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Reinventing Radio Astronomy – PAF Technology

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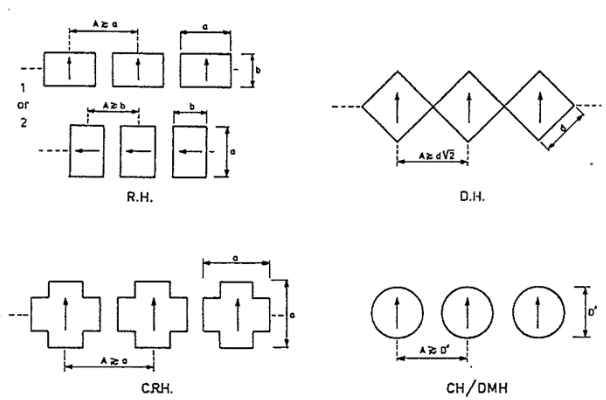
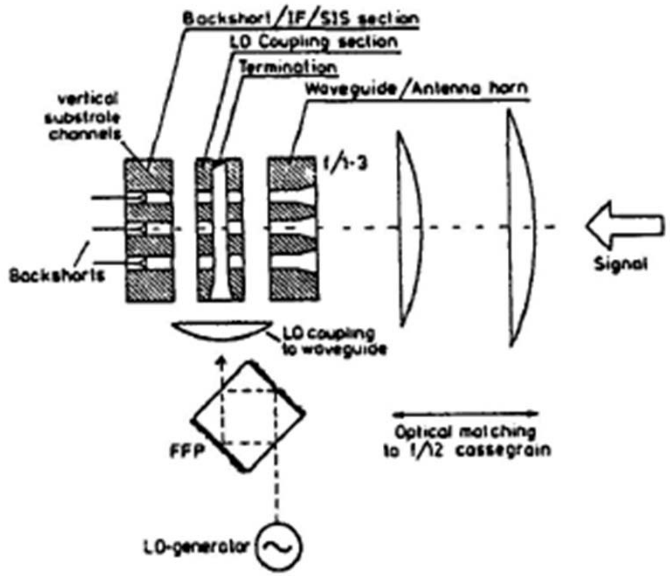
The origins

- Beginning of time
  - Optical and later infrared - power detectors/bolometers
  - Dual/quadruple feed systems for satellite ground station
- 1975? - Ron Ekers and V Radhakrishnan (Groningen) debate whether focal plane has all information
  - Interferometer vs lens at focus
- 1978 or so - Ron Ekers on sabbatical at CSIRO tries to interest antenna engineers in fully sampling focal plane

Still originating

- 1983 – Arnold van Ardenne does heterodyne multibeam mm receiver study
- 1987 – NRAO 7-beam 5.85 GHz receiver
- 1987 – Arnold van Ardenne starts work on 350 GHz array for JCMT
- 1988 – NRAO 8-beam Schottky mixer 230 GHz receiver





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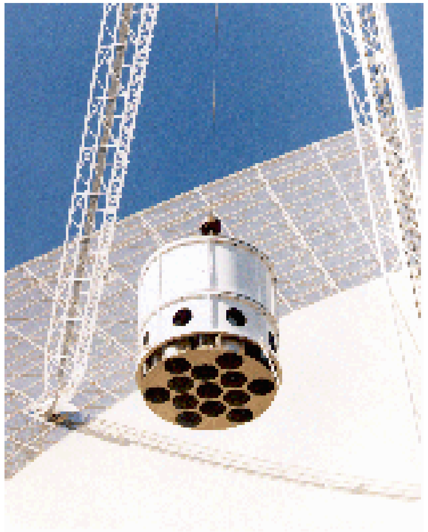
And more originating

- 1988 – Cornwell and Napier publish on theory of focal plane coherence to correct aberations, distortions etc.
- 1988 - Ron Ekers joins CSIRO and tries again with MMIC designers for AT Compact Array – runs into shaped dual reflectors!
- 1993 – Trevor Bird and Geoff Poulton multi-feed onboard satellite “illuminator” fo (CSIRO + Hughes)
- 1993 – Parkes 14 beam 21 cm receiver (Bird, Ekers Stavely-Smith, …)
- 1994 – Arnold van Ardenne et al publish 350 GHz linear array for JCM telescope
- 1995 – Conference on multi-feed systems for radio telesopes at NRAO



