High-Performance PAFs with CMOS LNAs

B. Veidt[1], L. Belostotski[2], T. Burgess[1], A. Beaulieu[2], J. W. Haslett[2]

[1]NRC Herzberg Astronomy and Astrophysics
Penticton, BC, Canada
[2]University of Calgary, Calgary, AB, Canada

PAF Workshop, Cagliari, 24–26 August 2016

National Research Council Canada
Conseil national de recherches Canada

Advanced Focal Array Demonstrator (AFAD) Project

- Purpose is to explore noise reduction in room-temperature L-band PAFs
  - custom low-noise LNA ICs
  - antenna structures to minimize loss
- Initial array had 41 elements with Avago LNA ICs
- Replacement of central 9 elements with elements using CMOS LNAs produced excellent results
- AFAD-C project
  - larger array $\sim$96 elements
  - all elements with CMOS LNAs
  - improved single-piece element
  - digital beamformer
  - testing on DVA-1 offset Gregorian reflector antennas

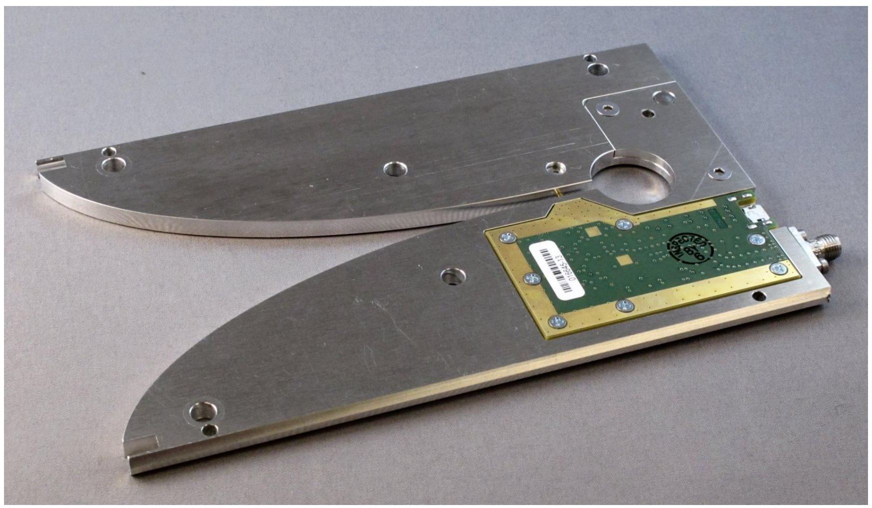
Key Parameters

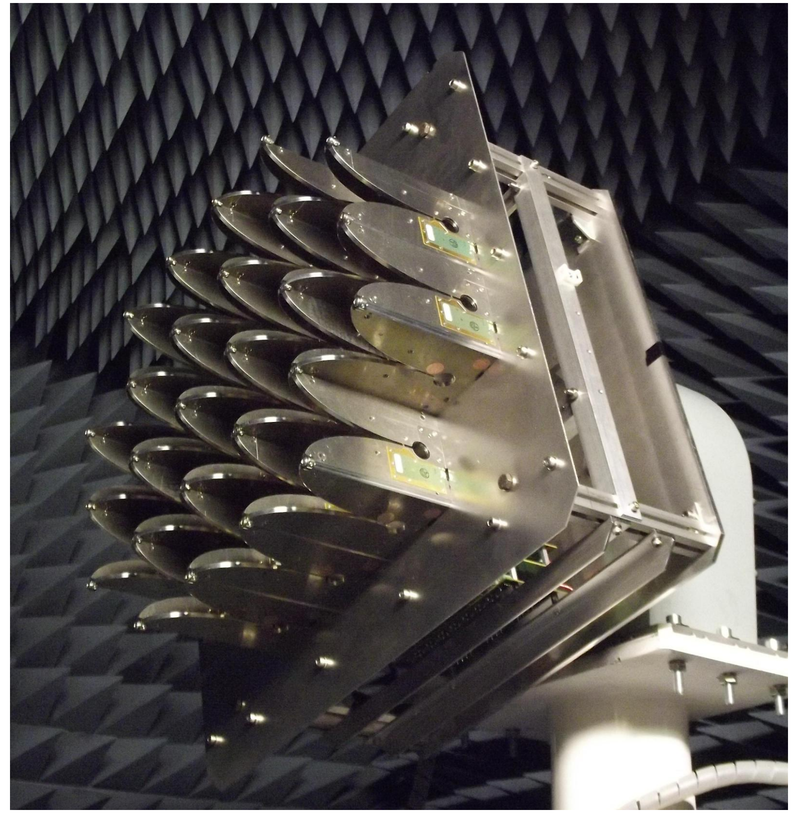
Frequency Range	0.7–1.5 GHz
Element Spacing	100 mm ($\lambda_{min}/2$)
Element Thickness	5 mm
Taper Length	113 mm
Slot Width	3 mm
Overall Length	158 mm
Element Mass	165 g

Focus on Reducing Noise in PAFs

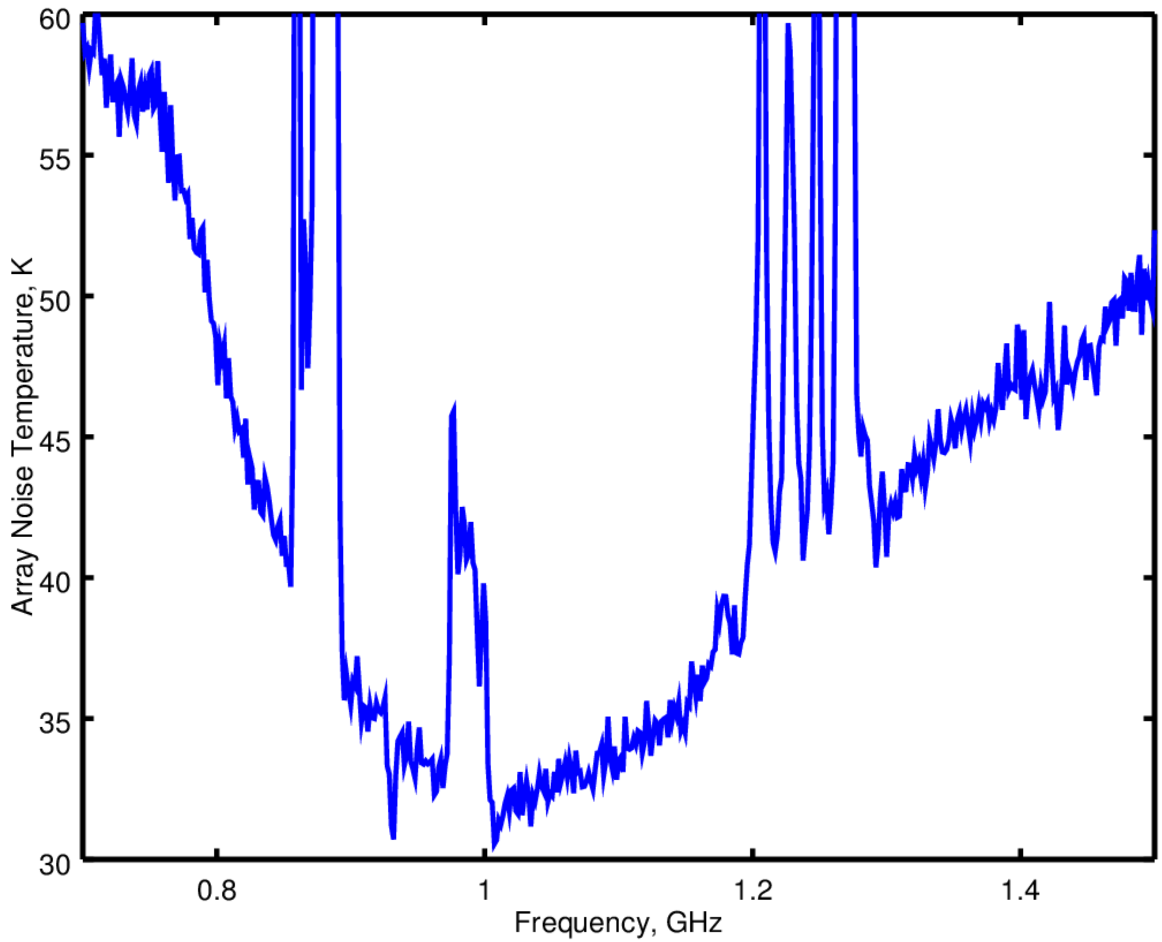
- Phased-array feeds seen as a way to expand the field-of-view of telescopes such as the Square Kilometre Array, Arecibo, ASKAP, and WSRT
- Work by various groups has shown that $T_{array} > T_{min}$
- Even PAFs using cryogenic LNAs have noise ∼36K (see Cortés-Medellin, *et al.*, IEEE Trans. AP, 2015)
- Are there ways to reduce the loss between the incoming radiation and the LNA input?
  - Make the element thick (3D) to spread surface currents over a larger area
  - This allows significant reductions in the amount of dielectric used
  - Allows LNA to be placed at feed point
- Other speakers will address cryogenic solutions

