# Phased Array Feed Development Update

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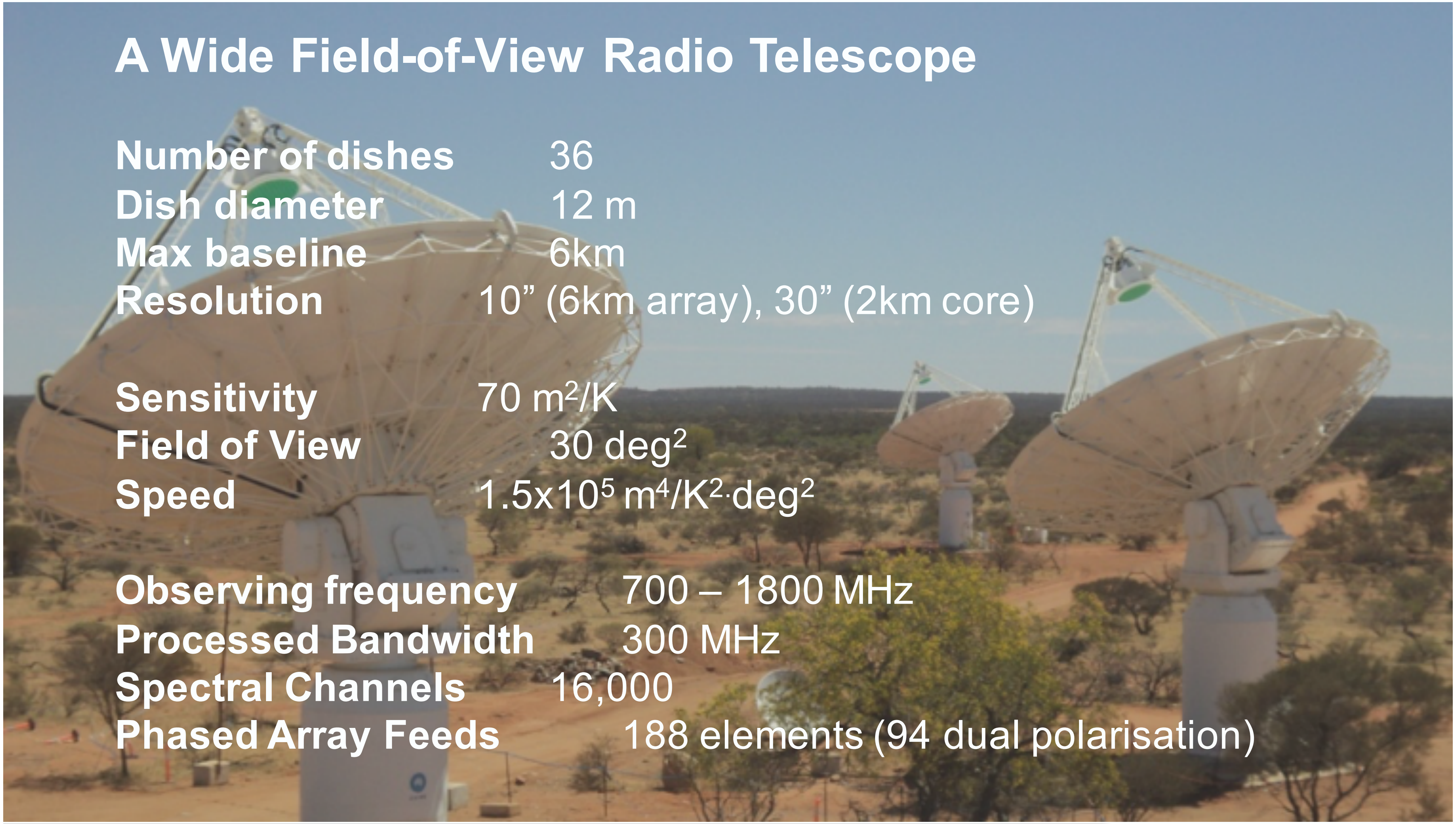
CSIRO – Technologies for Radio Astronomy, ASKAP Team, SKA PAF Group and APERTIF Team

07 March 2016

# Outline

- PAF Instruments
  - ASKAP
  - Parkes 64m – Bonn PAF (MPIfR)
  - APERTIF
- SKA PAF Development – SKA Dish
- Phased Array Feed Array Developments
  - AFAD
  - CryoPAF4
  - PHAROS
  - Chequerboard Array
  - Rocket Array
- Comparison of current PAFs
- The Future

# ASKAP – Australian SKA Pathfinder

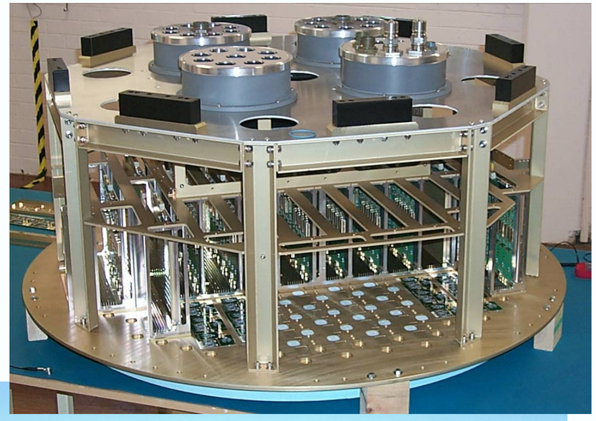


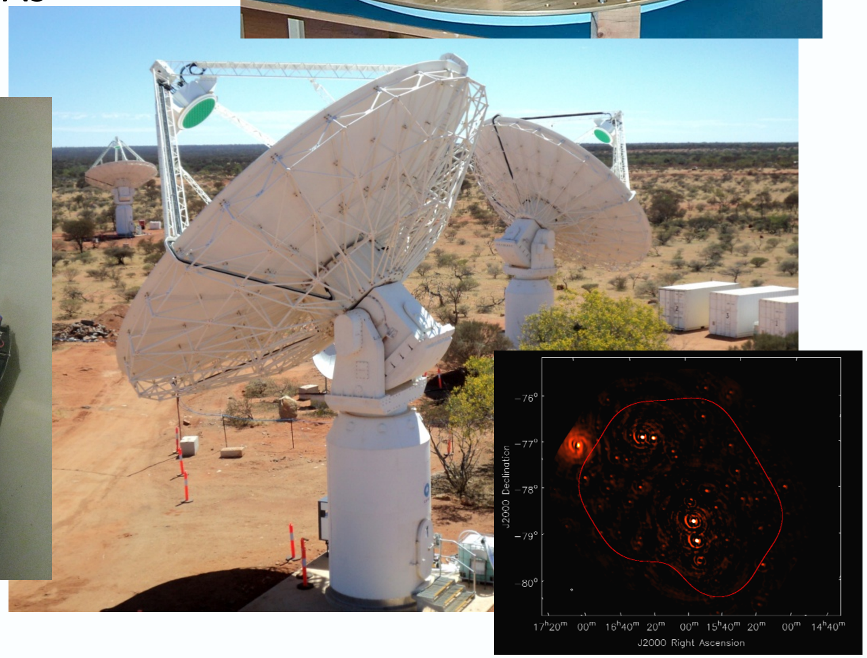
## A Wide Field-of-View Radio Telescope

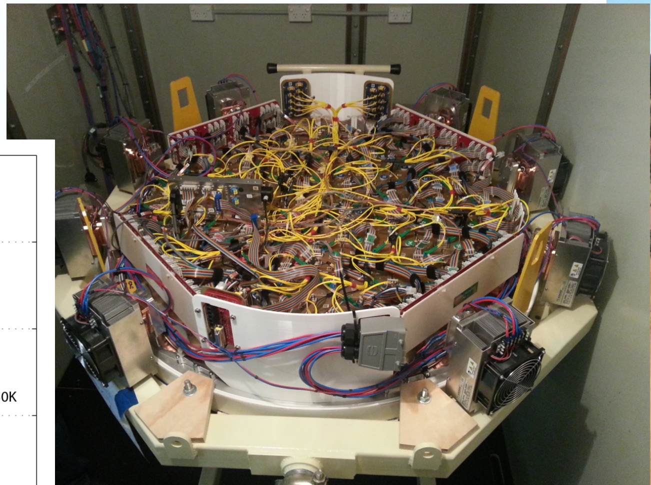
| | |
|---|---|
| **Number of dishes** | 36 |
| **Dish diameter** | 12 m |
| **Max baseline** | 6km |
| **Resolution** | 10” (6km array), 30” (2km core) |
| **Sensitivity** | 70 $m^2/K$ |
| **Field of View** | 30 $deg^2$ |
| **Speed** | $1.5 \times 10^5\ m^4/K^2 \cdot deg^2$ |
| **Observing frequency** | 700 – 1800 MHz |
| **Processed Bandwidth** | 300 MHz |
| **Spectral Channels** | 16,000 |
| **Phased Array Feeds** | 188 elements (94 dual polarisation) |

