A Phased-Array Feed Demonstrator for Radio Telescopes

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Outline

- ▷ Motivation
- ▷ Experiments: What the demonstrator will be used for
- ▷ Implementation: Design and construction of PHAD
- ▷ Follow-up work

Motivation: Why a Phased-Array Feed?

Quantity	CLAR	Arecibo	GBT	EVLA	EVLA FPA
A_{eff} [$\times 10^3$ m^2]	50	24	5.5	7.3	7.3
T_{sys} [K]	30	30	20	30	30
# Beams	115	7	7	1	26
FoV [deg^2]	0.3	0.02	0.16	0.28	16
Freq. [GHz]	0.1–2	1.2–1.5	1.4–1.8	0.3–40	0.7
Mapping Time [s/mJy^2/deg^2/MHz]	6	360	380	113	11

Motivation: Why Do We Want a Phased-Array Feed?

- ▷ Radio telescopes have been typically single-pixel detectors
- ▷ With a phased-array feed can sample a large area of the focal plane (ie. more efficient use of aperture)
- ▷ With a large beamforming network can produce multiple overlapping beams on the sky ⇒ radio camera
- ▷ With a versatile beamformer, now have additional capabilities:
  - ▷ correct surface errors
  - ▷ correct aberrations
  - ▷ null interference
  - ▷ variable-profile beam for LAR

Motivation: Prior Art

- ▷ Two groups have done initial phased-array feed experiments
  - ▷ Fisher & Bradley at NRAO Green Bank
  - ▷ Ivashina & Bregman at ASTRON
- ▷ Both used special-purpose arrays with limited time on a telescope
- ▷ Need to build upon that pioneering work ⇒ Phased Array Feed Demonstrator (PHAD)

PHAD Design Principles

- Engineering demonstrator, but as similar as possible to a science-capable system
  - Follow a development path that is direct to ultimate goal, avoiding blind alleys
  - Tackle practical issues of phased-array feeds (shielding, etc.)
- Maintain versatility throughout system for diagnostics and experimentation
  - Data storage for off-line diagnostics and experimentation
  - Real-time beamforming
  - Modular for experimentation and upgrading
- Demonstrate and explore the capabilities of phased-array feeds

PHAD Team

- ▷ Bruce Veidt (RF/Antennas)
- ▷ Gary Hovey (Digital Systems, formerly with ACSIS)
- ▷ Tom Burgess (Digital, formerly with ACSIS)
- ▷ Gordon Lacy (Mechanical, expert with composites)
- ▷ Sean Dougherty (Scientist)
- ▷ Peter Dewdney (Group Leader)

- ▷ Walter Brisken (NRAO)
- ▷ Christophe Craeye (UCL)

Experiments

- Calibration
- Detect satellites
- Detect astronomical sources
- Measure aperture efficiency
- Deep integration of weak sources
- Optimal beamforming
- Cancellation of spillover
- Correct off-axis aberrations
- Measure instrumental polarization
- Correct polarization errors
- Beamforming with failed elements
- Interference mitigation
- Null feed-strut scattering