Toward SKA

- 1995 – AvA drives research into aperture array for SKAI in Astron
- 1996 – Rick Fisher paper on fundamentals of phased array feeds on parabolic reflectors
- 1996 – Delft SKAI conference
  - AvA pushes dense aperture array based on growth projections of computing/processing.
  - Ron Ekers raises idea of concentrator plus array in his summary.
- 1997 – 1KT Technical Workshop Sydney
  - Ron Ekers refers to focal plane arrays in intro talk (plus more detailed talk later)
  - Harvey Butcher – arrays and focal plane arrays as Dutch focus
  - Arnold van Ardenne – comprehensive talk on arrays, station heirarchy, element types etc.
  - Rick Fisher – arrays and array beamforming principles.

First steps

- 2000 – Arnold commissions Vivaldi design with Dan Schaubert (U Mass.)
- 2001 – Arnold and others start Radionet FP5 Faraday program
- 2003 – Arnold has sabbatical in Sydney and Marianne Ivashina (Astron) starts testing at CSIRO of first Astron Vivaldi array tile.
- 2001/2 – Peter Hall requests white papers on SKA design options
  - Peter Dewdney et al propose large reflector (LAR) with PAF on aerostat as novel Canadian approach
  - Ron Ekers pushes concentrator with PAF as Australian approach – 1D with John Bunton's cylinder ideas as well as 2D
- 2003 – CSIRO embraces PAFs
- 2003 – First Astron PAF symposium
- 2005 – Peter Hall pushes for distinction between FPA and PAF nomenclature

More steps

- 2005 - Stuart Hay proposes connected dipole which soon evolves into a more broadband checkerboard array design (both enthusiastically embraced by myself).
- 2007(?) – Rick Fisher (NRAO), Karl Warnick (BYU) et al propose dipole phased array feed for GBT

Some working PAFs

- Apertif
  - 121 element,
- ASKAP
  - 188 element
- NRAO/BYU
  - 17 element
- PHAD

Motivations for PAFs

- Increased FoV
  - Survey speed $S \propto \left(\frac{A_{eff}}{T_{sys}} \right)^2 \Omega$
  - Simultaneous look directions (transient detection, interference rejection)
  - Cost reduction through re-use of dish
- Full sampling of image space
  - Aberration and reflector distortion, pointing correction
    - Potential dish cost reduction
  - Adaptive interference rejection and spillover reduction
  - Increased self calibration potential (multiple cal sources in FoV)
  - Near instantaneous large field imaging

But must hold the line on Aeff/Tsys!

Challenges and key technologies

- Competitive Tsys
  - Challenges in cooling – radiative loss $P = \sigma A T^4$ ~500 W/m^2
  - Feasible at 5 GHz and above – PHAROS (Glynn et al)

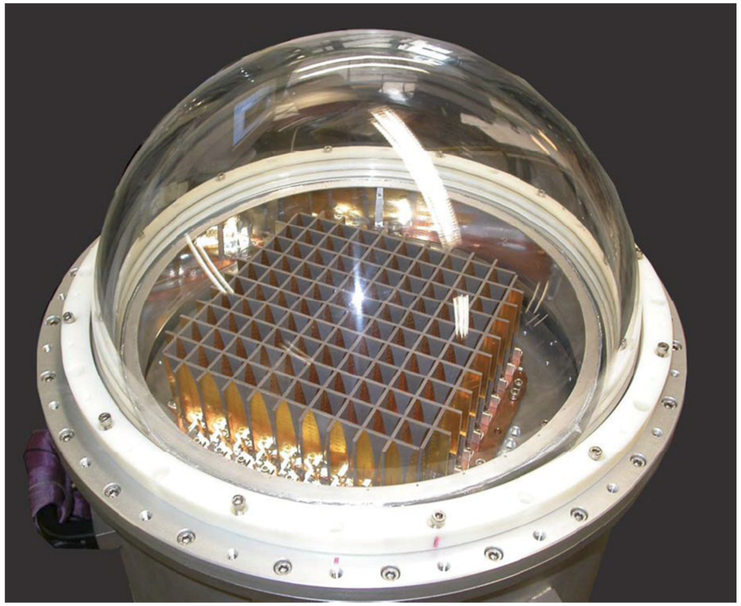


Fig. 2 Vivaldi Antenna inside Cryostat with Radome (RF transparent insulation removed)