AFAD Element and Array

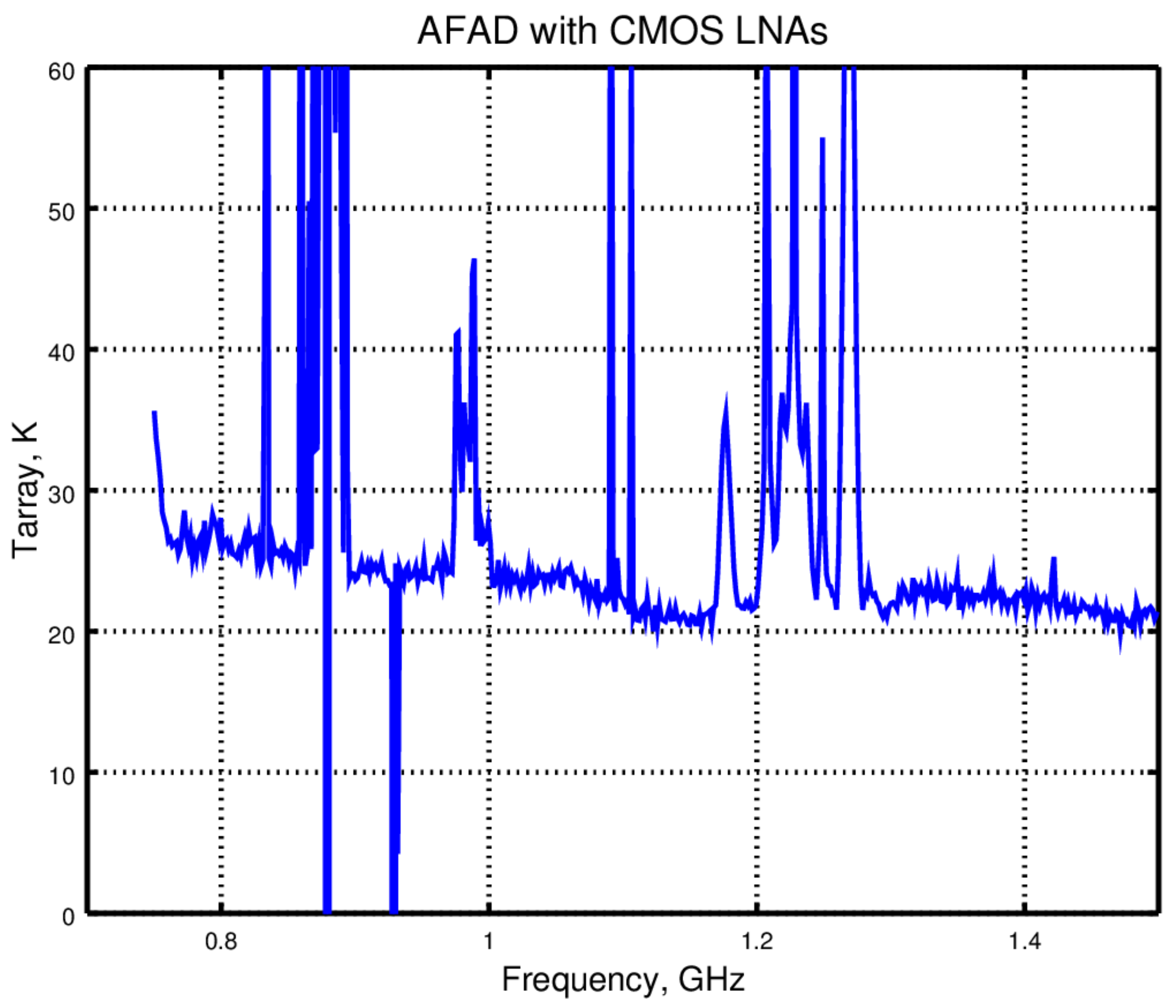




Results with Avago (MGA 16516) LNA IC



Results with UofC CMOS LNA



How These Measurements Were Made

Base	2 m $\times$ 2 m
Opening	4.1 m $\times$ 4.1 m
Height	2.3 m

Noise Calculations

- Y-Factor

$$T_{array} = \frac{T_H - YT_C}{Y - 1}$$

- Uncertainities
  - $Y \sim 10 \rightarrow$ error from T_H is negligible
  - $\Delta Y < 0.3$ dB $\rightarrow Y_{ratio} \sim 10 \pm 0.7 \rightarrow \Delta T_{array} \sim \pm 2$K

- T_C estimate

$$\begin{array}{ccccccc} T_C & = & T_{CMB} & + & T_{atm} & + & T_{gal} \\ & & \uparrow & & \uparrow & & \uparrow \\ & & 2.7 & & 2 \pm 1 & & \mathrm{GSM} \pm 16\% \end{array}$$

