Phased Array Antennas for Radio Astronomy

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January 2013
Outline

- Introduction to radio astronomy
  - Technology timeline for radio astronomy instruments
  - Basics of astronomical observations
- Research challenges for astronomical phased array antennas
- Modeling and design of high sensitivity active phased array receivers
  - Correlation matrices and microwave network theory
  - Why designing high-performance active arrays is more complicated than designing single-port antennas
  - New IEEE standard antenna terms for array receivers
  - Active impedance matching
- Experimental campaigns and results
- Other applications
Radio Astronomy Systems Research at BYU

Faculty Directors: Karl F. Warnick, Brian Jeffs

High Impact Research Contributions

- Major experiments at national radio observatories
- International recognition for work in array feeds
- Organizers of two journal special issues
- Significant international collaboration
  - Netherlands, Germany, Canada, Australia, Germany
- $3M+ in external (NSF) funding

Graduate Student Research

- Students mentored by faculty and scientists
- Excellent placement of MS grads into Ph.D. programs (MIT, Stanford, BYU)
- Student-directed experimental research

Undergraduate Mentoring

- Supported by NSF REU
- Mentored by graduate researchers and faculty
- Engaged in instrumentation senior projects

Grad & ugrad students test their array feed at NRAO

(left) Installing the array on the 20m dish
(right) Array image of Cygnus radio sources

BYU Phased Array Feed on Arecibo Telescope
January 1961: The first-ever special issue in the IRE Transactions was on Radio Astronomy. From the special issue editorial: “Antenna and feed characteristics in radio astronomy represent the limits of progress in radio optics at any time...[and] have provided to all radio science and technology a wellspring of fundamental knowledge that is applicable in almost every advanced endeavor...” [L. Berkner, IRE President, 1961]

Radio Astronomy

- Pulsars
- Cosmic jets
- Gravitational lenses
- Galactic center
- Black holes
- Astrochemistry
- Age of the universe
- Cosmology
- Dark matter, dark energy

Images courtesy of NRAO/AUI
Single-Pixel Reflector Antennas

Green Bank Telescope (GBT)
http://www.astro.virginia.edu/whyastro/GBT+140.jpg

Arecibo (Puerto Rico)
http://www.icc.dur.ac.uk/~tt/Lectures/Galaxies/Images/Radio/Arecibo.jpg

500 Meter Telescope (FAST) – China
Under construction
Aperture Synthesis Arrays (Very Sparse)

Very Large Array (VLA), Socorro, NM
Image courtesy of NRAO/AUI

Atacama Large mm-Wave Array (ALMA)
Image courtesy of NRAO/AUI

Very Long Baseline Interferometer (VLBI)

Other arrays:
- Westerbork – The Netherlands
- PAPER Array – Green Bank W.V
- LOFAR – Northern Europe
- LWA – Southwestern U.S.
- ATA – Berkeley
- Etc...
Multiple Pixel Feeds

- One feed per beam
- Each feed matched to reflector
- Sparse array
- Focal plane/field of view not fully sampled

Arecibo L-band feed array (ALFA)
http://physics.gmu.edu/~lhorne/ALFA1.jpg

Parkes multibeam feed
Image courtesy of Parkes Observatory, ATNF / CSIRO
Square Kilometer Array (SKA)

- To be built by international community over next decade
  - Recent siting decision (2012): Western Australia and South Africa
- Pathfinder projects currently underway
- Thousands of elements
- Dense array core
- Sparse elements over thousands of kilometers
- Expected cost $1.5 billion

Images courtesy of Neil Roddis, SKA PDO
Types of Dense Phased Arrays

**Aperture arrays** - direct view to sky
- LOFAR – Low frequency array, Northern Europe
- LEDA, PAPER, others
- SKA core

**Phased array feeds (PAFs)**
- Large reflectors – GBT, Arecibo, Westerbork
- Small reflectors – SKA
Trend is towards arrays of increasing density...