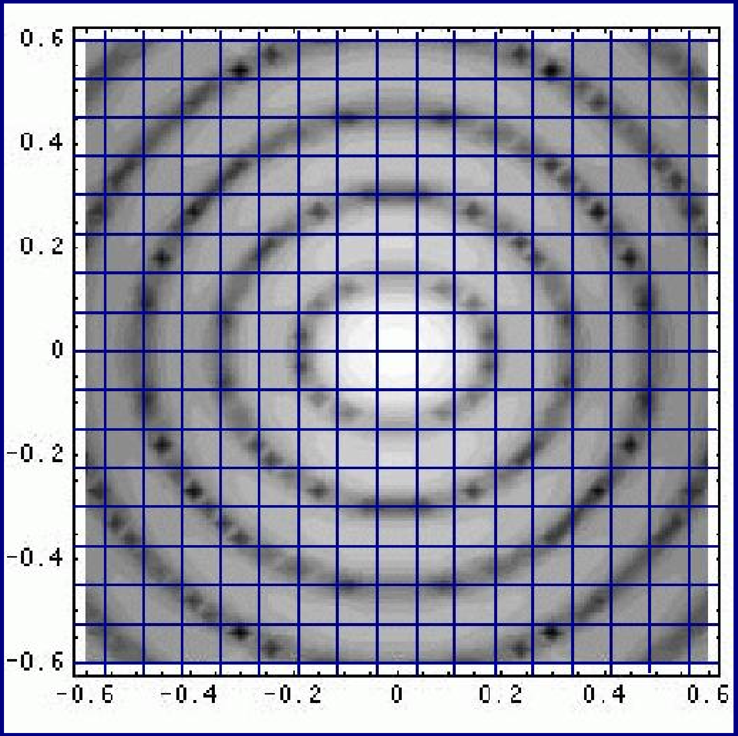
Implementation

- Will be an engineering (not science) demonstrator
  - modest sensitivity $T_{sys} \sim$ 50–100K
  - modest bandwidth $\sim$ 1 MHz
  - several hundred active elements
  - dual-polarized
- Store data for off-line beamforming
- Capable of realtime beamforming with FPGAs
- 1–2 GHz
- Use prime-focus reflector antenna (DRAO 26-m)

Implementation: Reflector Antenna

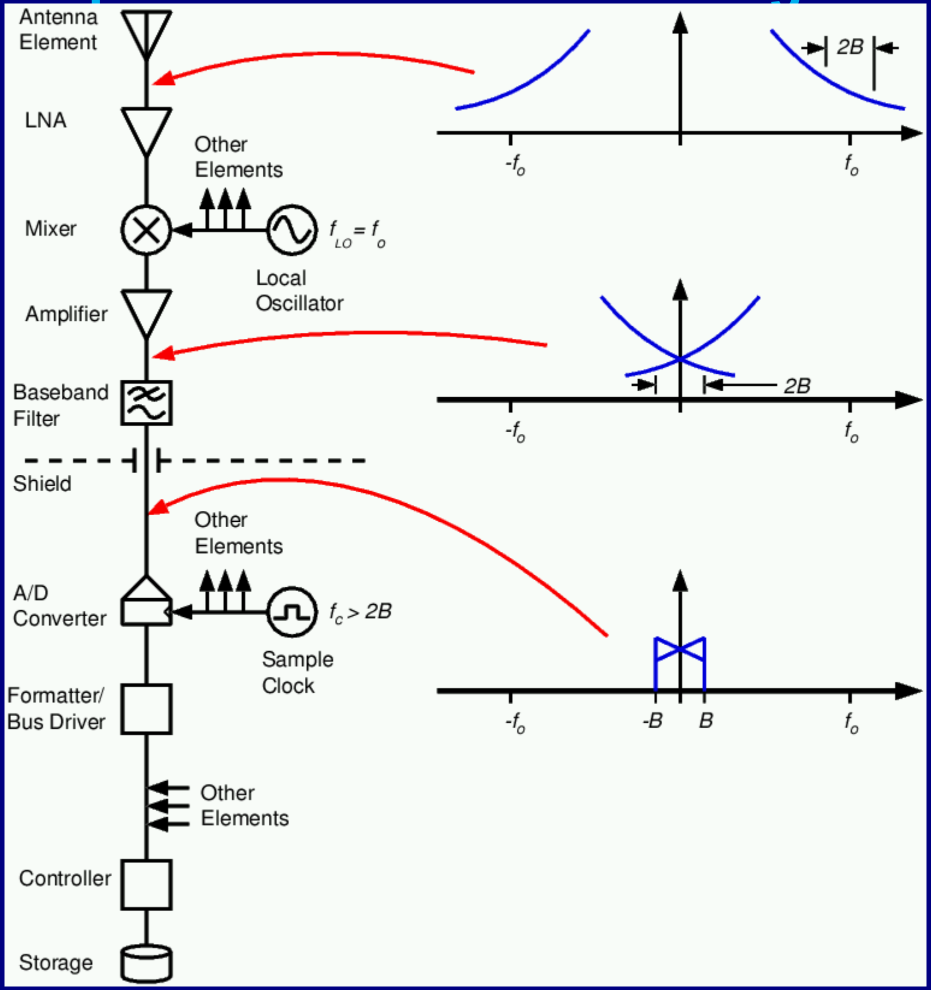
- ▷ 25.6 metre diameter
- ▷ $f/D = 0.3$
- ▷ Spillover angle = 80°
- ▷ Surface-scattering efficiency rolls off ~ 2 GHz