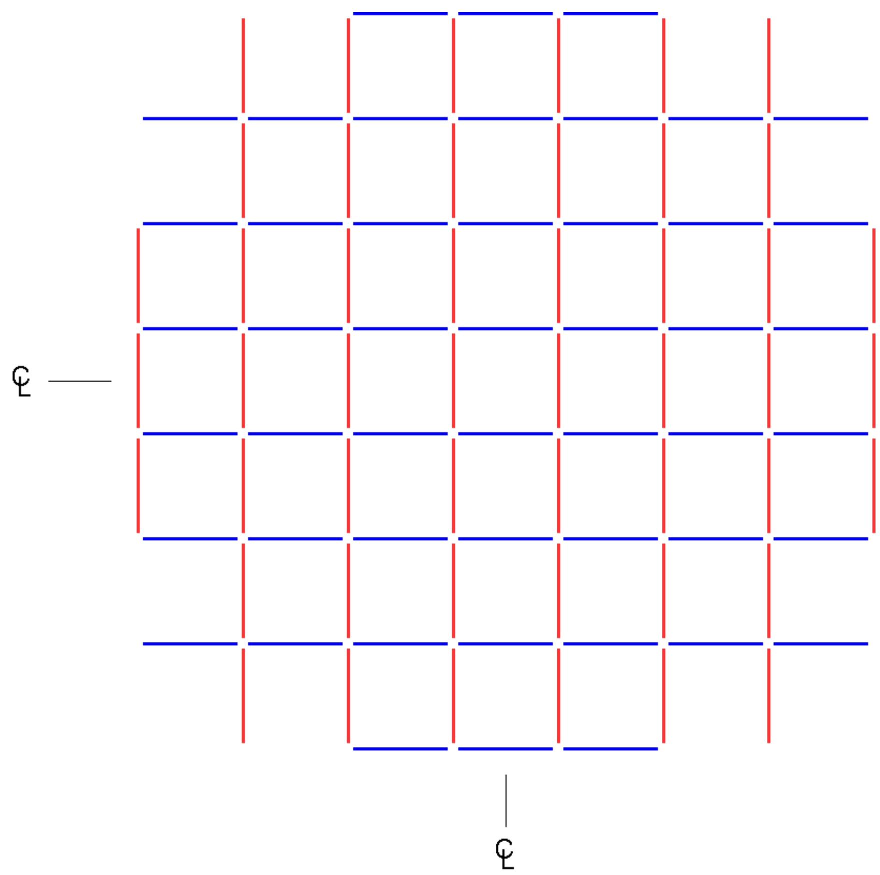
- Overall

$$\Delta T_{array} = \sqrt{1^2 + 1.5^2 + 2^2} = 2.7\text{K}$$

Comments

- New results are a motivation to make a large array with all CMOS LNAs
  - $\sim$ 96 elements
  - suitable for multi-beam operation on a dish
- Two factors in the difference in performance
  - Inherent device performance (GaAs vs CMOS)
  - Circuit design
    - Avago LNA used conventional non-array design
    - CMOS LNA was designed as part of an array

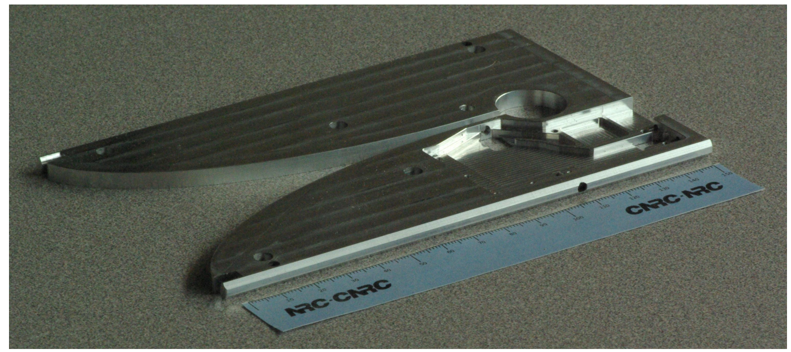
Possible 96-Element Array Configuration



Refinement of Element Fabrication

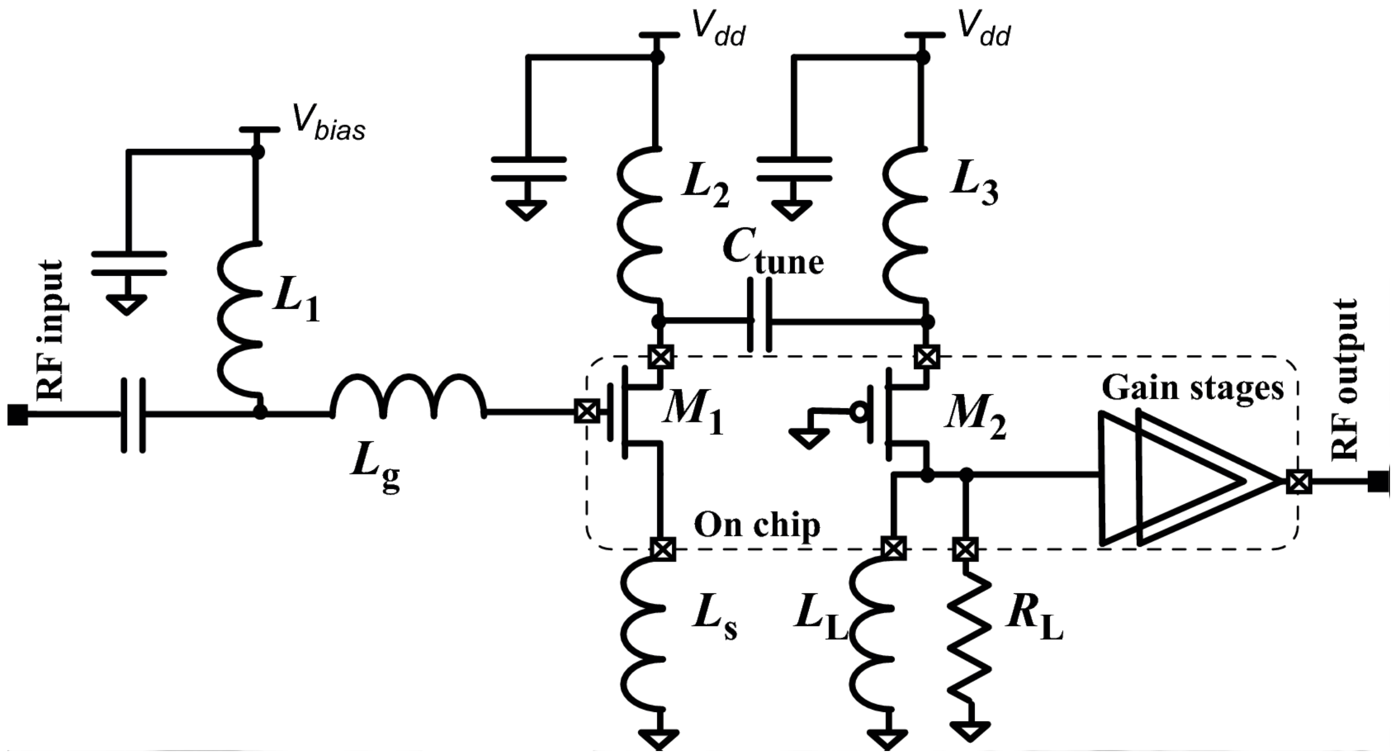
- Original 2-piece mechanical design
  - required several alignment jigs in fabrication
  - additional machining steps for overlap joint
  - pin + screws