  - Also NRAO-BYU dipole to cryogenic receiver
  - Micro-coolers for receiver? (eg. Schreuder & bij de Vaate)
  - Uncooled receiver technologies became main game for 21 cm
  - Understanding and control of all noise contributions key

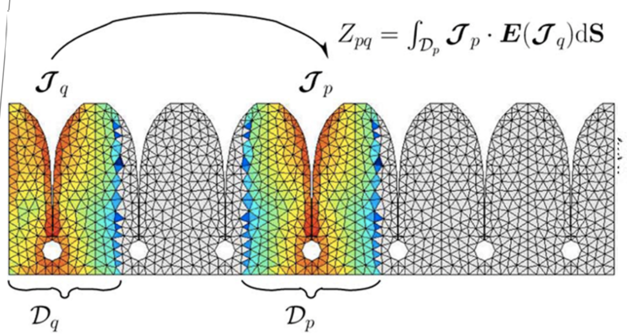
Array challenges

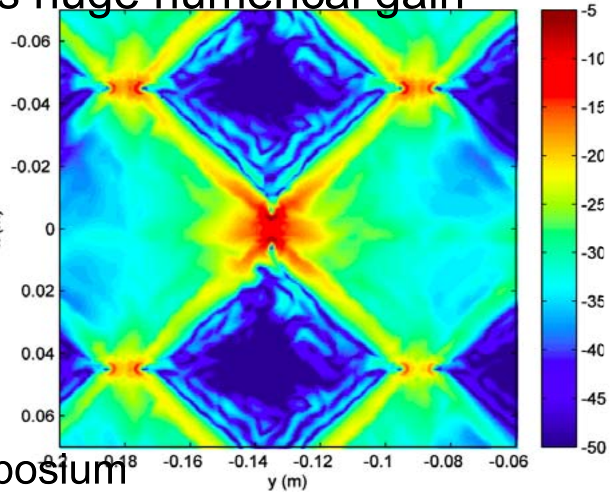
- Coupling to free space
  - Low scattering off array
  - Element beam requirements (pol too)
  - Influence of inter-element coupling
  - Scan blindness and excitation of undesired modes
  - Sampling requirements
- Coupling to receivers
  - Noise and power matching
  - Influence of inter-element coupling
- Broad bandwidth designs and matching
- Beamforming requirements
- Detailed element design and EM+receiver modelling
- Measurement and verification
- From modelling,measurement to insight and improvement
- Cost!!!

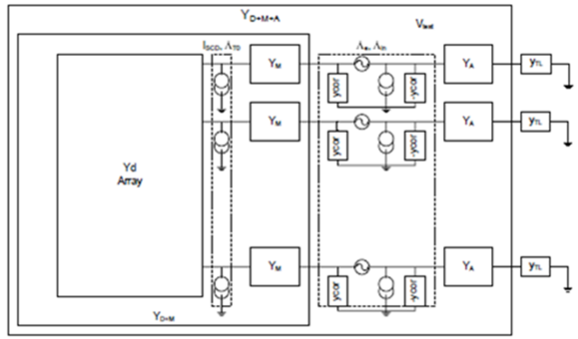
- Much work on arrays had apparently been done but it was classified!

The modelling challenge

- Commercial simulators – eg CS Microwave Office and Studio, …
  - Very computationally intensive
  - Accurate (in the right hands)
- Astron and CSIRO increasingly pursued custom simulation
  - Need to combine EM with electronic to simulate system
  - Many involved (Ivashina, Maaskant, Woestenburg – Astron)(Hay, Kot, Christophe, O’Sullivan – CSIRO, Mittra – Penn State U, Craeye - ???)
  - CBFM – provides huge numerical gain