Implementation: Focal-Plane Fields



- ▷ GRASP calculation of 26-m dish
- ▷ At 1 GHz
- ▷ Grid represents Vivaldi array
- ▷ Element spacing $= \lambda/4$

Implementation: Block Diagram



Implementation: Sensitivity Calculations

$B \sim 10^6$ Hz

$\tau \sim 1$ s

$T_{sys} \sim 100$K

$A_e \sim 260$ m^2

$$\Delta T = \frac{K_s T_{sys}}{\sqrt{B\tau}} = 0.1\text{K}$$

$$\Delta S = \frac{2k_B}{A_e}\frac{K_s T_{sys}}{\sqrt{B\tau}} = 1\text{Jy}$$

Source	Flux	DR
CasA	3100 Jy	35 dB
CygA	2200	33
3C295	29	15
3C48	21	13
3C286	17	12

Implementation: System Gain

- ▷ $P = k_B T B$
- ▷ $T = 300\text{K}$
- ▷ $B = 10^6\ \text{Hz}$
- ▷ $P = -114\ \text{dBm}$
- ▷ $P_{A/D} = +12\ \text{dBm}$
- ▷ $G = 12 + 114 = 126\ \text{dB}$

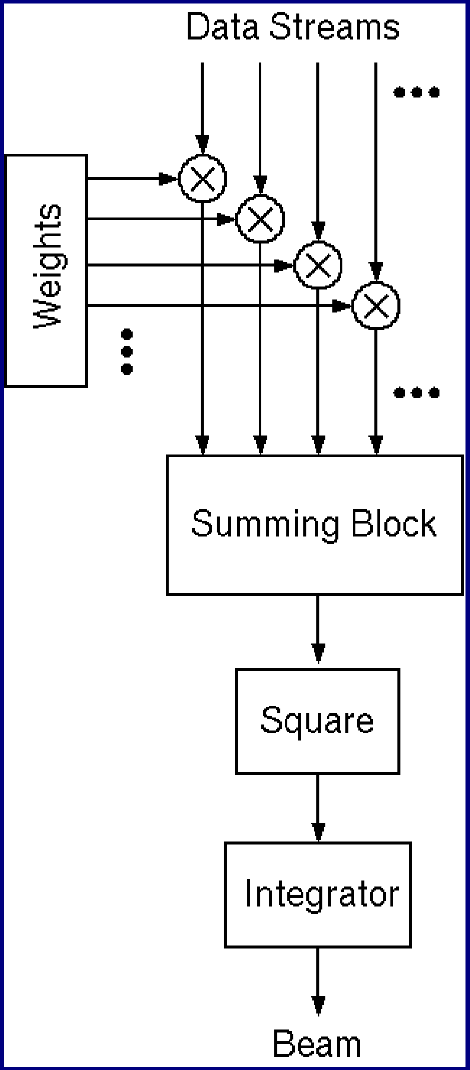
Implementation: Data Rate

▷ $D = 2BNQ$

▷ $D = 2 \times 10^6 \times 200 \times 8 = 3.2 \times 10^9$ b/s $=$ 400 MB/s

▷ 1.5 seconds of data will fill a CD!