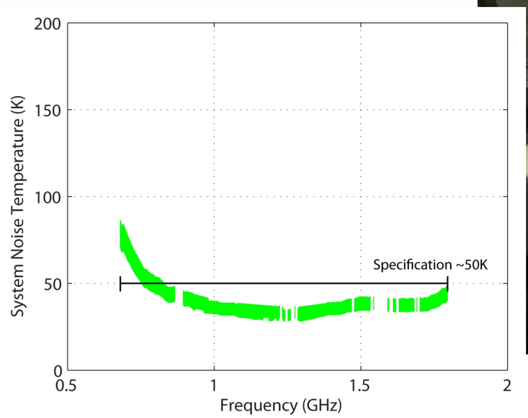
# ASKAP – Australian SKA Pathfinder

- Boolardy Engineering Test Array (BETA)
  - Decommissioned February 2016
  - 6 antennas fitted with Mk. I Chequerboard PAFs
  - Conversion and baseband sampling at antenna
- ASKAP Design Enhancement (ADE)
  - 9 antennas currently outfitted
  - Mk. II Chequerboard Phased Array Feed/LNAs
  - Direct sampling at central site







# ASKAP – Science Commissioning

- First 25 Beam Image – Full ASKAP FoV
  - Centre frequency – 850MHz
  - Bandwidth – 48MHz
  - 5 antennas – Mk. II PAFs fitted
  - 25 Beams – ASKAP FoV at this frequency
  - 30 square degrees

The image was produced in a 12 hour observation of the Apus test field using 5 Mk. II Phased Array Feeds.

The beam footprint as made up of 25 beams, in a 5 x 5 square, and is the first image to instantaneously cover approximately 30 square degrees – that is, the full ASKAP field of view.

The data for the observation were calibrated and imaged on the ASKAP real time computer, Galaxy, located at the Pawsey supercomputing centre in Perth, Western Australia.

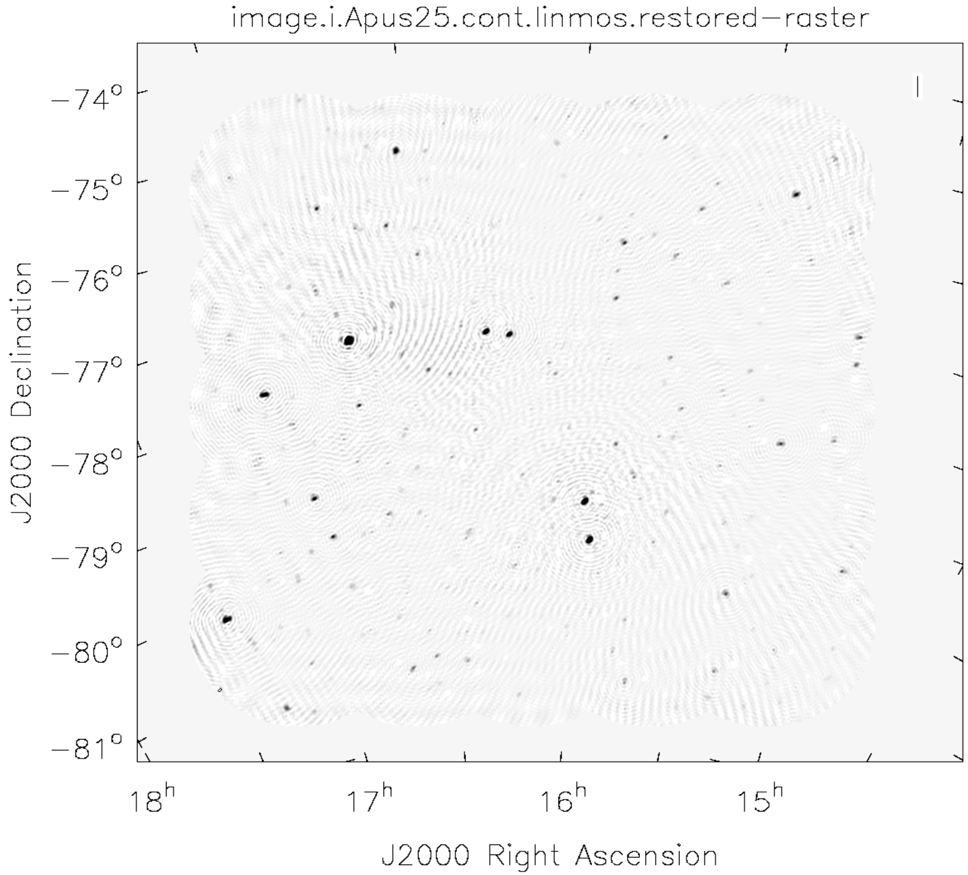
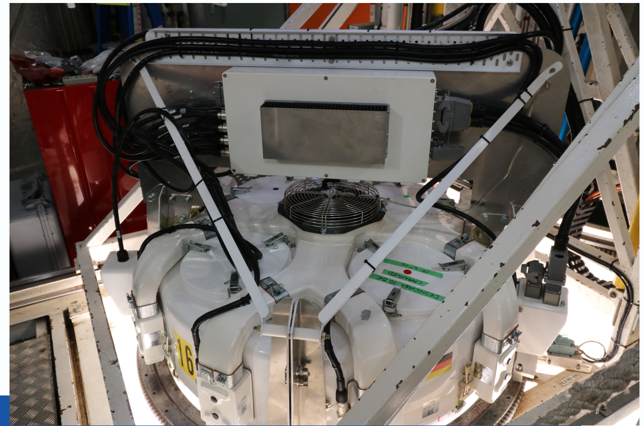
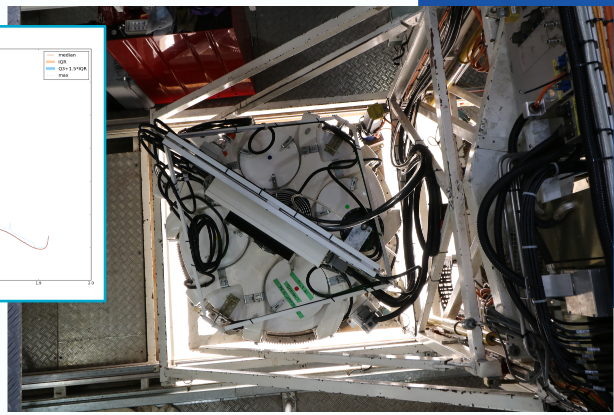


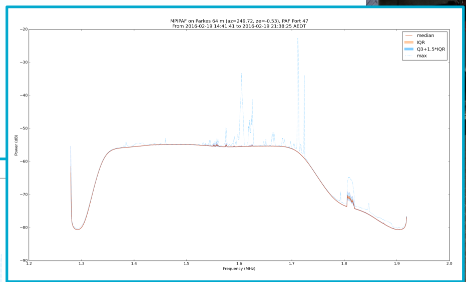

Image Credit: Josh Marvil

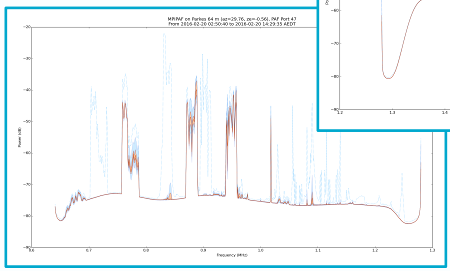
# Parkes 64m – Bonn PAF (MPI)