- Last 75 years: Single-pixel large dish antennas
- Last 50 years: Sparse aperture synthesis arrays
- Last 5 years: Multi-pixel cluster feeds (moderately sparse)
- Present: Dense aperture phased arrays and phased array feeds
Phased Array Feeds

- Replace standard single pixel horn reflector feed with a phased array
- **Advantages of phased array feeds:**
  - **Primary driver:** Increased field of view
  - Rapid astronomical sky surveys
  - Multiple electronically formed beams
  - High sensitivity, efficiency
  - Beam pattern optimization
  - Adaptive interference mitigation
Phased Array Feed Development Efforts

- Apertif (Astron, The Netherlands)
- PHAD (DRAO, Canada)
- ASKAP (CSIRO, Australia)
- BYU/NRAO L-band PAF for Green Bank Telescope (U.S.)
- Cornell L-band PAF for Arecibo (BYU signal processing back end)
- PAF for China 500 m FAST Telescope (BYU/NAOC Collaboration)
- mm-wave array feed for GBT (UMASS/BYU Collaboration)

Credit: David McClenaghan, CSIRO
Credit: Tony Willis, NRC - CNRC
Credit: German Cortez, Cornell CRSR
Credit: David McLenaghan, CSIRO
Design Challenges for Phased Arrays Feeds

- **Broadband**
  - Near term: 300 to 500 MHz bandwidth at L-band, >2:1 long term

- **High sensitivity**
  - Astronomical signals have very low SNR (-30 to -50 dB)
  - 80% aperture efficiency, >99% radiation efficiency
  - System temperature below 30 Kelvin at L-band

- **Stable gain (radiometric detection)**

- **High dynamic range (weak signals near bright sources)**
  - Stable, well characterized sidelobes

- **High polarimetric accuracy**

- **Immunity to radio frequency interference (RFI)**

- **Massively high data rates for back end real time digital signal processing (spectrometer, beamformer, correlator)**

*Ultra-high performance requirements for astronomical observations has created a new field of research in phased array antenna technology*
Heritage of the BYU/NRAO PAF Design

- **90’s:** R. Fisher’s array of sinuous elements
  - Complex impedance behavior, poor matching
- **2000’s:** Goal was to move to the opposite extreme: a simple, well-modeled, low-loss design
  - Dipole array effort began in 2005 – thin dipoles
  - Emphasis on low noise above all else
  - 2009 – Fat dipole effort to improve bandwidth and matching
- **2010** – Dual pol dipole (dual feed ports design is challenging)
- **2012** – Dipole element for cryogenic PAF
Phased Array Projects at BYU

- **PAFs:**
  - 19 element low loss, high efficiency active impedance matched array
  - 19 x 2 element dual-polarized array
  - Cryogenic 19 x 2 – elements (BYU), dewar (R. Norrod, NRAO), LNAs (S. Weinreb, Caltech), back end (BYU, NRAO)

- **Signal processing**
  - Multichannel downconverter boards
  - 40 channel narrowband data acquisition system
  - 64 channel FPGA-based 50 Msample/sec real time spectrometer/correlator/beamformer

- **Algorithms**
  - Controlled beam shape, RFI mitigation, polarimetric calibration

- Arecibo PAF feasibility study (G. Cortes)
- Focal L-band Array for Green Bank Telescope (FLAG)
- mm-wave array feed for GBT (UMASS, BYU)
Overview of a PAF Receiver System

- **Front end (analog)**
  - Antenna elements (19 elements to hundreds of elements)
  - Low noise amplifiers (ambient temp. or cryogenic)
  - Receiver chains (downconverters, filters, amplifiers)
  - LO distribution network
  - Signal transport

- **Back end (digital)**
  - Digitizers, antialiasing filters
  - RFI shielding
  - Calibration and algorithms for beamformer weights (PC)
  - Real time beamformer (B engine), correlator (X engine), and/or spectrometer (F engine)
  - Interface to telescope control system,
  - Management and control

- **Post-processing**
  - Image formation, mosaicing, RFI flagging, etc.
  - Data archiving
Radiometric Detection

Output power with antenna pointing at source of interest (one pixel in raster scan): 

\[ P_{on} = P_s + P_n \]

Output power with antenna steered away from the source of interest:

\[ P_{off} = P_n \]

\[ P_{on} - P_{off} = P_s \]