Implementation: Data Processing

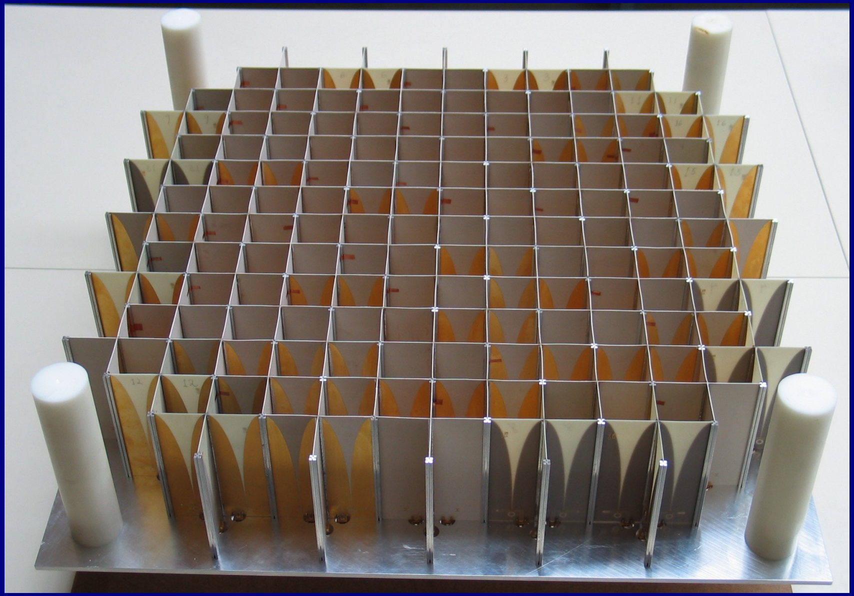


- ▷ OCTAVE simulation using complex random numbers
- ▷ 1.6 GHz AMD CPU with 512 MB RAM
- ▷ 5×10^4 samples in 0.6 seconds
- ▷ Equivalent to 0.05 second observation
- ▷ Longer observations easily handled with data partition

Implementation: Antenna Array

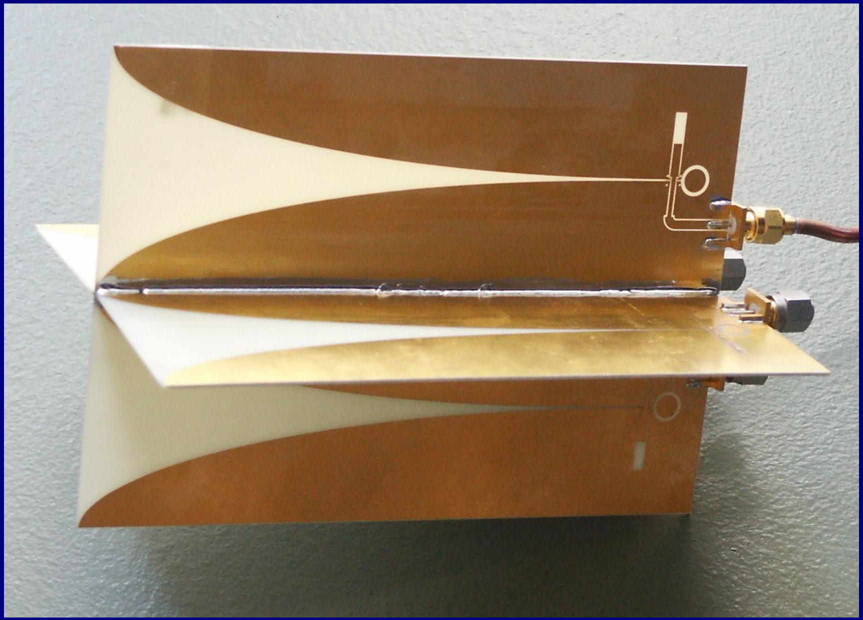
- ▷ Nearly universal agreement that Vivaldi is best for arrays
- ▷ Element spacings from $\lambda/10$ to $\lambda/2$ (conventional) or to λ (high f/D)
- ▷ Ed Reid's PhD thesis project (University of Alberta)
  - ▷ element design
  - ▷ loss analysis
  - ▷ weight reduction
  - ▷ slot-line to coax transition
  - ▷ fabrication/assembly techniques

Implementation: Antenna Array



- ▷ 1.8–6 GHz
- ▷ $\lambda/2$ spacing at 3 GHz
- ▷ minimum spacing $= \lambda/3$
- ▷ 742 mm × 742 mm
- ▷ 340 elements
- ▷ Scale design to 1–2 GHz