- ASKAP PAF (Mk. II) built by CSIRO for MPIfR
  - ASKAP Digitiser and Beamformer
  - GPU Correlator
  - Modified RF signal chain – Additional filters (RFI)
- Commissioning on Parkes 64m antenna
  - Replaces Parkes multibeam receiver (13 beam)
  - Installation – February 2016
  - Commissioning/software development
  - Removal – September 2016
  - Installation on Efflesberg – late 2016









# APERTIF specifications

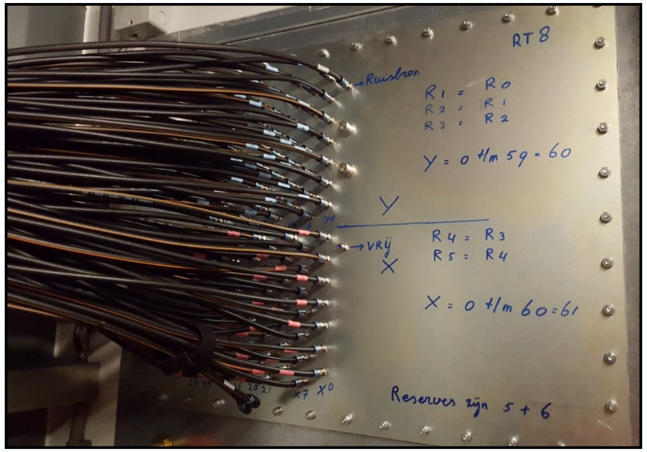
| | |
|---|---|
| **Frequency range** | 1130 – 1750 MHz |
| **Instantaneous bandwidth** | 300 MHz |
| **Channel bandwidth** | 12 kHz |
| **Polarization** | Dual linear |
| **Reflectors** | 12 x 25m |
| **Baselines** | 36 to 2412 m |
| **System temperature** | 70 K |
| **Aperture efficiency** | 75% |
| **Simultaneous beams** | 37 dual pol |
| **Field of view** | 8 $deg^2$ |
| **“Survey speed increase”** | 17x |

# Status APERTIF up to now

- 12 dishes mechanically upgraded
  - 6 dishes currently fully installed
  - 6 dishes ready for hardware
  - Noise Source System installed for one dish
- HF cabin ready for correlator
- Software verification
- Correlator verification (→ first fringes)
- APERTIF-6 software ready (to control instrument)

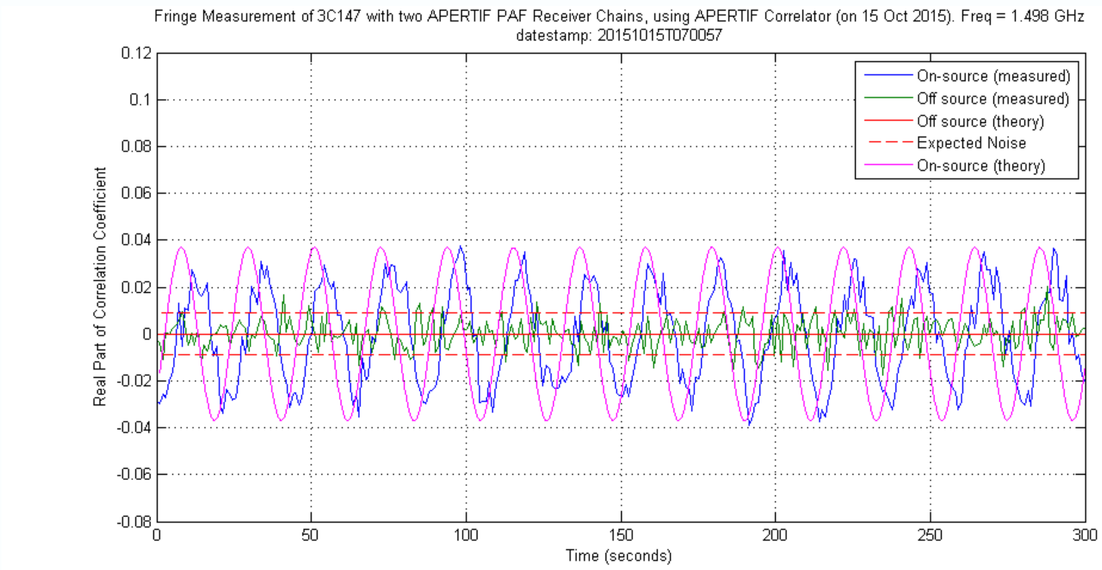
# Currently ongoing and future

- Commissioning APERTIF-6
- APERTIF-12 Installation
  - Hardware for another 6 dishes (dual polarized)
- Further development of correlator firmware
- APERTIF-12 software development (user software) (expected end of 2016)
- Start Science Commissioning (April 2016)
- First science APERTIF 2017

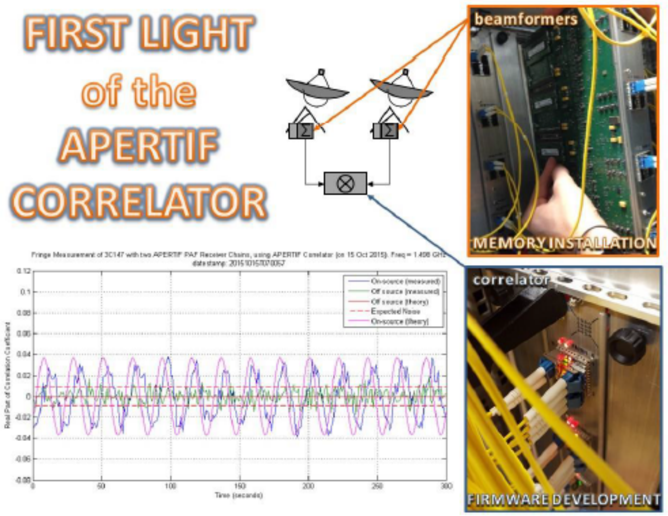


# Verification Correlator Firmware → First Fringes

- Using sky input data, verify
  - Correct cross-correlation product




**Daily Image** 16-11-2015




**First Light of the APERTIF Correlator!**

**Submitter:** Boudewijn Hut and Hajee Pepping for the APERTIF team

**Description:** The hard work on the APERTIF correlator is paying off - on 8 October 2015, the first real-life fringe was measured on a celestial radio source, using two WSRT dishes! This is not only a great success from a technical perspective, but it also showed that such a complex system can be delivered on time.

In the weeks before reaching this milestone, the firmware (DESP) and commissioning teams cooperated seamlessly. The new correlator module was installed on a UniBoard FPGA, and step by step the optical fibers, new DDR3 memory, beamformer modules and receiver chains were included. This systematic approach allowed us to find (and squash) any bugs in an early stage.

The inset on the top right shows the installation of new DDR3 memory at a beamformer. This memory is used for the transpose operation (see daily image 19-05-2015). The data stream is then transmitted to the correlator by means of optical fibers. The bottom right inset shows the optical fiber interface on a correlator UniBoard.

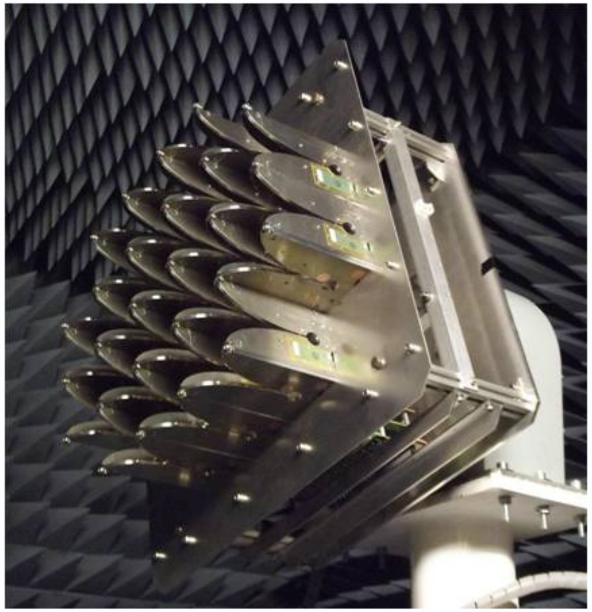
The actual fringe is shown in the bottom left graph. It is measured using a single 12.207 kHz channel at 1.498 GHz. Two WSRT dishes on a 288 m East-West baseline were pointed at 3C147 for a period of 300 seconds, without any delay tracking. Also shown is a measurement towards the zenith, away from any strong source, where the correlation should be negligible, or rather noise-like. The measured variance of the correlation coefficient is indeed as expected.