Noise power estimation error: 

\[ \Delta P_n = \frac{\alpha P_n}{\sqrt{Bt}} \]

Reducing system noise is critical!
Phased Array Feed Beamforming

- Horn feed is electrically large and collects nearly all focused signal energy
- Feed elements are small, and signal is collected by multiple elements
- Airy spot moves across the feed for steered beams
- Beam steering to first order is accomplished by changing amplitudes of element output weighting coefficients
- Power loss for widely steered beams with focal spot near the edge of the array leads to efficiency reduction – 1% sensitivity drop defines field of view
- Sensitivity is a function of beam steering direction and fluctuates across the array FoV
Phased Array Feed Antenna Design Goals

- Phased array with 19+ elements for wide field of view - many formed beams and multiple pixels
- Dual polarized
- Integrated balun to allow for single-ended LNAs
- Ground plane backed
- Bandwidth: 300 MHz at 1.5 GHz (1 dB sensitivity)
- High efficiency:
  - Radiation efficiency >99% (very low ohmic/dielectric losses)
  - Aperture efficiency >70%
  - Spillover efficiency >95%
- High sensitivity (A/T) over the array field of view
Research Questions

- How should antenna gain and other figures of merit be defined for an active phased array?
- What impedance should array elements be designed for to maximize SNR?
- How does mutual coupling affect antenna performance?
- What is the best achievable efficiency with a phased array?
- Can phased arrays be as sensitive as a state-of-the-art horn antenna with liquid helium-cooled electronics?
- How can computational electromagnetics tools be combined with microwave network system models to optimize an entire system including a phased array antenna elements, receiver electronics, and signal processing?
Design Process

BYU
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Research Group

PAF front end

Array Element Geometry and Configuration

EM Model

Reflector Model

Network Model

Beamforming Algorithm

Sensitivity, Field of View, Bandwidth, Survey Speed
Phased Array Feed System Model

Reflector → Array Feed → LNAs → Receiver Chains (Downconversion, basebanding, sampling) → Digital Beamforming

- Physical Optics
- Full wave EM simulation
- Network Theory
- Signal, noise correlation matrices
- Array Signal Processing
How is a phased array characterized electromagnetically?

Thevenin equivalent source network:

- Embedded open circuit loaded received voltage patterns: \( \mathbf{v}_{oc}(\hat{p}, \Omega, E_0) \)
- Mutual impedance matrix: \( Z_A \)
- (Scattering parameters also needed to fully characterize array)

\[
\overline{E}(\mathbf{r}) = \hat{p}E_0e^{-j\mathbf{k}\cdot\mathbf{r}}
\]
Receive voltages in terms of transmit patterns

- Array antennas are typically modeled as transmitters
- Using the electromagnetic reciprocity principle, the open circuit loaded voltages at the receive array terminals are:

\[ v_{oc,n} = \frac{4\pi j r e^{jkr}}{\omega \mu I_0} E^{inc} \hat{p} \cdot \overline{E}_n(r) \]

Embedded radiation field pattern with current \( I_0 \) into the \( n \)th array element and all other elements open circuit loaded, evaluated in the direction of arrival of the incident field.

For array feeds, the embedded pattern includes reflector scattering.

Receive Array Network Model

Loaded voltages at array ports:

\[ v_L = Z_L (Z_L + Z_A)^{-1} v_{oc} \]

Array output voltage vector:

\[ v = gQ v_{oc} \]

(assumes uncoupled receiver chains)
Array Signal and Noise Model

Array output signal and noise contributions before beamforming:

\[ \mathbf{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} = \mathbf{v}_{\text{sig}} + \mathbf{v}_{\text{ext}} + \mathbf{v}_{\text{loss}} + \mathbf{v}_{\text{rec}} \]

Array output correlation matrix:

\[ \mathbf{R}_v = \mathbb{E}[\mathbf{vv}^H] = \mathbb{E} \left\{ \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix} \begin{bmatrix} v_1^* \\ v_2^* \\ \vdots \\ v_N^* \end{bmatrix} \right\} = \mathbf{R}_{\text{sig}} + \mathbf{R}_{\text{ext}} + \mathbf{R}_{\text{loss}} + \mathbf{R}_{\text{rec}} \]