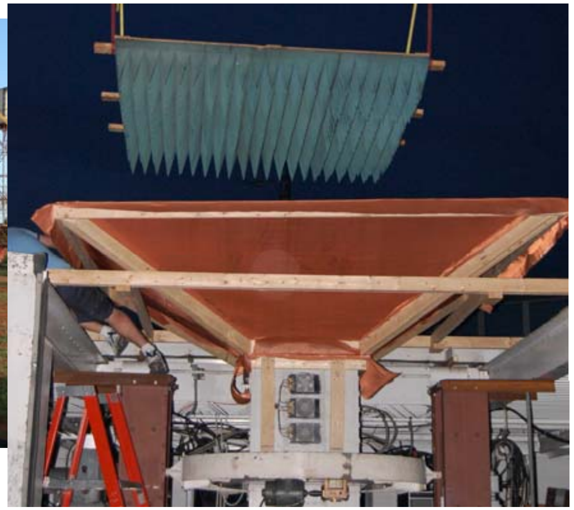


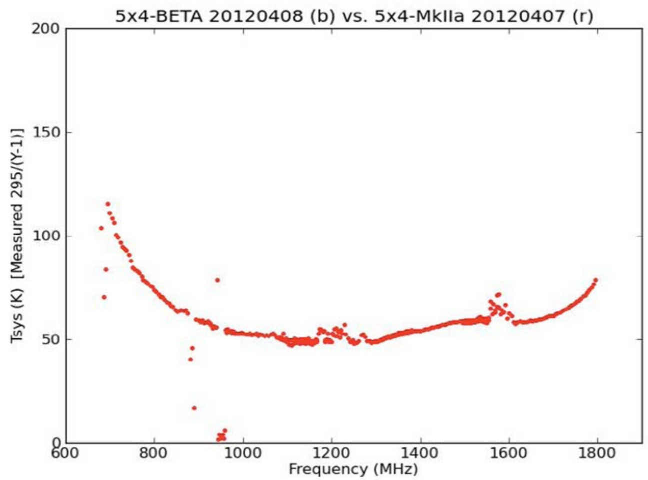




The measurement challenge

- Large arrays with wide angle coverage are challenge to accurately measure
  - Astron and CSIRO both have near field antenna ranges
- Array as aperture with receivers
  - “Popcorn” box/shield with absorbing lid – Astron/NRAO/CSIRO
  - Moveable absorber – CSIRO
  - Full spectral cross correlation all ports!





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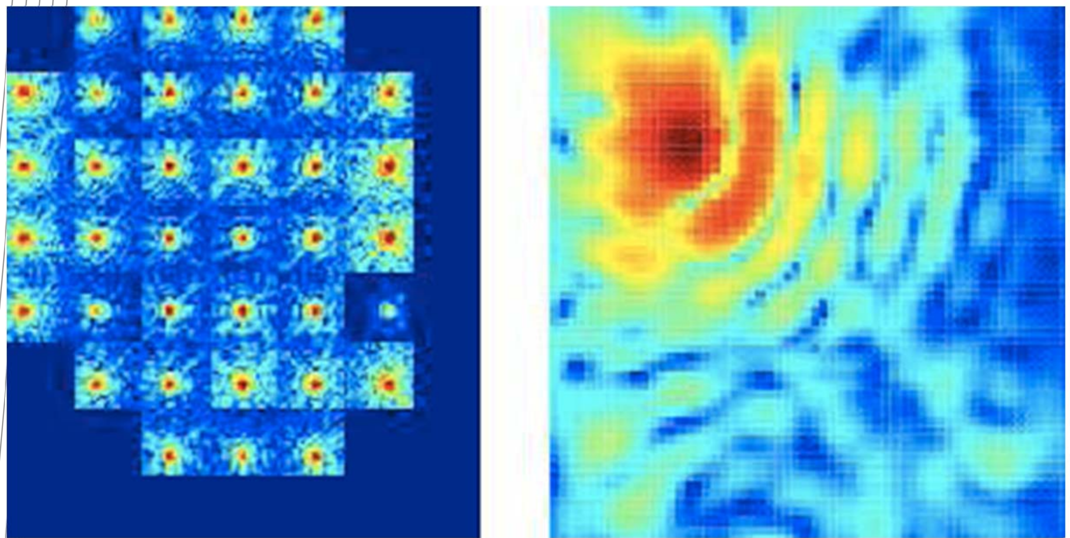
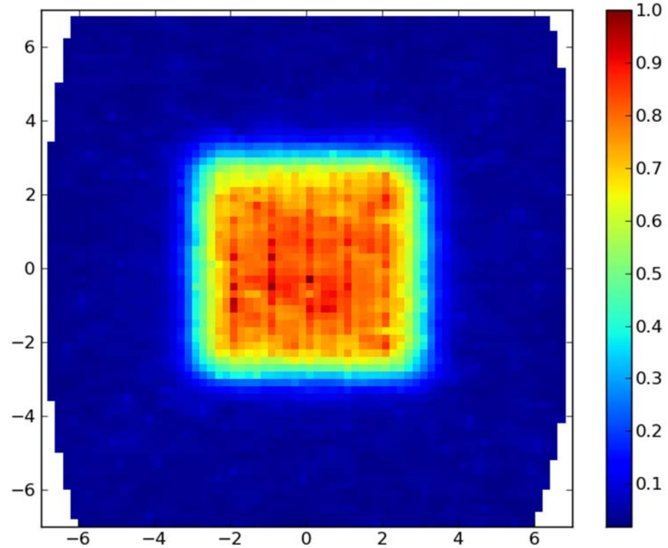
The measurement challenge(2)