# SKA PAF Development – SKA Dish

## CSIRO PAF Design

- Chequerboard array
- Australian SKA Pathfinder (ASKAP) Mk. II
- RF over Fibre signal transport
- 650 – 1670MHz band (SKA - Band 2)


Credit: A. Chippendale, CSIRO



Credit: B. Veidt, NRC Canada

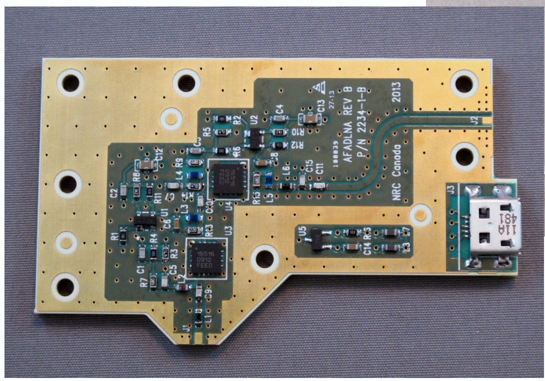
## NRC PAF Design

- Thick Vivaldi Array
- Advanced Focal Array Demonstrator (AFAD)
- Cryogenic cooling (CryoPAF)
- 1.5 – 4.0Hz band (SKA - Band 3)

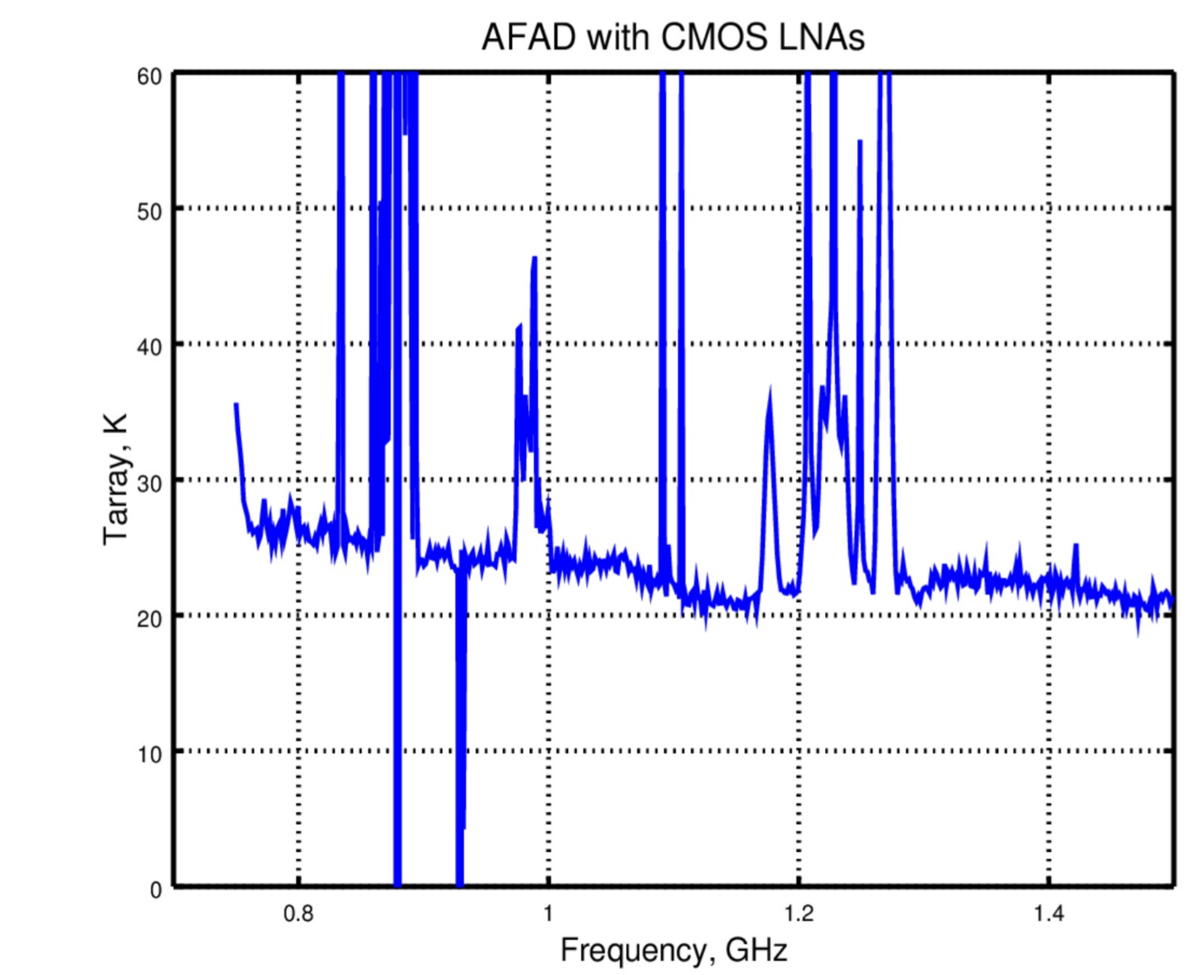
# AFAD – NRC Canada

## Key Parameters

- Frequency Range: 0.75 – 1.5GHz
- Element Spacing: 100mm (λ/2)
- Element Thickness: 5mm
- Taper Length: 113mm
- Slot Width: 3mm
- Overall Length: 158mm
- Number of Elements: 41
- Element Mass: 165g



# Measured Performance with CMOS LNAs




- Measured performance of the AFAD Array in aperture array mode using the NRC Hot/Cold Test Facility (HCTF) located at DRAO, Penticton.
- The AFAD Array comprised of 9 CMOS LNAs in centre of the array; the remaining 32 array elements have commercial HEMT LNAs.



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## Conclusions

- Obtained good results with CMOS LNAs in centre array

## Future Work

- Construct a 96 element array with all elements using CMOS LNAs
- Single piece element design
- Digital beamformer
- Demonstrate array on DVA-1 dish with offset Gregorian optics