Implementation: Antenna Element

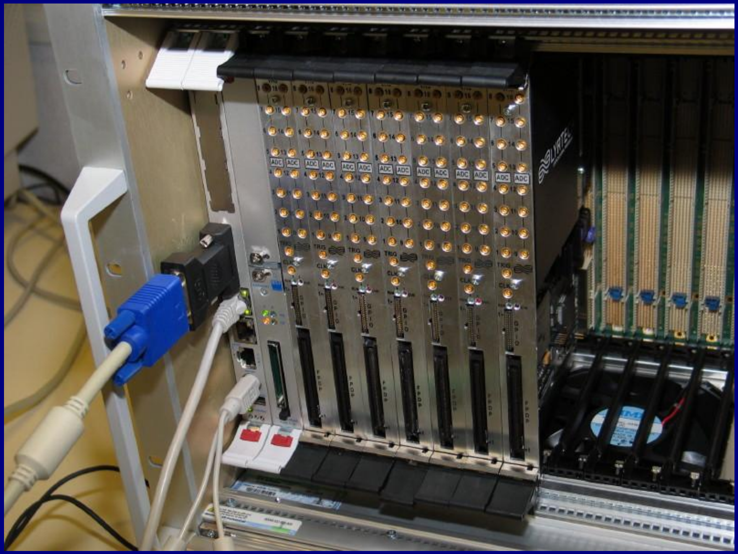


- ▷ Note slotline-to-CPW transition
- ▷ Note modularity
  - ▷ easily replace passive elements with active elements

Implementation: Receivers

- ▷ LNAs
  - ▷ Agilent ATF-34143 HEMT ⇒ NF ∼ 0.5 dB (35K) but more complex circuit
  - ▷ Maxim or Agilent LNA chip ⇒ NF ∼ 1 dB (70K) less complex circuit
- ▷ Receivers
  - ▷ select one of many “receivers on a chip”
  - ▷ decision on degree of complexity on-chip (eg. PLL on-chip?)
  - ▷ DSB or SSB?
- ▷ Low parts-count, low cost

Implementation: Signal Processor



Lyrtech (`www.lyrtech.com`)

- ▷ 105 MS/s @ 14-bits
- ▷ 16 channels/card
- ▷ 128 MB RAM per card ⇒ 1 MHz BW for 4 sec
- ▷ One Xilinx Vertex-II FPGA per card
- ▷ Matlab/Simulink programming interface
- ▷ Goal to have 192 channels

Implementation: Shielding

- ▷ We will have digital electronics in close proximity to array elements and to sensitive receivers
- ▷ Critical to reduce self-generated interference to very-low levels
- ▷ Also need to minimize RF cross-talk between elements
- ▷ We don’t know the levels yet
- ▷ Attack the problem experimentally with a subset of prototype receiver elements

Development Beyond PHAD

- PHAD will not be sensitive enough or have sufficient bandwidth for radio astronomy
- Also concerned about fabricating and packaging large number of receiver components
- Can an array be made light enough for an LAR focal package?

Low-Mass Vivaldi Array

- ▷ New mechanical engineer that is an expert in fabrication of composite structures (Gordon Lacy)
- ▷ Use Vivaldi substrate (0.25 mm) as a structural element
- ▷ Bond PCB together with conductive epoxy
- ▷ Solid PCB backplane
- ▷ Estimate 22 kg/m^2 including antenna, LNA, and support frame
- ▷ Need to fabricate prototypes to verify feasibility

Low-Noise Ambient Temperature LNAs

- University of Calgary Electrical Engineering
- Leonid Belostotski (PhD Candidate) & Prof. Jim Haslett
- Goal to develop room temperature IC LNAs
  - use new materials such as SiGe
  - take advantage of CMOS scaling to smaller feature size and higher f_T
  - circuit design methods (eg. discovery of error in Shaeffer & Lee's CMOS noise equations has led to a new set of noise optimizations)