- Array at focal plane
  - WSRT 25 m – single and interferometer
  - Greenbank 20 m
  - Parkes 12 m and 64 m interferometer
  - Mileura 12 m single dish and 3 element interferometer



Apertif 2008



Sensitivity – composite Beam Parkes 2012

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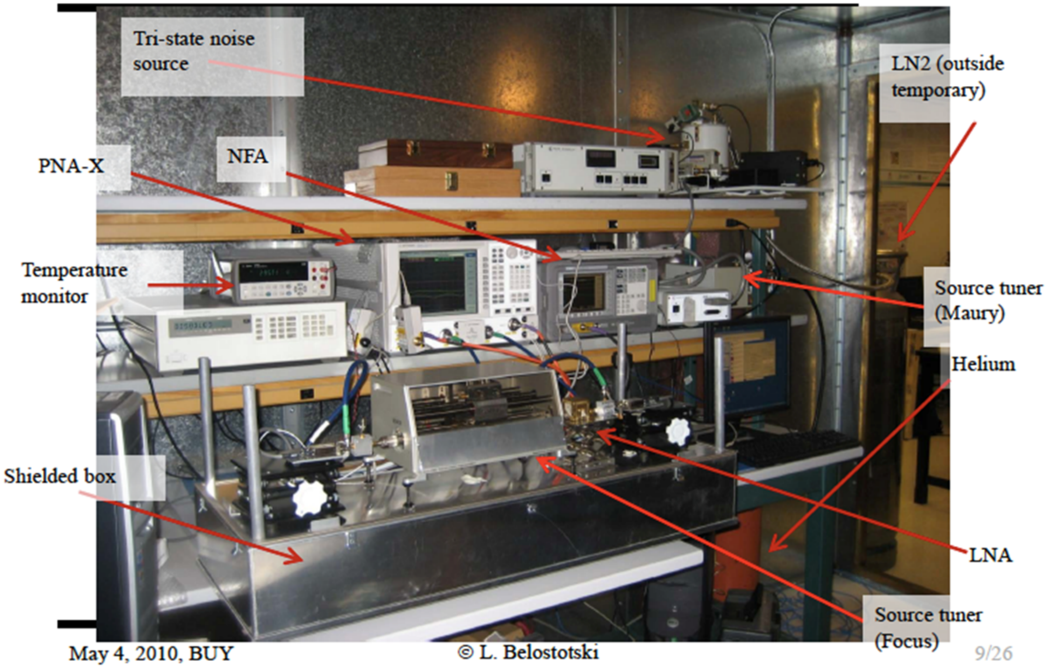
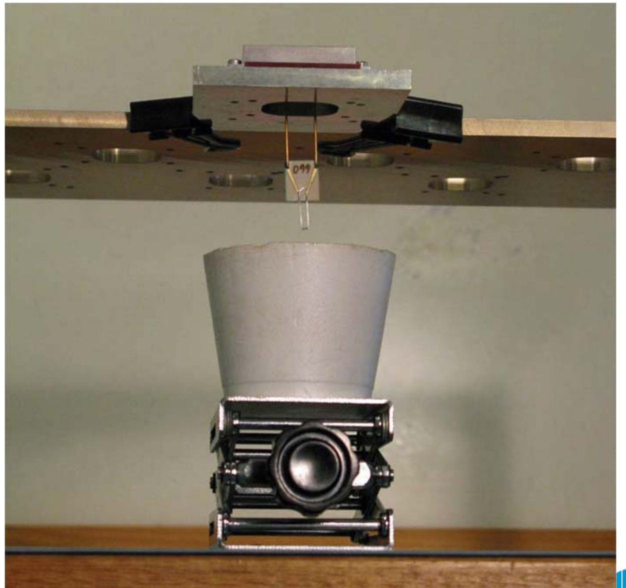
The measurement challenge (3)