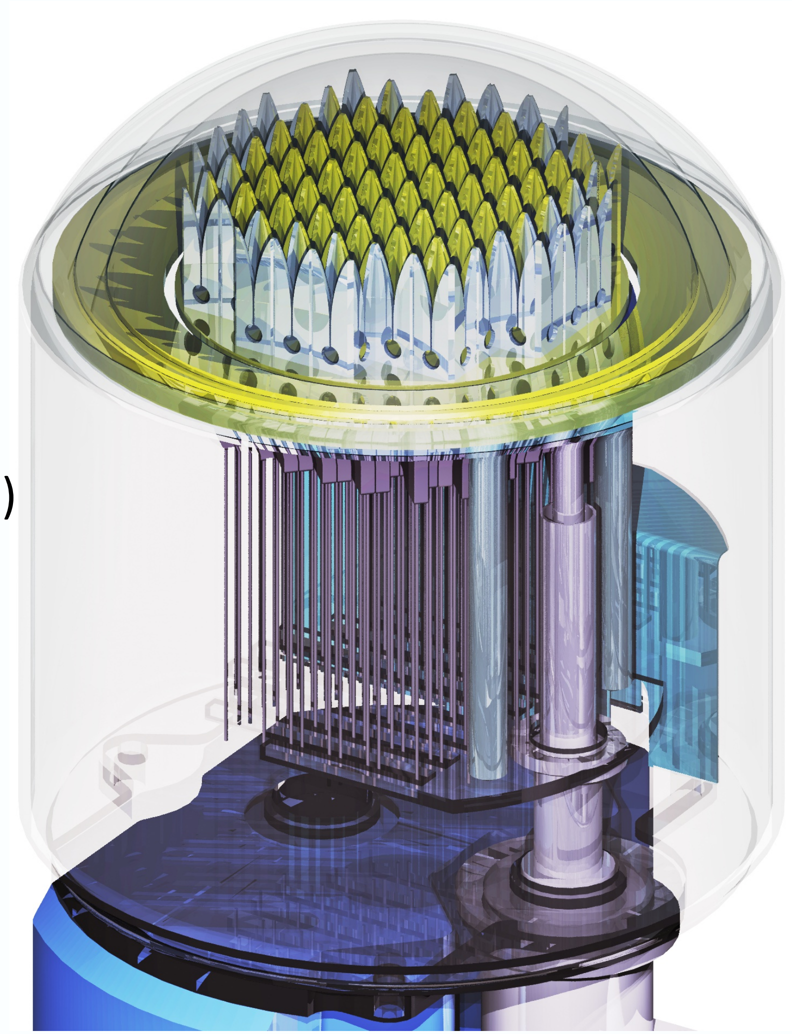
# CryoPAF4 – NRC Canada

## History

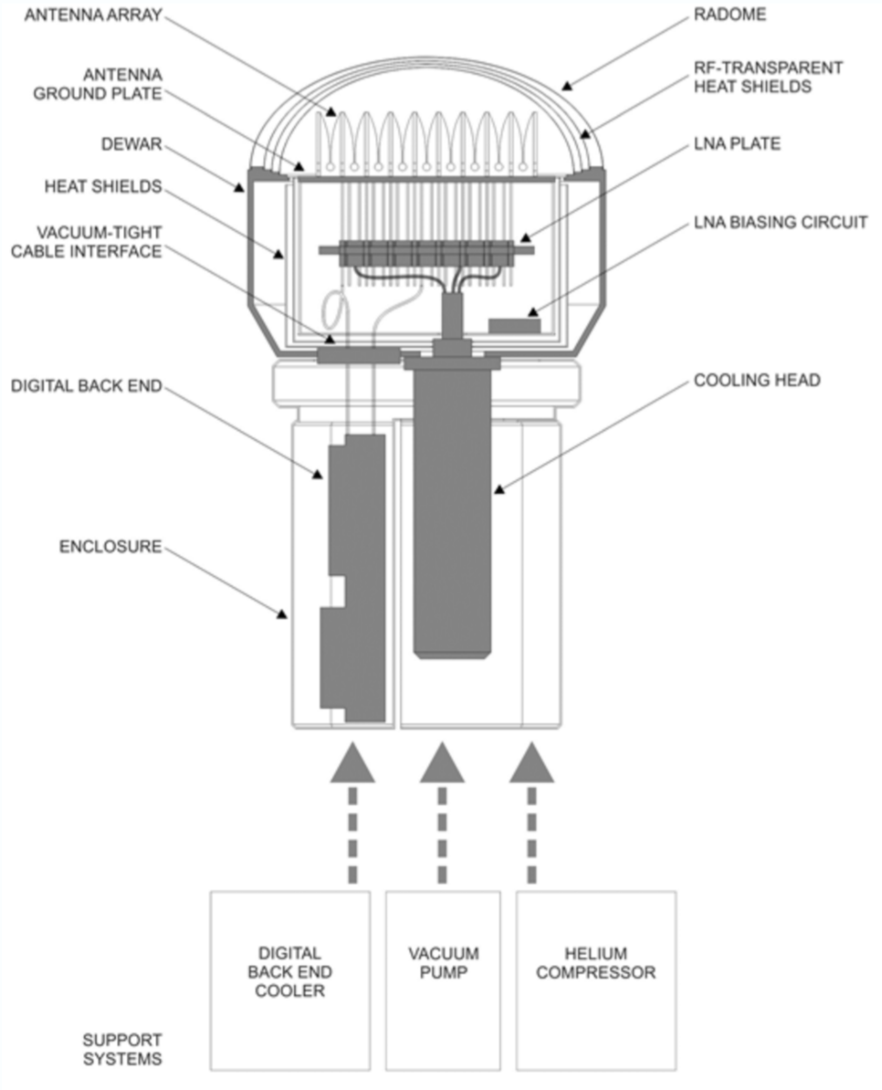
- 2014: SKA DISH consortium, “Band 3”
- 2015: NRC project, new frequency

## Goals

- Frequency: 2.80 – 5.18 GHz
- System temperature: 16K
- Elements: Vivaldi – 96 active (140 in total)
- Cryogenically cooled elements and LNAs (15K)
- Dual linear polarization
- Digital back end – 36 beams at 500 MHz
- Sampled at RF



# System Description




## Description

- Composite radome
- Infrared filters/heat shields & metal radiation shields
- 140 element array of all- metal Vivaldis
- Elements: Vivaldi – 96 active (140 in total)
- Elements and LNAs cooled to 15K
- 3.5K noise 3-stage LNAs, 40 dB gain
- Receiver package includes filtering and post LNA amplification – Room temp
- Digital back end – 36 beams at 500 MHz
- Sampled at RF

# Estimated System Temperature

| | Radome | Blade + coupling* | connector | LNA | Filter | PA | Coax | DBE |
|---|---|---|---|---|---|---|---|---|
| Gain/Loss (dB) | -0.02 | -0.10 | -0.10 | 40.00 | -1.00 | 35.00 | -2.00 | -1.00 |
| Noise Figure (ratio) | 1.00 | 1.00 | 1.00 | 1.01 | 1.26 | 3.00 | 1.58 | 30.00 |
| Noise Temp (K) | 1.34 | 0.35 | 0.35 | 3.50 | 75.09 | 580 | 169.62 | 8410.00 |
| Cumulative Noise Temp (K) | 1.34 | 6.69 | 7.05 | 10.73 | 10.74 | 10.82 | 10.82 | 10.82 |
| Cumulative GkTeB (dBm) | -87.35 | -102.46 | -97.50 | -54.91 | -55.87 | -20.83 | -22.83 | <-- |
| Physical Temperature (K) | 290 | 15 | 15 | 15 | 290 | 290 | 290 | 290 |
| | | cryogenic | | | room temperature | | | |
| Bandwidth (GHz) | 100 | 2.5 | 26 | 3 | 26 | 3 | 26 | 2.5 |

| | | |
|---|---|---|
| Cosmic Background | 2.7 | |
| Atmosphere | 2 | |
| Spillover | 3 | |
| Receiver* | 10.82 | * includes 5K mutual coupling |
| Total System Temperature | 18.52 | K |

The total receiver noise temperature is 10.82K, which when added to the cosmic background, atmosphere, and approximate spillover results in 18.52K total system temperature.