New 1-Piece Element



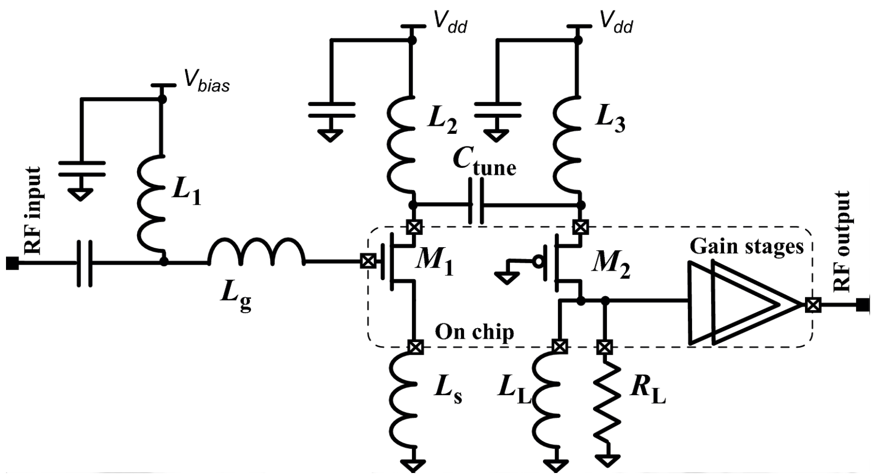
- ▷ 2-piece design was driven by difficulty of drilling probe pin holes at the centre
- ▷ Custom tooling eliminates this problem
- ▷ Similar to original proof-of-concept by Craeye and Sarkis!

LNA IC Simplified Circuit Diagram



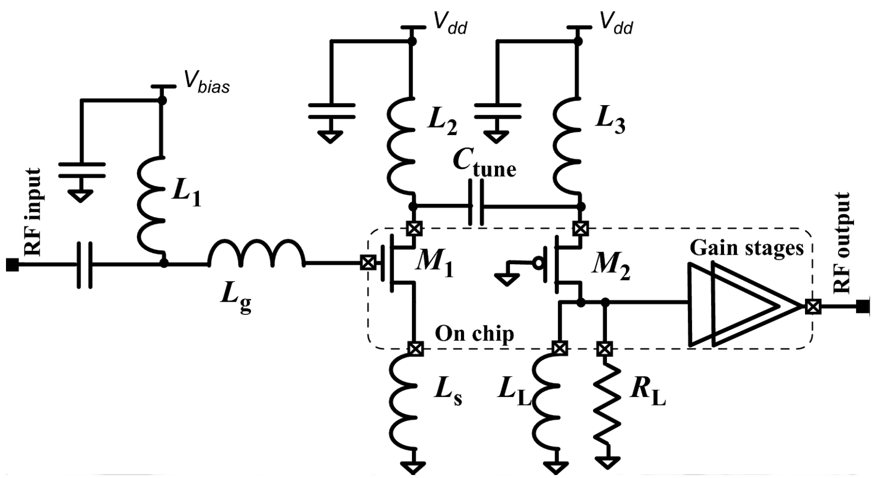
$$L_g = 14 \text{ nH}$$
$$L_s = \sim 1 \text{ nH}$$
$$C_{tune} = 5.6 \text{ pF}$$

Conventional (No Array) Design



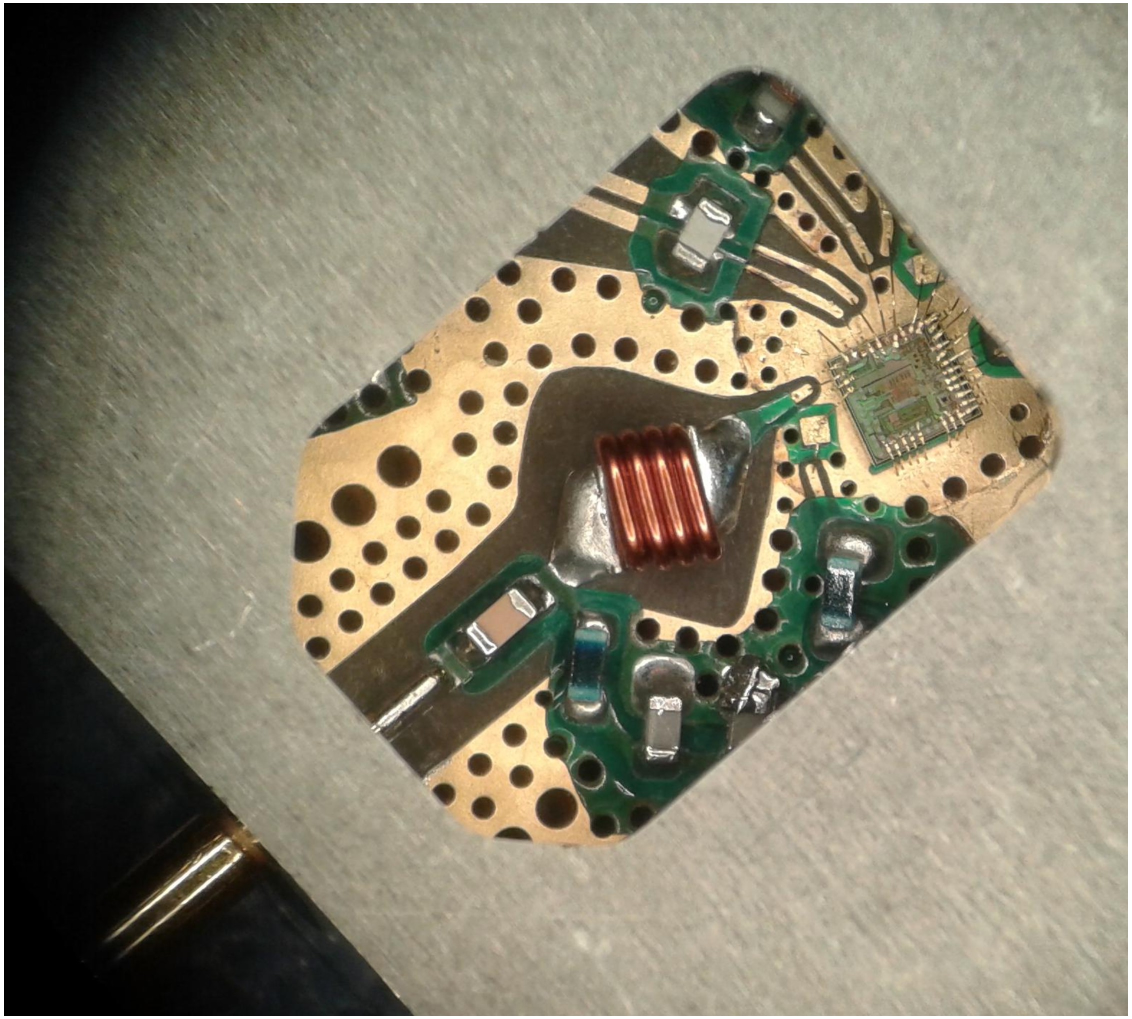
- ▷ Want power match $\simeq$ noise match
- ▷ But $S_{11}^* \neq \Gamma_{opt}$ for M_1
- ▷ Tune with L_g and L_s
  - ▷ feedback through L_s increases real part of Z_{in}
  - ▷ resonate at f_{upper} where T_{min} is highest