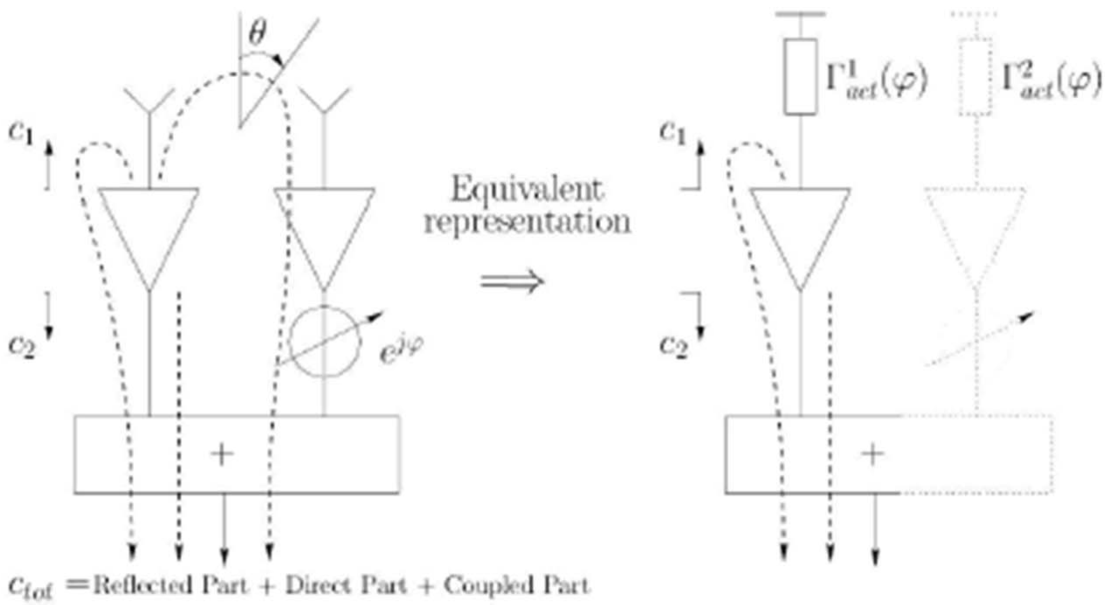
- LNA measurement – differential and/or impedance not 50 Ohm
  - Need all signal and noise parameters to fully characterise array behaviour
  - Belolotski et al and Astron using tuner-based system to move source impedance over Smith chart
  - CSIRO (Shaw) multiple cooled source impedances





The insight bit

- An example noise matching:
- Power transfer and optimum noise match properties first investigated by brute force modelling
- Maaskant and Woestenburg (2007) come up with active reflection coefficient for beamformed array.



Further insights

- Hay produces a nice concise formulation which shows fundamental extra array coupling contribution to receiver noise

$$T_{sys} = T_{\min} + T_0 \frac{\mathbf{w}^{\mathrm{T}} \left(\mathbf{L}_{narray} + \mathbf{L}_{spill} + \frac{N}{G_{opt}} \left(\mathbf{Y}_{\mathrm{D}} - Y_{opt} \mathbf{I} \right) \left(\mathbf{Y}_{\mathrm{D}} - Y_{opt} \mathbf{I} \right)^{\mathrm{H}} \right) \mathbf{w}^*}{\mathbf{w}^{\mathrm{T}} \mathbf{w}^* G_D}$$

- Ivashina et al extend active array reflection to equivalent system formulation which allows quantification of various efficiencies
- Infinite array approx allows easy Fourier domain view of noise, beamforming etc.