Beam output power:

\[ P_{\text{out}} = \mathbf{w}^H \mathbf{R}_v \mathbf{w} \]
Array Beamforming

Beam output SNR:

\[ \text{SNR} = \frac{P_s}{P_n} = \frac{w^H R_s w}{w^H R_n w} \]

Maximum-SNR beamformer:

\[ R_n w = \lambda_{\text{max}} R_s w \]

Rank-one signal case:

\[ R_s = \sigma_s^2 d_s d_s^H \]
\[ w = R_n^{-1} d_s \]
\[ d_s = \text{Signal steering vector} \]

(Obtained by pointing the dish at a bright calibrator source)
Key Figure of Merit – Beam Sensitivity

\[
\frac{A_e}{T_{sys}} = \frac{k_B B}{S_{sig}} \text{SNR} \quad (\text{m}^2/\text{K})
\]

\[
\sim \frac{G}{T_{sys}}
\]

\[
= \frac{\eta_{rad} \eta_{ap} A_p}{T_{sky} + \eta_{rad} (1 - \eta_{sp}) T_g + (1 - \eta_{rad}) T_a + T_{min}/\eta_n}
\]

\[
\begin{array}{c}
T_{sp} \\
T_{loss} \\
T_{rec}
\end{array}
\]
Antenna Figures of Merit for Active Array Receivers

- What is the gain of this active array?
- …aperture efficiency?
- …radiation efficiency?
- …system noise temperature?
- Surprisingly, under the current IEEE Standard for Antenna Terms, none of these figures of merits are well defined for this antenna!

This general architecture includes:
- Active arrays
- Beamforming arrays
- Digital arrays
- MIMO eigenchannel
- MRI coil array
- etc.
Active array receivers include amplifiers, are nonreciprocal, and may include digital signal processing.

Some traditional antenna parameters cannot be used directly.

Directivity is ok – it’s a function purely of the pattern shape.

- Can be measured for any black box receiver that has an identifiable output signal for a wave arriving from a given direction.

Gain and aperture efficiency are not well defined for active arrays.

- Does an active array receiver with integrated signal amplification even have a radiation efficiency?
- With multiple array elements, how can the amplifiers and antenna elements be separated by a reference plane in order to define available signal power?
- What about digital arrays? How do we define gain and aperture efficiency when the output signal is a voltage waveform created using digital signal processing from samples of array outputs?
Active Receiving Arrays

- Available power is required to define aperture efficiency and gain
- The reference plane between array and electronics is multiport – how to define available power at array ports?
- The available power at the beam output includes amplifier gain, conversion loss, digital scale factors, etc.
- Scaling is essentially arbitrary
- How to normalize the beam output power in a meaningful way?
Existing Active Array Figures of Merit

- Receiving pattern directivity
- **Solid-beam efficiency**: ratio of the power received over a specified solid angle when illuminated isotropically by uncorrelated and unpolarized waves to the total received power (rarely used)
- **Embedded element efficiency**: measures the efficiency of a radiating element in a large array (long used in the classical array antenna literature)
- **Array gain or SNR gain**: ratio of array output SNR to SNR of a single sensor (commonly used by array signal processing community)
- “**Array efficiency**”: array gain divided by standard directivity [Jacobs, 1985] (important but obscure paper, cited only twice in Google scholar)
Array gain is equal to directivity for an active array with lossless elements if the reference sensor is taken to be an isotropic radiator and the external noise distribution is isotropic [Warnick & Jeffs, 2006]

This suggested a fundamental connection between figures of merit used in the antenna community and array gain, used by the signal processing community.

Basic principle: for a reciprocal antenna, the integral used to obtain total radiated power is essentially the same integral that gives the external noise power received from an isotropic noise distribution.