Next Level



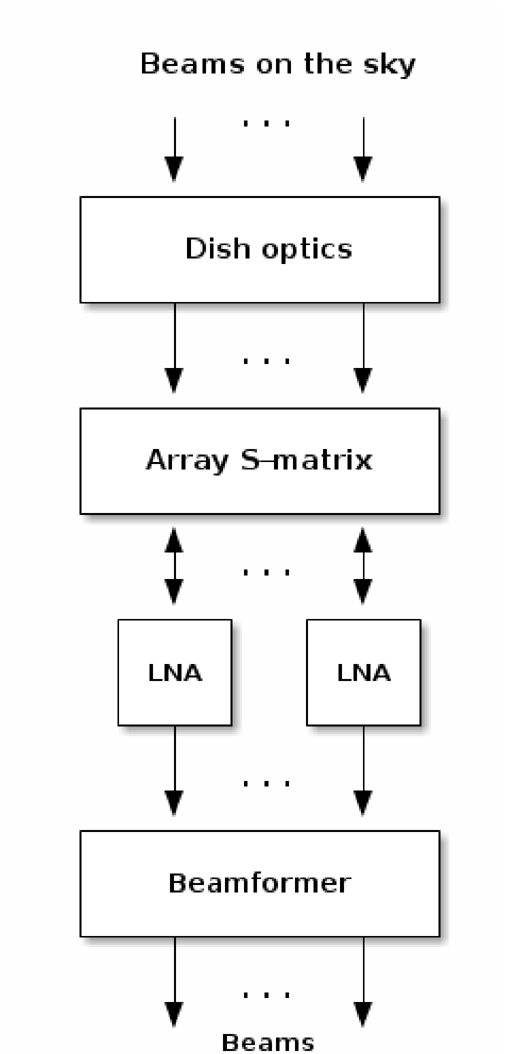
- ▷ Add C_{tune}
- ▷ Changing C_{tune} changes real part of Z_{in} of LNA but **not** Γ_{opt}
- ▷ C_{tune} provides power match in the lower part of the band

What the CMOS LNA Looks Like



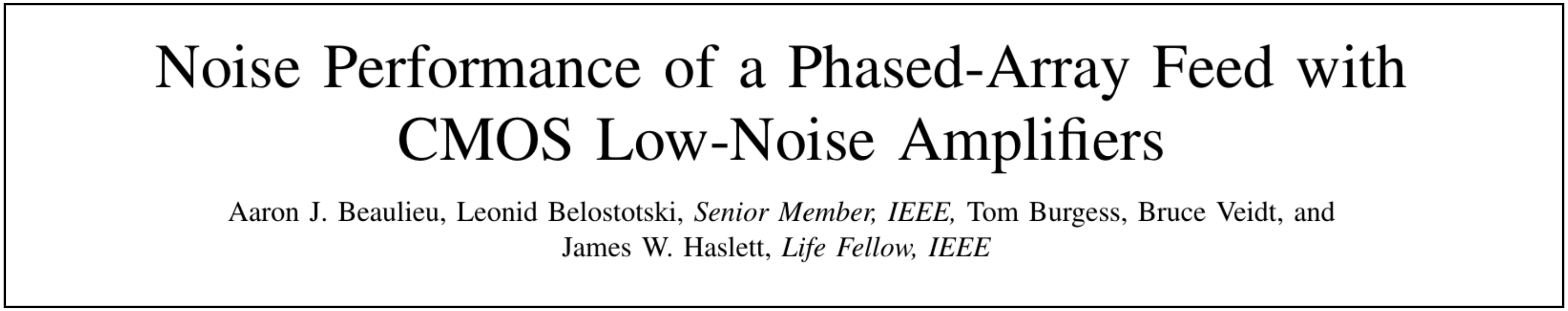
[From Beaulieu *et al.*, AWPL, 2016]

LNA Matching Problem for Arrays



- ▷ Noise emitted from LNA input coupled to other LNAs
- ▷ coupling described by the array S-matrix
- ▷ leads to active noise match
- ▷ but dependent upon beamformer weights
- ▷ weights dependent upon beams on the sky

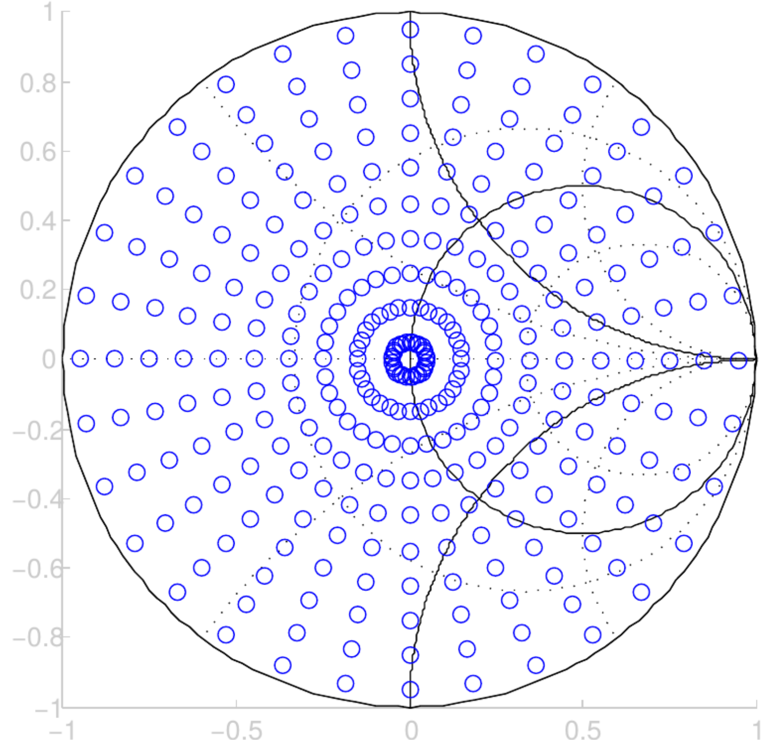
Simplifications in This Design



[IEEE AWPL, early access]

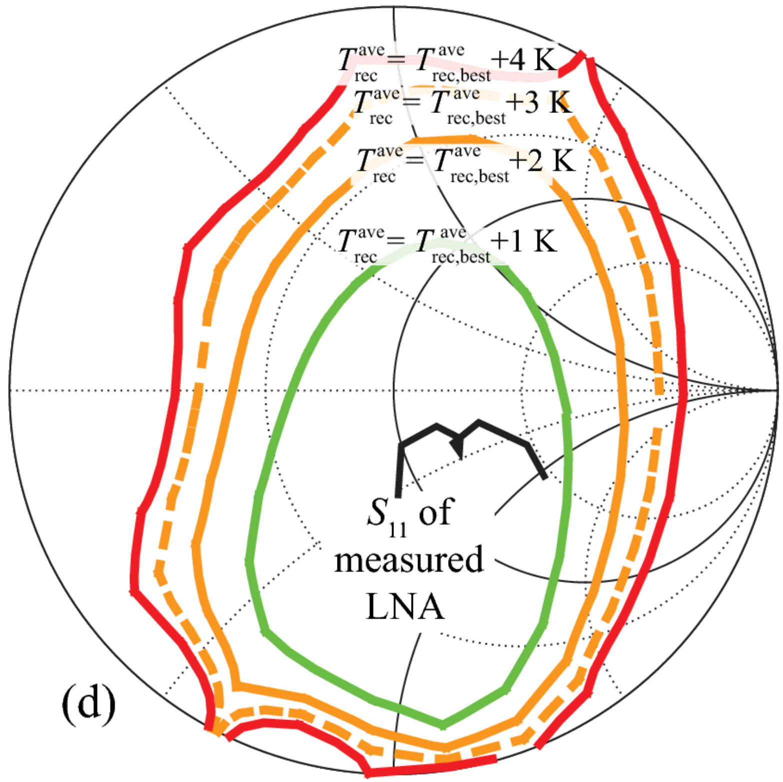
- Uniform and tapered weights for central 3×3 co-pol elements
  - no variable placement of focal spot on array
  - no variation of focal spot size as a function of frequency
- Don't consider the case of elements shared between beams