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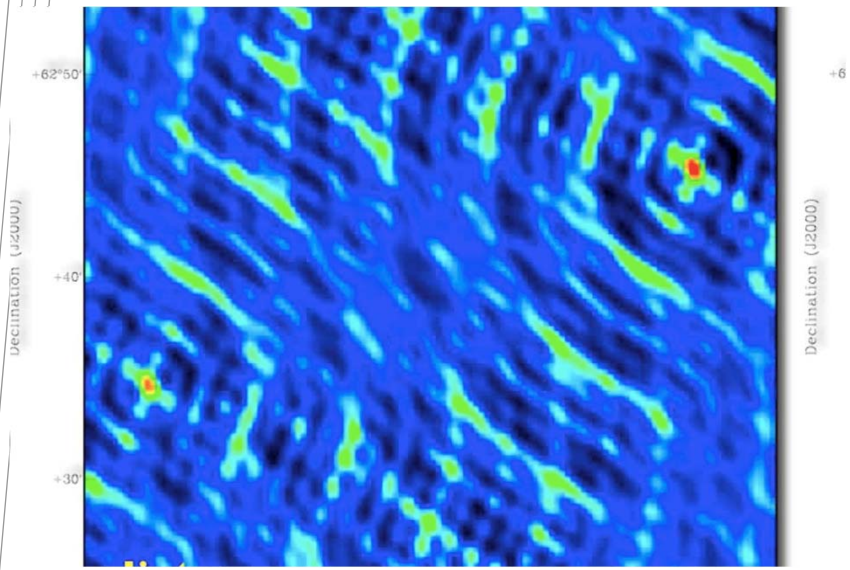
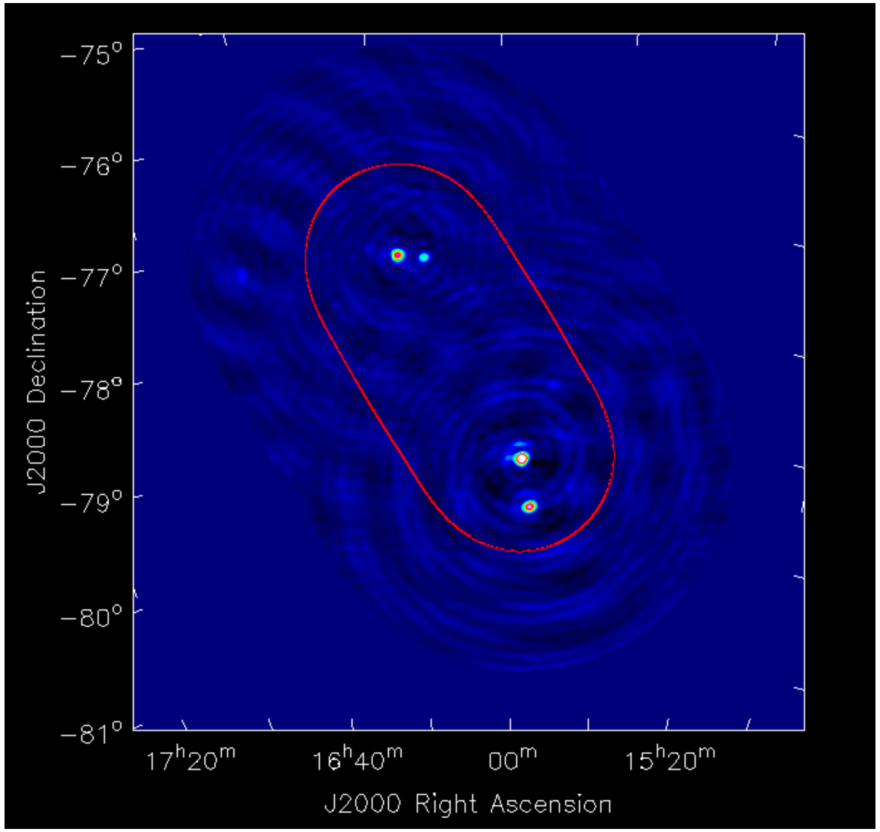
Astronomical



C286 – Apertif 3 interferometer
single PAF (2010)



PKS 1610-771, PKS 1606-772,
PKS 1549-790 and PKS 1547-795
ASKAP – 3 element interferometer(2103)

Further challenges

- PAF
  - Lowest noise vs cost and power
  - Vivaldi vs Checkerboard vs ??(bandwidth, losses, cost)
  - Micro-cooling?
- Signal distribution, beamforming and correlation
  - Cost, power, size
- Processing and imaging
  - Calibration, self-cal and automatic calibration of FoV response

Other Applications

- Satellite TV - Linear Signal 2013
- Mobile satellite telecoms
- Medical applications – Breast cancer screening