Since that realization, all key antenna terms have been extended to active receivers, including digital arrays, integrated amplifiers, nonreciprocal antennas, etc. – anything with an identifiable output port! [Warnick, Ivashina, Maaskant, Woestenburg, 2009, AP-S Antenna Standards Working Group, 2011]
**Fundamental Noise Theorem** of Array Receivers

By conservation of energy:

\[ A_{mn} = \int r^2 d\Omega \overline{E}_m \cdot \overline{E}_n^* \]

- Embedded element pattern overlap integral matrix
- Part of array mutual resistance matrix due to antenna losses
- Real part of array mutual impedance matrix

Twiss’s theorem:

\[ R_{t,iso}^{oc} = 8k_B T_0 B \text{Re}[Z_A] \]

Array noise response:

\[ R_{t,iso}^{oc} = 16k_B T_0 B A + 8k_B T_0 B R_{A,ohmic} \]

Relates array radiation properties (element patterns) and loss part of mutual impedance matrix to the array noise response
**New terms:**
- Isotropic noise response
- Active antenna available gain
- Active antenna available power
- Receiving efficiency
- Noise matching efficiency

**Updated terms:**
- Noise temperature of an antenna
- Effective area

**isotropic noise response.** For a receiving active array antenna, the noise power at the output of a formed beam with a noiseless receiver when in an environment with brightness temperature distribution that is independent of direction and in thermal equilibrium with the antenna.

**active antenna available gain.** For a receiving active array antenna, the ratio of the isotropic noise response to the power at the terminals of any passive antenna over the same bandwidth and in the same isotropic noise environment.

**active antenna available power.** For a receiving active array antenna, the power at the output of a formed beam divided by the active antenna available gain.

**2.251 noise temperature of an antenna.** The temperature of a resistor having an available thermal noise power per unit bandwidth equal to that at the antenna output at a specified frequency.

NOTES
1—Noise temperature of an antenna depends on its coupling to all noise sources in its environment, as well as noise generated within the antenna.
2—For an active antenna, the temperature of an isotropic thermal noise environment such that the isotropic noise response is equal to the noise power at the antenna output per unit bandwidth at a specified frequency.

**2.115 effective area (of an antenna) (in a given direction).** In a given direction, the ratio of the available power at the terminals of a receiving antenna to the power flux density of a plane wave incident on the antenna from that direction, the wave being polarization matched to the antenna. See: polarization match.

NOTES
1—If the direction is not specified, the direction of maximum radiation intensity is implied.
2—The effective area of an antenna in a given direction is equal to the square of the operating wavelength times its gain in that direction divided by 4π.
3—For an active antenna, available power is the active antenna available power.

**Receiving efficiency.** For a receiving active array antenna, the ratio of the isotropic noise response with noiseless antenna to the isotropic noise response, per unit bandwidth and at a specified frequency.

NOTE—Equivalent to radiation efficiency for a passive, reciprocal antenna.

**Noise matching efficiency.** For a receiving active array antenna, the ratio of the noise power contributed by receiver electronics at the output of a formed beam, with receivers impedance matched to the array elements for minimum noise, to the actual receiver electronics noise power at the formed beam output, per unit bandwidth and at a specified frequency.

The isotropic noise response of any antenna is the output noise power with the array immersed in a noise environment with angle-independent brightness temperature.

- The array is in thermal equilibrium with the environment.
- External noise and loss noise contributions only (does not include electronics noise).
- All powers are assumed to be over a specified system noise equivalent bandwidth $B$.

The equation for isotropic noise response is:

$$P_{t,iso} = P_{ext}[T(\Omega) = T_{iso}] + P_{loss}(T_{ant} = T_{iso})$$

where $T(\Omega) = T_{iso}$.
Active Antenna Available Gain

- Ratio of the isotropic noise response of the antenna under test to the isotropic noise response of a single-port passive antenna
- Includes all electronic amplification, receiver conversion loss, and digital scale factors

\[ G_{\text{rec}}^{\text{av}} = \frac{P_{t,\text{iso}}}{k_B T_{\text{iso}} B} \]

\( k_B = \text{Boltzmann's constant} \)
Effective Area

- When internal gain is normalized out properly, an active array antenna has a meaningful effective receiving area.
- Ratio of active array available signal power to the incident signal flux density.
- Defined as a note under the existing definition of effective area.