Constellation of S_{11} points



- ▷ Initially assume LNA can present any passive S_{11}
  - ▷ map out noise performance as a function of S_{11} at each frequency
- ▷ Later constrain by S_{11} for actual components

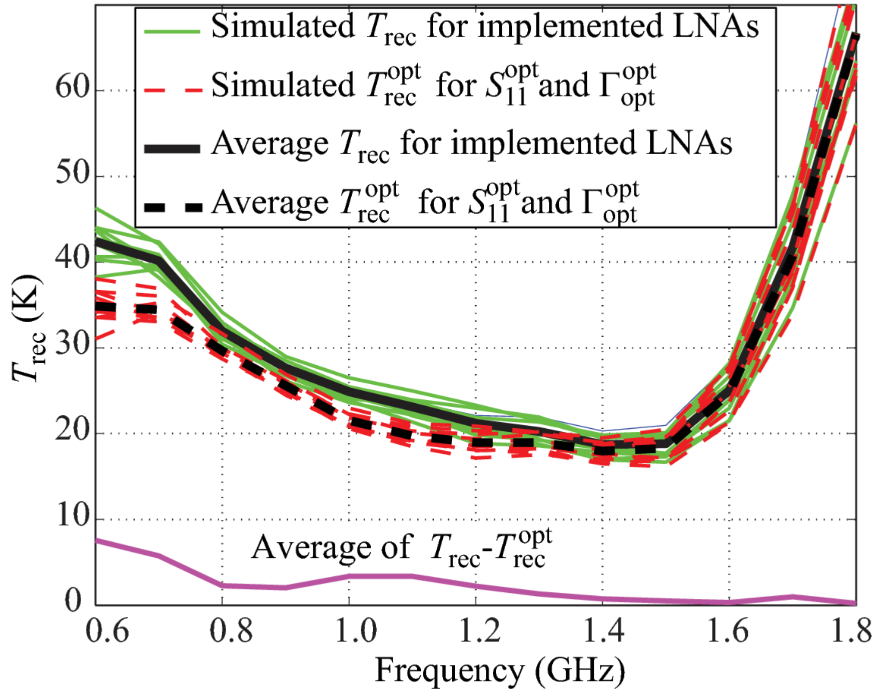
Average Beam-Equivalent Noise Temperature



[From Beaulieu *et al.*, AWPL, 2016]

▷ Averaged over 0.7–1.5 GHz

Noise Temperature Compared with Optimal Case



[From Beaulieu *et al*., AWPL, 2016]

- ▷ For 11 LNAs
- ▷ $\left|S_{11}^{opt}\right| \rightarrow 1$ but not a practical implementation
- ▷ Small penalty for actual S_{11}

Refined Design Process

2508 IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 63, NO. 6, JUNE 2015

Low-Noise Amplifier Design Considerations For Use in Antenna Arrays

Leonid Belostotski, *Senior Member, IEEE*, Bruce Veidt, Karl F. Warnick, *Fellow, IEEE*, and Arjuna Madanayake, *Member, IEEE*

- ▷ Addresses the problem of design when beamformer weights are unknown (usual case)
- ▷ Looked at numerous design methods for LNAs embedded in arrays and compared with optimal result
- ▷ Set LNA Γ_{opt} near average passive array reflection coefficient
- ▷ Set LNA $|S_{11}|$ as large as possible (effect is important for cases with high coupling)

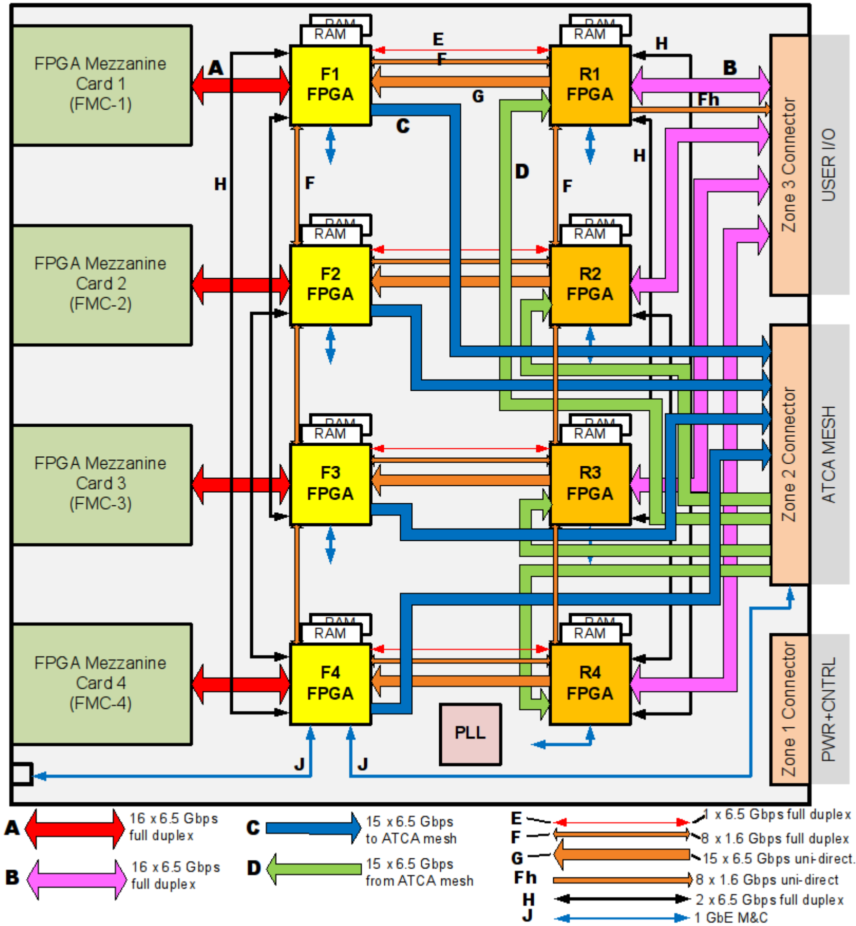
Digital Beamformer

- Digital beamformer much more versatile than an analog BF
  - more elements
  - frequency channels
  - arbitrary weights
- Measure PAF performance in aperture-array mode.
- Measure PAF performance on an offset Gregorian dish.
  - compare with AA results
- Measure PAF performance as a function of the number of bits
- Measure PAF performance as a function of the filter bank channel width
- Explore update rate of the array covariance matrix calculation