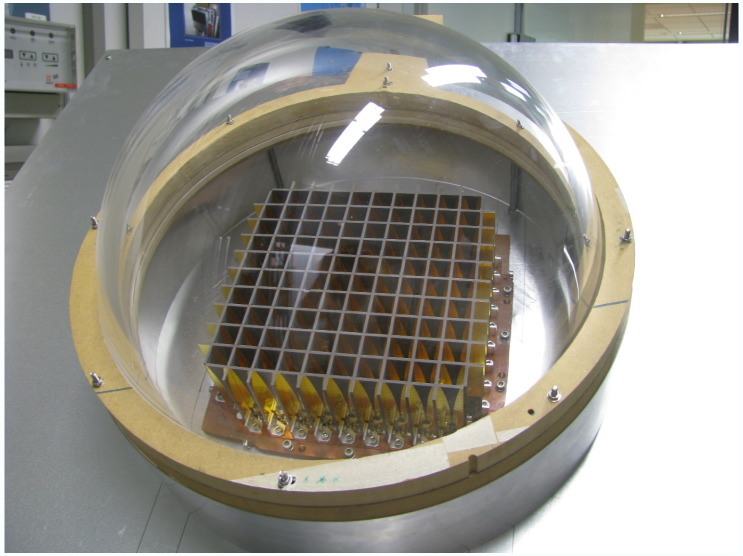
# Power Budget

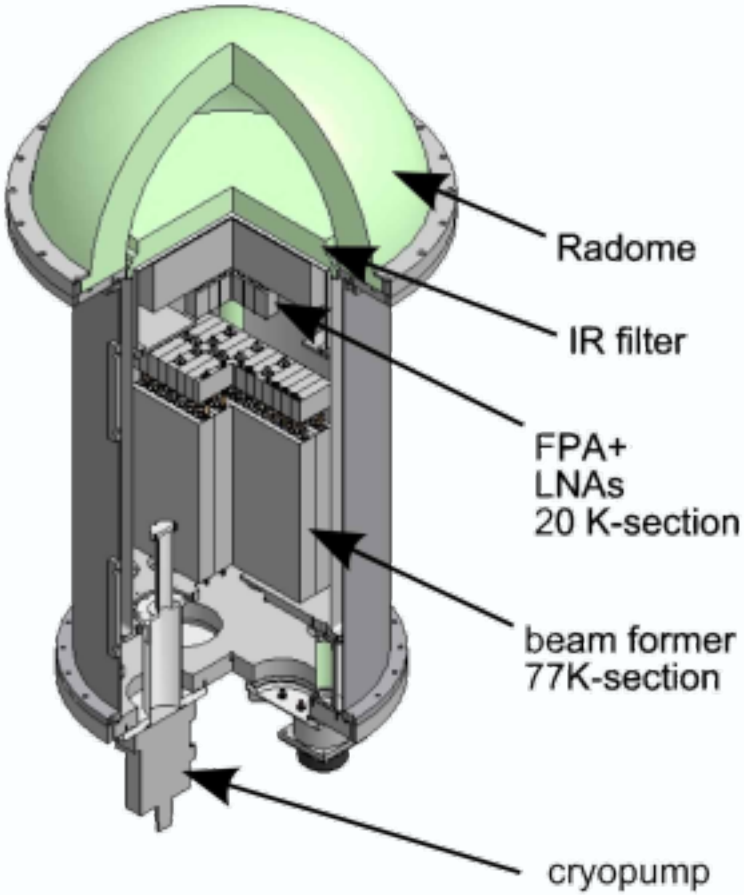
- Cold heads
  - Single stage Gifford-McMahon compressed helium for cooling LNA array. 5W at 15K capacity, 0.29% efficiency, 1.7 kW power.
  - Single stage pulse-tube compressed helium for heat sinking 96 dewar – DBE coaxial cables. 45W at 70K, 0.65% efficiency, 700W power.
- Helium lines
- Helium compressor
  - Single compressor to deliver 2.4 kW
- Heat Shields
  - RF transparent heat shields between radome and antenna array to reflect infrared radiation.
  - Concentric thin metal cylinders at 15K, 70K, 300K - thermal insulation to most critical components: LNAs

| ***PBS component*** | ***Power (W)*** |
|---|---|
| ***PAF Feed/LNA*** | |
| *Crogenic LNAs (15mW each)* | 1.5 |
| *LNA Bias* | 2 |
| *Warm Amplifiers (~200mW each)* | 19.2 |
| ***PAF Feed/LNA total*** | **22.7** |
| ***PAF Digital Back End (details in sec 5)*** | |
| *ADC modules (96 channels)* | 219.4 |
| *PowerMX motherboard* | 122.3 |
| *Beamformer daughter boards (3)* | 158.3 |
| *Beamformer/ACM/output board* | 126.8 |
| ***PAF Receiver total*** | **626.8** |
| ***PAF System Cooling*** | |
| *PAF Feed/LNA cryogenic cooling* | 2400 |
| *PAF DBE cooling* | 1250 |
| ***PAF System Cooling total*** | **3650** |

# PHAROS– JBCO, ASTRON, INAF

- Cryogenic receiver
- MMIC 4-8GHz LNA (ASTRON)
- Analog MMIC based beamformer

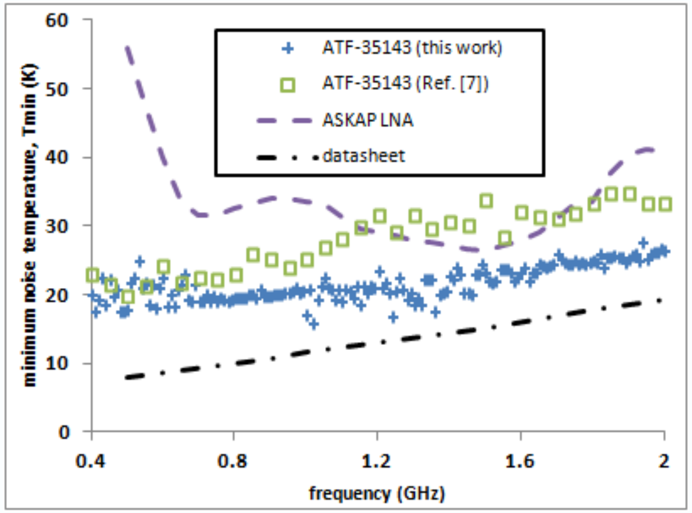


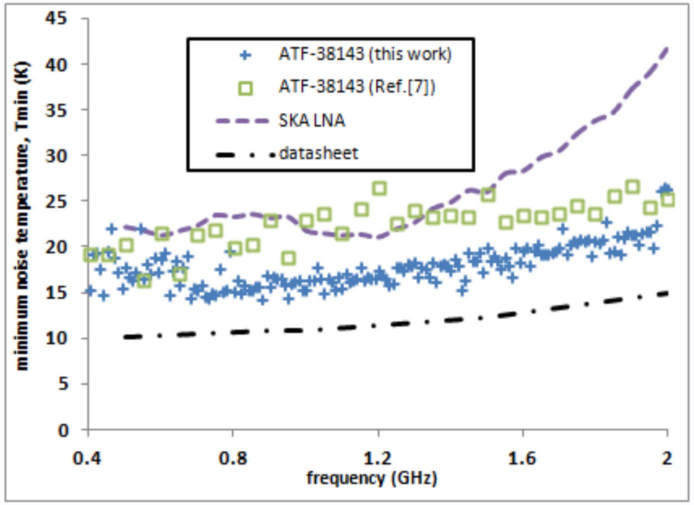


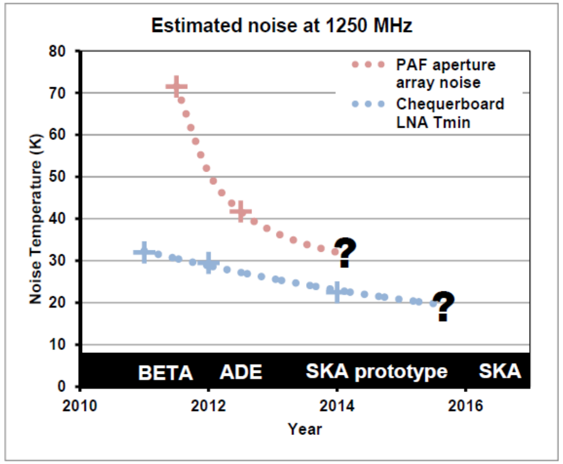
# Chequerboard Array - CSIRO

## Ongoing Work

- Reducing PAF Tsys – Reduction of $T_{LNA}$ = 5K – 7K over ASKAP Mk II LNA achieved in laboratory
- Understanding of feed wire loss and dielectric effects
- Additional devices being evaluated for Mk. IV and beyond
- Improved element geometry (particularly edge elements)