\[ A_e = \frac{P_{\text{sig, out}}}{G_{\text{rec}} S_{\text{sig}}} \]
An equivalent antenna temperature can be defined for any output power contribution:
- Total system noise
- External noise, spillover noise, sky noise
- Receiver noise
- Loss noise

Can be interpreted as the temperature of an isotropic external noise distribution such that the resulting output thermal noise power at the antenna port is equal to the output power term in question:
- i.e., power referred to a “perfect sky”, analogous to referring power in a network to equivalent power at the source

Allows a complex active array to have a well-defined noise figure:

\[ T_{sys} = T_{iso} \frac{P_{noise}}{P_{t,iso}} \]
Noise Matching Efficiency

- For active arrays, the effect of receiver electronics (LNAs, etc.) on SNR is harder to untangle from other effects than for a single-port antenna
- Numerator is the equivalent receiver noise temperature
- Denominator is the minimum receiver noise temperature that results when receivers are ideally noise matched to the array
- Measures the quality of the impedance match between array elements and receiver electronics
- Includes the effect of mismatch on signal coupling from the array output ports to receiver input ports and on amplifier noise figures
- **A new efficiency figure of merit for active arrays**

\[ \eta_n = \frac{T_{\text{rec}}}{T_{\text{min}}} \]

Matched to active impedances for minimum noise
Radiation and receiving efficiency:
- Transmitting antenna has a radiation efficiency (classical term)
- Receiving antenna has a receiving efficiency (new term)

Ratio of external noise power from an isotropic noise distribution to the sum of external noise and loss noise

Measures the noise added by ohmic, dielectric, and other losses in the antenna itself with a specific reference for the external noise (isotropic brightness temperature)

For a passive, reciprocal antenna, receiving efficiency is equal to radiation efficiency

\[ \eta_{\text{rec}} = \frac{P_{\text{ext,iso}}}{P_{t,\text{iso}}} = \frac{P_{\text{ext,iso}}}{P_{\text{ext,iso}} + P_{\text{loss}}(T_{\text{ant}} = T_{\text{iso}})} \]

\[ P_{\text{ext,iso}} = P_{\text{ext}}[T(\Omega) = T_{\text{iso}}] \]
Measurement Techniques

- All figures of merit require the isotropic noise response
- How can it be measured?
  - Full receiving pattern measurement: gives external part of isotropic noise response
  - Network analyzer: array mutual resistance matrix based on Twiss’s theorem
  - Free space Y factor method: gives external part of isotropic noise response

Hot source: \[ R_{\text{hot}} = \frac{T_{\text{hot}}}{T_{\text{iso}}} R_{\text{iso}} + R_{\text{rec}} + R_{\text{loss}} \]

Cold source: \[ R_{\text{cold}} = \frac{T_{\text{cold}}}{T_{\text{iso}}} R_{\text{iso}} + R_{\text{rec}} + R_{\text{loss}} \]

\[ R_{\text{iso}} = \frac{T_{\text{iso}}}{T_{\text{hot}} + T_{\text{cold}}} (R_{\text{hot}} - R_{\text{cold}}) \]

\[ R_{\text{rec}} + R_{\text{loss}} = \frac{T_{\text{hot}} R_{\text{cold}} - T_{\text{cold}} R_{\text{hot}}}{T_{\text{hot}} - T_{\text{cold}}} \]

How can we realize a very cold isotropic noise field?
The sky is quite cool at microwave frequencies...

Ground shield blocks thermal radiation from warm ground
When the source admittance is equal to the optimal admittance, there is an optimal compromise between signal power transfer and amplifier noise minimization, and SNR at the output is maximized.
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]:

- Source impedance determines equivalent receiver noise (SNR)
- Active impedances are related to the way amplifier forward and reverse noise waves couple through the array and combine at the beamformer output
- Scan angle dependent
- Equal to self impedances for an uncoupled array

\[ Z_{\text{act},n} = \frac{1}{w_{oc,n}^*} \sum_{m=1}^{M} w_{oc,m}^* Z_{mn} \]
Array Impedance Matching Strategies

- Build elements with isolated impedance 50Ω (suboptimal)
- Add a decoupling network so the impedance matrix is diagonal (lossy)
- Design LNAs so that the optimal source impedance is equal to the active impedance for one beam (boresight)

**Design the array to present matched active impedances to front end amplifiers and maximize sensitivity (G/T) over field of view**
  - 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) and spillover efficiency
Challenges:

Beamformer weights are required to compute efficiency and active impedances, but the weights are not known until the array is designed.