Beamformer Specifications

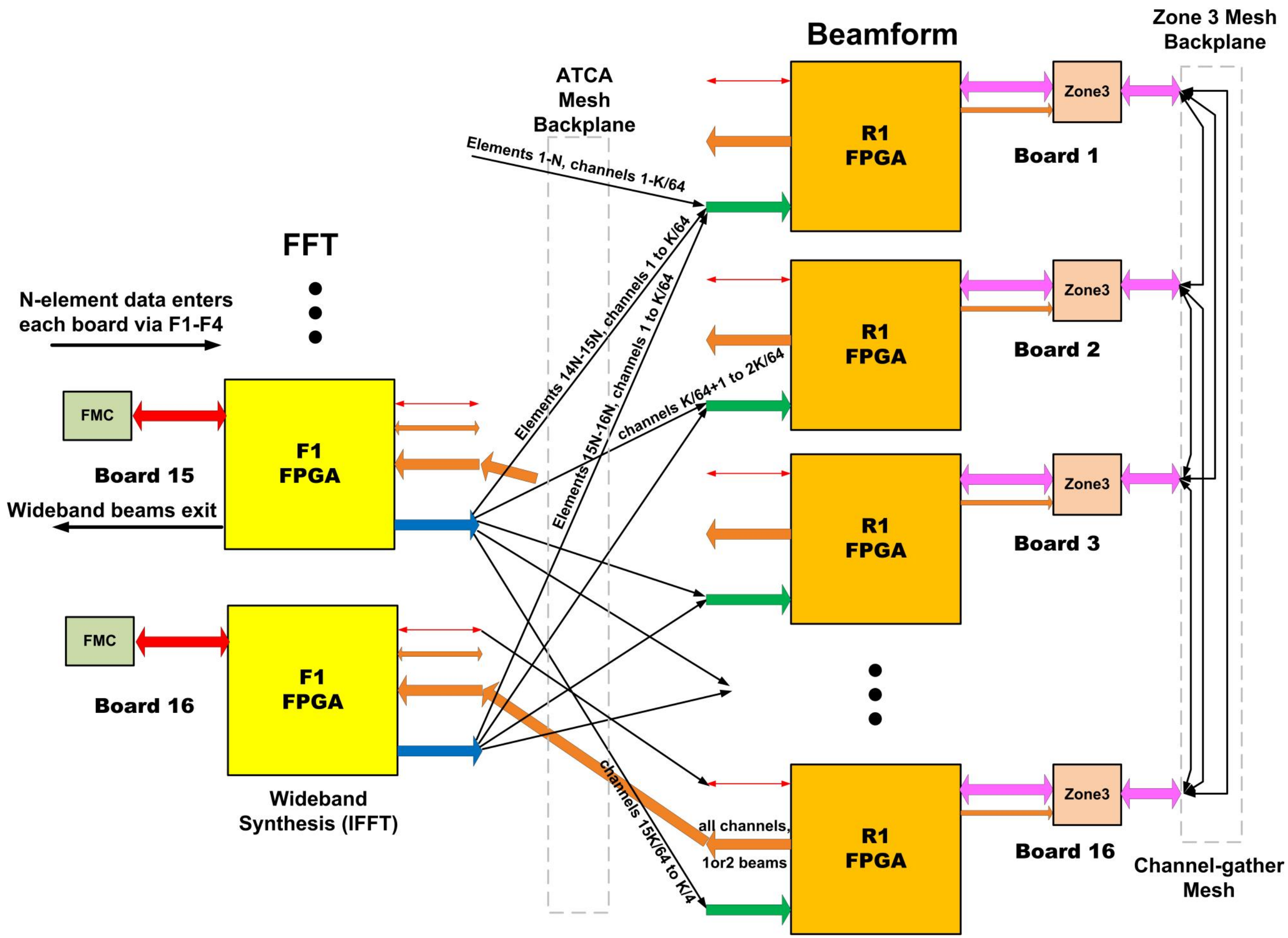
- f_{in}= 750 to 1500 MHz (no frequency conversion in front end)
- RF bandwidth: at least 300 MHz
- filter bank channel width: nominally 1 MHz but adjustable
- number of elements: $\sim$ 100 total
- number of output beams: at least 1 per polarization
- scalar beamforming (i.e. use only one polarization per beam)
- number of ADC bits: at least 8 but adjustable downwards
- array covariance matrix calculation update rate not known
- location: to be determined (behind array or on ground next to pedestal)

Digital Beamformer Implementation



- ▷ DRAO-developed Kermode board
- ▷ Eight × Xilinx Virtex-6 SX475T FPGAs per board
- ▷ Four × mezzanine cards
- ▷ Uses ATCA form-factor and backplane
- ▷ Developed in collaboration with Lyrtech (now Nutaq)
- ▷ Nutaq developed board firmware development kit