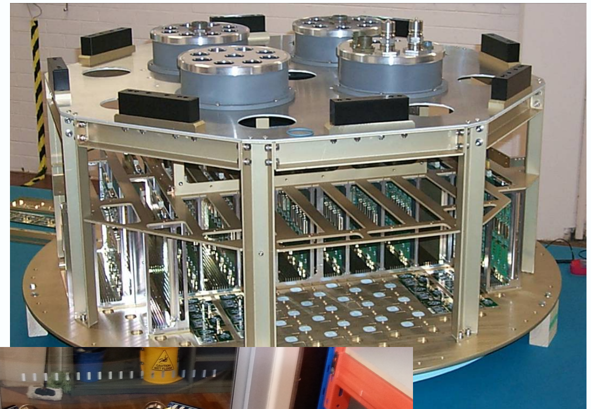



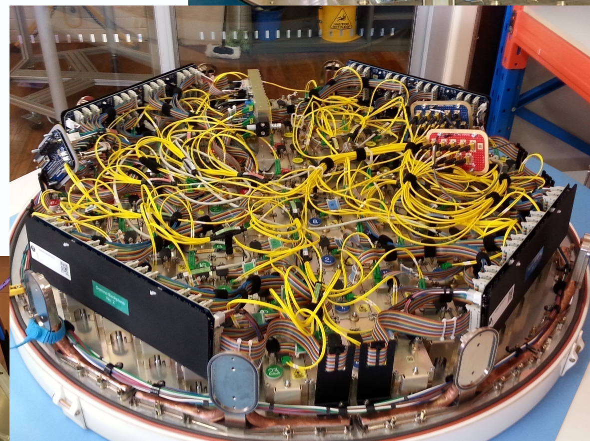



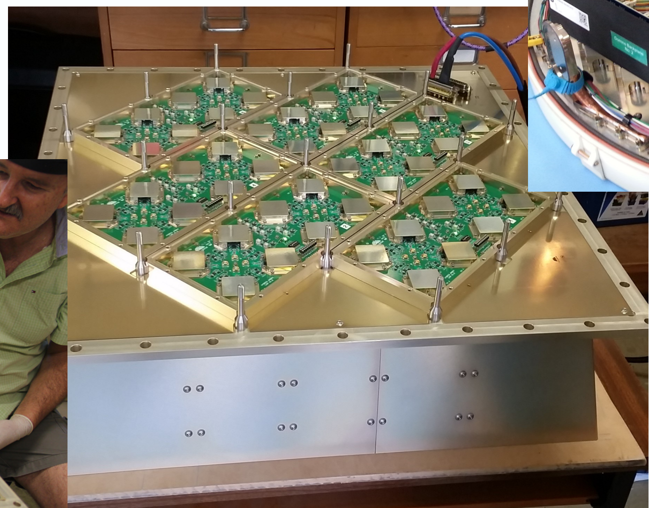
# Rocket Array – CSIRO

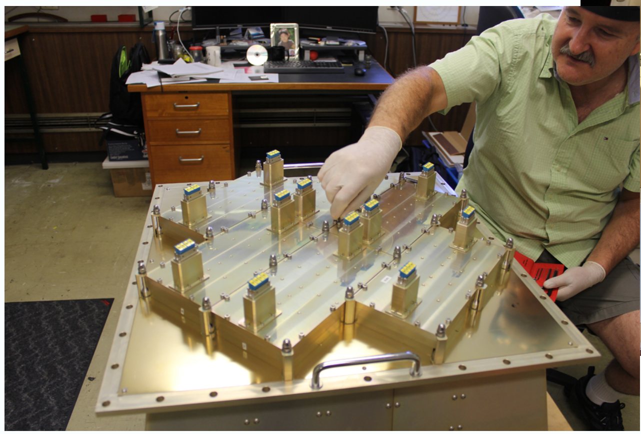
## CSIRO SKA PAF Program

- Initially focussed on 650 – 1670 MHz (band 2)
- Common RF signal chain (Bands 1, 2, 3)
- Reducing system temperature ($T_{LNA}$)
- Ongoing evolution of ASKAP feed package (Mk. II → Mk. III → Mk. ?)
- 'Rocket' element demonstrated 5 x 4 array (40 Elements)



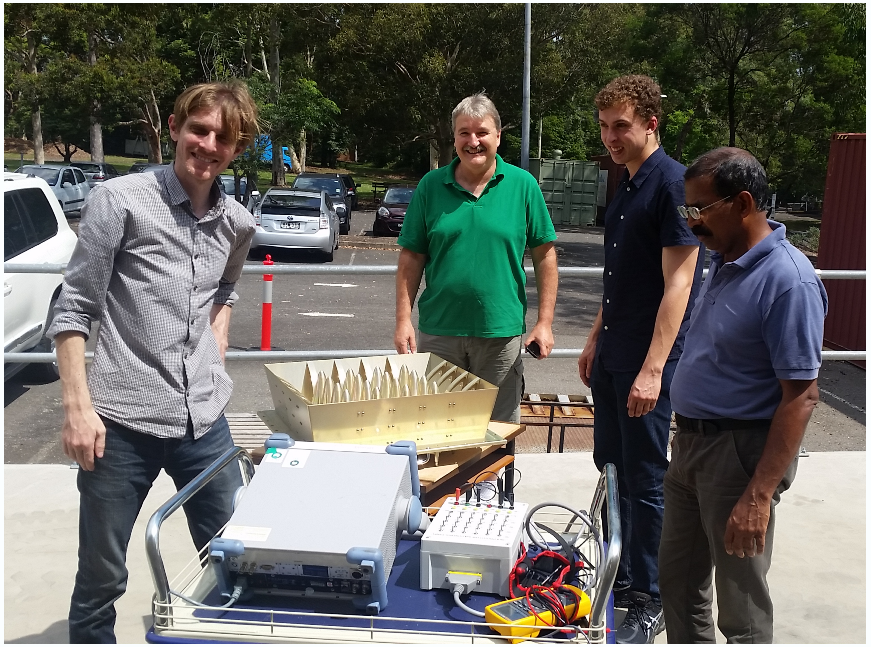


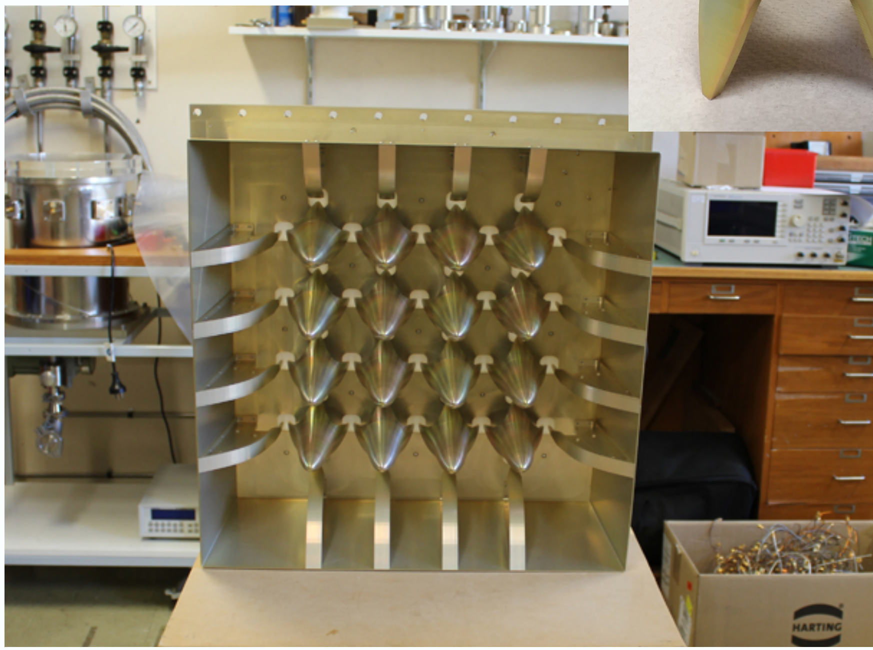




# Element and LNA Design

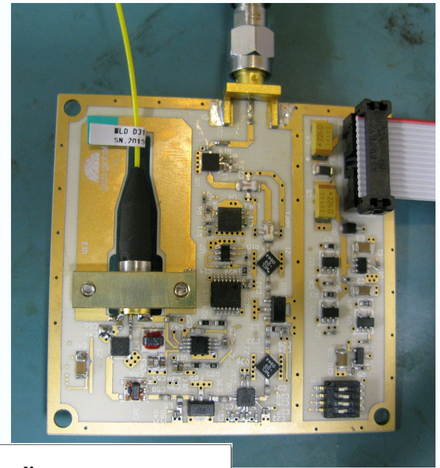
- Element based on a conical solid of revolution
- Edge elements designed to reduce the effect of the edge discontinuity
- Feed line loss minimised
- Balanced LNA – Differential impedance 180Ω
- Commercial HEMT LNA – TriQuint TQP3M939 & TQP3M9040
- 5 x 4 array constructed as proof-of-concept