The antenna design optimization couples the full system – array, receivers, beamforming algorithm!
Mechanical Issues

- Manufacturability
- Robustness – solder joint failure
- Copper/gold plating for low loss and environmental passivation
  - Difficult to plate inside surfaces
- Moisture in coaxial lines
- Connectors
- Polarization balance

All these need to be factored into the design framework before optimization
Single-Polarized Array
Dual-Polarized Array
Passive and Active Return Loss

Center Element

Return Loss (dB)

Frequency (GHz)

- Isolated Measured
- Isolated Model
- S(1,1) Measured
- S(1,1) Model
- $\Gamma_{act,11}$ Measured
- $\Gamma_{act,11}$ Model
Noise Temperature and Sensitivity Figure of Merit

BYU Radio Astronomy Systems Research Group

~500 MHz 1 dB Sensitivity Bandwidth
Finished Dewar
Cryogenic PAF Front End
### Measured Receiver Sensitivity

<table>
<thead>
<tr>
<th></th>
<th>Modeled Tsys/Efficiency</th>
<th>Measured Tsys/Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temp PAF</td>
<td>68 K</td>
<td>87 K</td>
</tr>
<tr>
<td>Cryo PAF (May 2011)</td>
<td>31 K</td>
<td>49.6 K</td>
</tr>
</tbody>
</table>
| Green Bank Telescope L-band Single Pixel Feed | 29 K | |}

World record sensitivity for a phased array
Focal L-Band Array for Green Bank Telescope (FLAG)

**BYU Radio Astronomy Systems Research Group**

- **X Engine:**
  - Correlator/Beamformer, Spectrometer, Pulsar
  - Sample clock function gen and distribution

- **F Engine:**
  - Direct RF sampling, digital down conversion and FFT

Array aperture, Antenna elements, LNAs, Cryo system, Down converters

Signal Transport: Optical fiber and modems

Front End (GBT)

Back End (Jansky Lab)

- ROACH FPGA
- 20 port 10Gb Ethernet Switch Fujitsu XG2000 Series XFP
- Rack Mount PC
- 1 TB SATA RAID 0 Disk Array
- 1/2 existing

**Attached PCs:**
- System control and data storage

- (× 10)
- ADC 1 Gsps
- Ch. 1
- ROACH FPGA
- (existing)

- (× 40)
- ADC 1 Gsps
- Ch. 4
- ROACH FPGA
- (existing)

- (× 10)
- ADC 1 Gsps
- Ch. 40
- ROACH FPGA
- (existing)

- CX4 copper 10 Gb ethernet links

- Sample clock function gen and distribution

- (existing)

X Engine:
- Correlator/Beamformer, Spectrometer, Pulsar

Signal Transport:
- Optical fiber and modems

**Array aperture, Antenna elements, LNAs, Cryo system, Down converters**
Other Applications of Active Arrays

- High-efficiency steered-beam array feeds for satellite communications
- Magnetic resonance imaging (MRI) coil arrays
- Near Field MIMO arrays
- BYU Medical Imaging Facility
Conclusions

- Significant progress on large-dish phased array feeds around the world
  - U.S., Europe, China, Canada, Australia
  - Cryogenic PAFs, experimental campaigns, measured results
  - New designs in progress

- Major open issues
  - G/T minimization
  - Back end signal processing
  - Deploying a science-ready system including front end, signal transport, and back end

- Ongoing work:
  - Polarimetric array (dual polarization)
  - Phased array feeds for Green Bank Telescope, Arecibo Telescope, China FAST telescope
  - mm-wave phased array feed for GBT (with UMASS)
  - Square Kilometer Array (SKA) technology demonstrator instruments
  - Calibration and beamforming algorithms
  - RFI mitigation
  - Signal processing hardware and algorithms
  - Commercial satcom phased arrays