corrected PSD Estimator

- Spatial filtering followed by a temporal processing algorithm to remove bias caused by pattern rumble [Jeffs and Warnick, 2006]
- Interferer subspace projection operators can be factored out of windowed PSD estimator
- With interferer motion, averaged projector becomes full rank and can be inverted
- *The average or effective beam pattern is the desired quiescent pattern*
- *Noise floor variance increase due to pattern rumble is corrected*



RFI

Signal

Bias corrected subspace projection removes RFI and corrects pattern rumble effect

Conclusions and Future Work

- Sensitivity is 25% lower than idealized model
  - Model underestimates mutual coupling
  - Blockage, diffraction, reflector/feed interactions are not modeled
- Aperture efficiency is 50-60%
  - Preliminary T_{sys} calibration
  - Model: 78% aperture efficiency
- Multiple beam formation demonstrated
  - High sensitivity beams can be steered using calibrations
  - Calibrations are stable for > 1 day
- Adaptive RFI mitigation demonstrated

Future work:

- Final system temperature calibration (spillover efficiency measurement?)
- Field of view imaging using calibrator grid
- Check sensitivity degradation over time/steering angle/sky position

Research Problems

- Low loss, broadband, dual-pol antenna elements with well-behaved impedances
- Modeling, measuring, and minimizing antenna ohmic losses
- Accurate modeling and measurement of embedded element patterns and mutual impedance
- Experimental demonstration of competitive beam sensitivity, efficiency, and noise temperature
- RFI mitigation algorithms which achieve larger null depths

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