Integrated Receiver/Optical Transmitter Modules

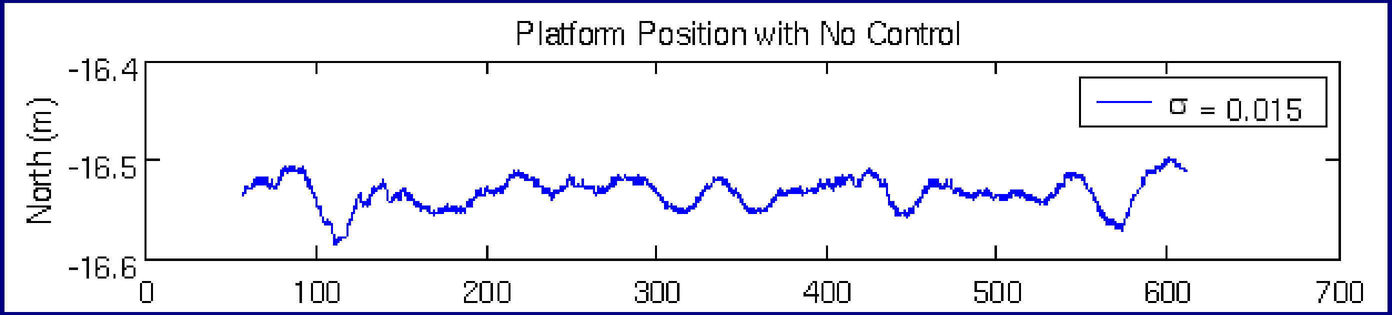
- ▷ Contract with BreconRidge Manufacturing Solutions (Ottawa)
- ▷ BreconRidge specializes in RF/optical communications systems design and fabrication
- ▷ Reality check on LAR data communications requirements
- ▷ Looking at signal chain from the output of the LNA to the input of the beamformer on the ground
- ▷ Four-phase work plan:

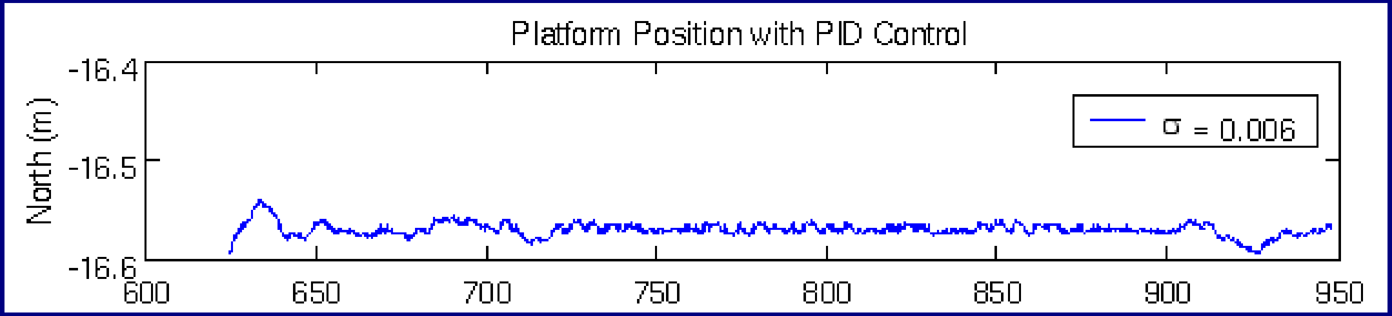
1. System architecture ⇒ no show stoppers
2. Critical subsystems and components ⇐ Just awarded
3. LAR system performance analysis
4. LAR mechanical concept

Conclusions

- Have described a Phased-Array Feed Demonstrator (PHAD)
- PHAD is an engineering demonstrator to explore design problems associated with phased-array feeds
- PHAD will also demonstrate the capabilities of phased-array feeds
- Have a development path with external collaborators leading to astronomy-capable systems

Bonus: Airborne Platform Stability with Active Control





- ▷ Platform at ∼170 m
- ▷ Wind speed ∼3.5 m/s
- ▷ $\sigma \simeq \sigma_{GPS}$

(DRAO LAR Group and McGill University—Nahon & Lambert)