Digital Beamformer Implementation



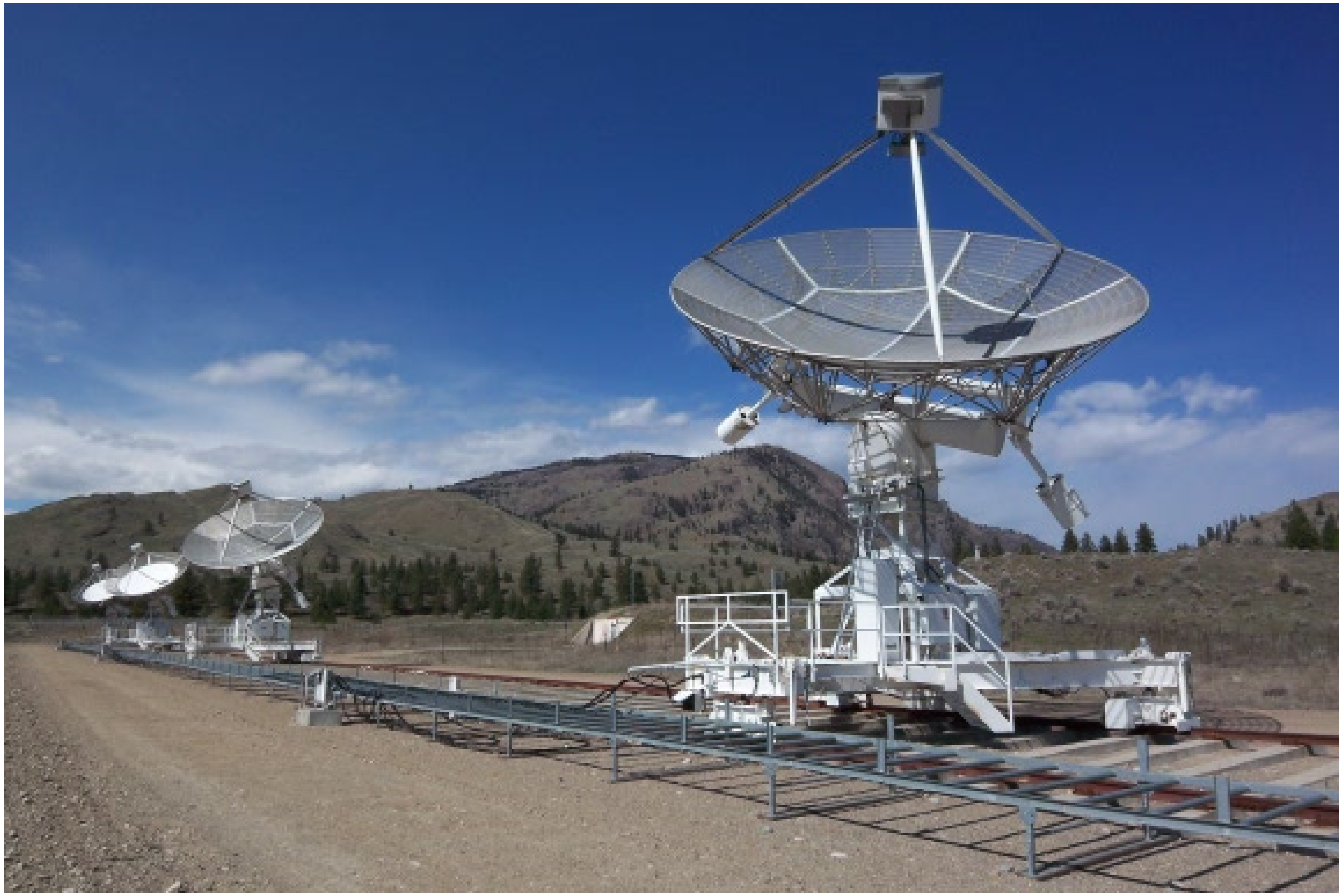
Status

- ▷ 100+ one-piece Vivaldi elements have been fabricated
- ▷ 100 LNA boards have been fabricated (SMT + wirebond components) and installed in elements
- ▷ Backplane and support structure components have been fabricated; need to be assembled
- ▷ 4×4 analog BF and bias supply units being layed out
- ▷ Kermode boards being fabricated

References

- Beaulieu, Belostotski, Burgess, Veidt, & Haslett, "Noise Performance of a Phased-Array Feed with CMOS Low-Noise Amplifiers", IEEE Antennas and Wireless Propagation Letters, 2016
- Belostotski, Beaulieu, Burgess, Veidt, & Haslett, "Low Noise Phased-Array Feed with CMOS LNAs" 2016 USNC URSI National Radio Science Meeting, 2016
- Veidt, Burgess, Yeung, Claude, Wevers, Halman, Niranjanan, Yao, Jew, & Willis, "Noise Performance of a Phased-Array Feed Composed of Thick Vivaldi Elements with Embedded Low-Noise Amplifiers", EuCAP, 2015
- Belostotski, Veidt, Warnick, & Madanayake,"Low-Noise Amplifier Design Considerations For Use in Antenna Arrays", IEEE Trans. Antennas and Propagation, 2015, vol. 63, pp. 2508–2520
- Belostotski, Haslett, Veidt, Landecker, Gray, Hovey, Sheehan, & Messing, "The First CMOS LNA on a Radio Telescope", ANTEM, 2014

Some History... An Early PAF?



Dual-Frequency Feed

408 MHz Front End

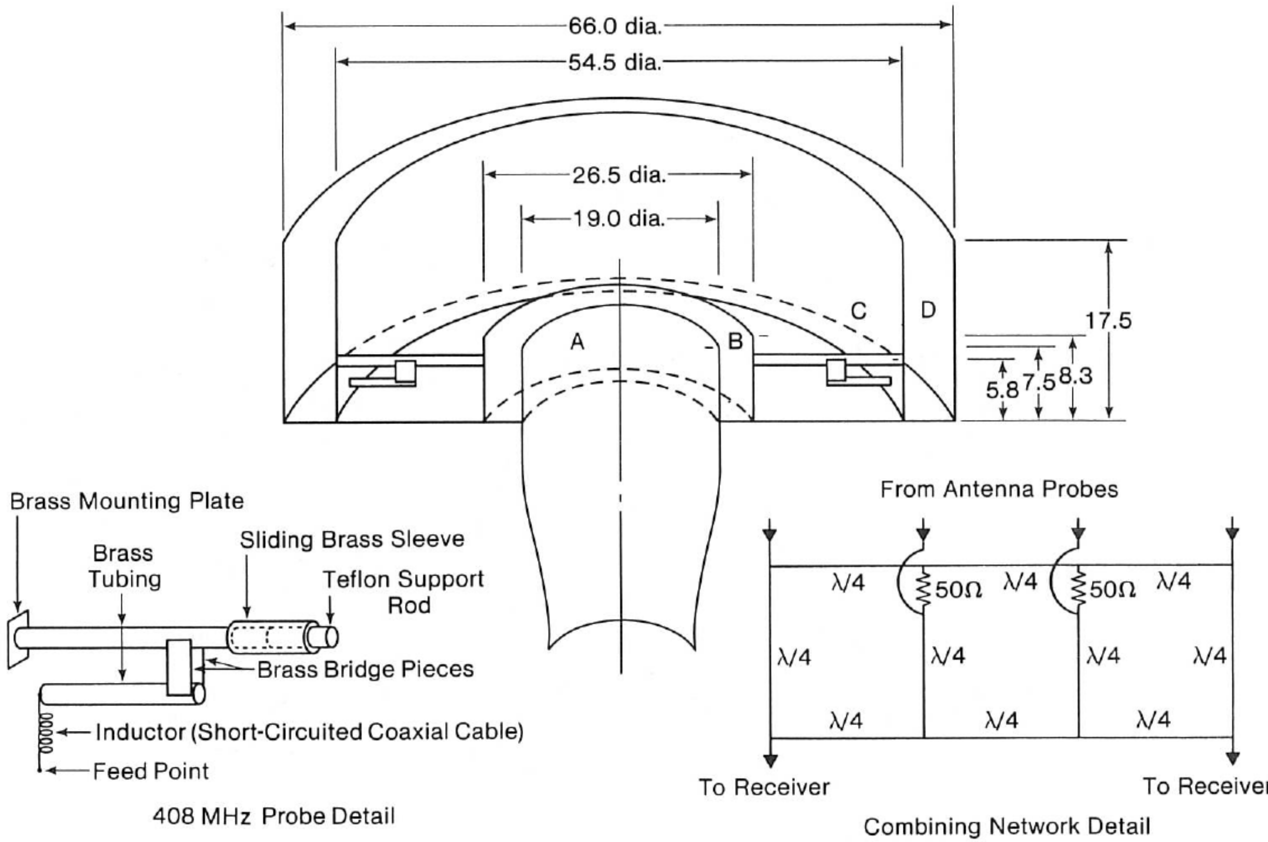


Fig. 1. Dual-frequency feed for 9-m paraboloidal reflectors. Dimensions are shown in centimeters. Insets show details of the 408-MHz probes and a sketch of the coaxial cable combining network.

From: Veidt, Landecker, Dewdney, Vaneldik, & Routledge, "A 408-MHz Aperture Synthesis Radio Telescope", **Radio Science**, 1985, pp. 1118–1128

Comments

- Probes are actually monopole radiators: do not set up a proper waveguide mode because horn is too short ($\sim \lambda/4$)
  - pattern for each probe is non-symmetric
- Combining network acts as beamforming network
  - combine opposing pairs of elements $\Rightarrow$ make pattern more symmetric
  - progressive 90° phase shift $\Rightarrow$ circular polarization
- What would a modern implementation look like?
  - have LNAs at the probes
  - use a digital beamformer
  - might be able to improve radiation properties with proper calibration of beamforming weights

Thank You