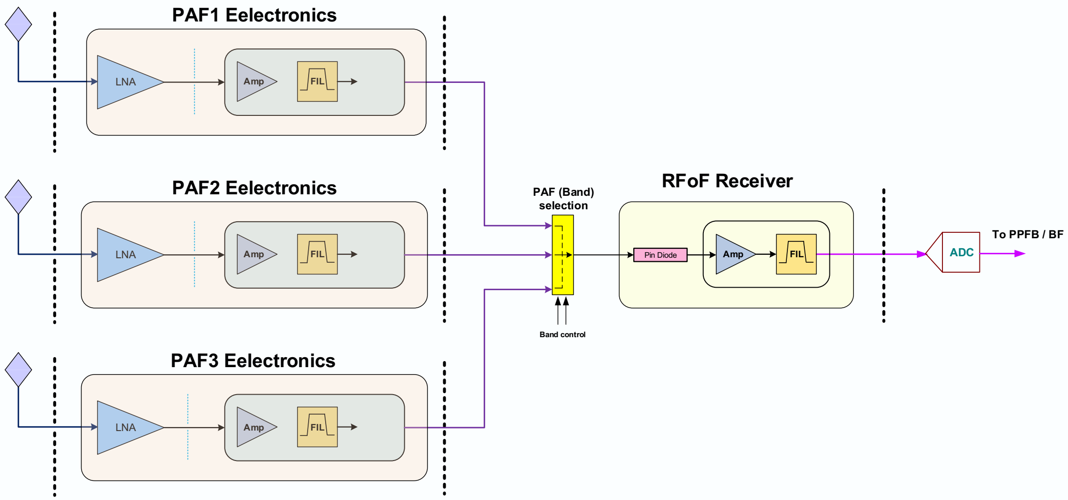




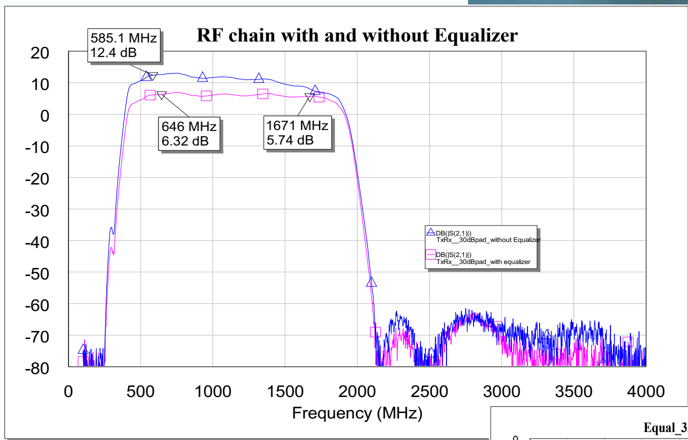
# RF Signal Chain

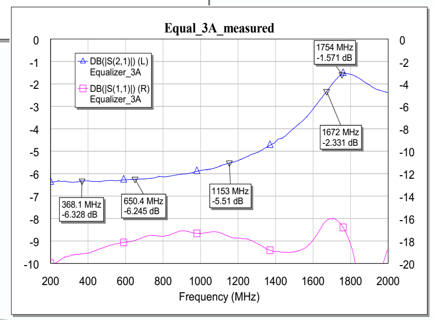
- Leverage off other developments – SKA
- Common RF system architecture – SKA bands (1, 2, 3)
  - ➢ RF over Fibre (RFoF) for signal transport (ASKAP)
  - ➢ Integrated 8 channel assembly completed and tested
  - ➢ Allows direct interfacing with ASKAP digital backend





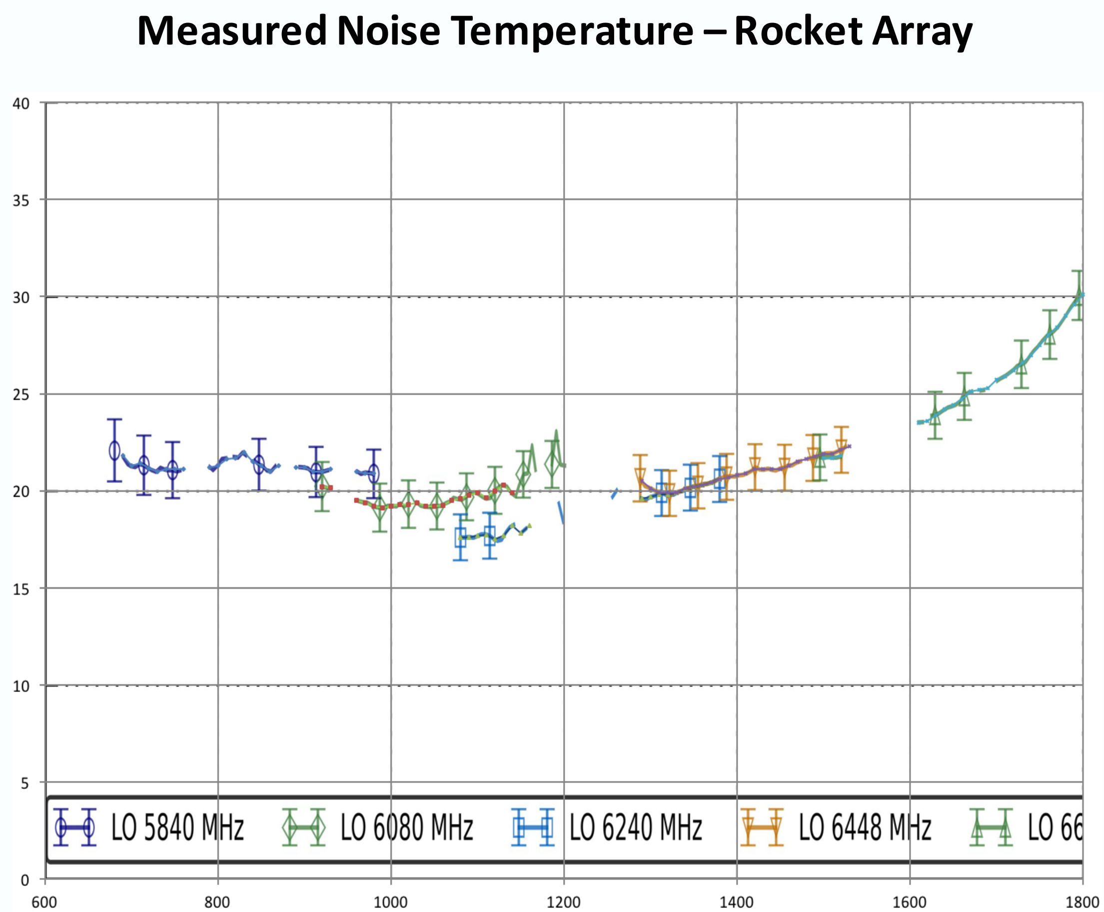

Simplified System Block Diagram
(Y. Chung 2015)




Prototype RF Signal Chain Gain

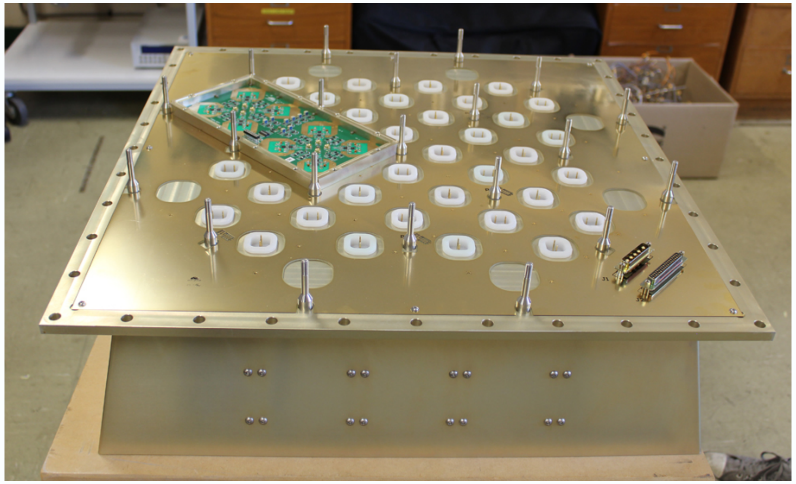
# Measured Performance – Parkes Test Facility

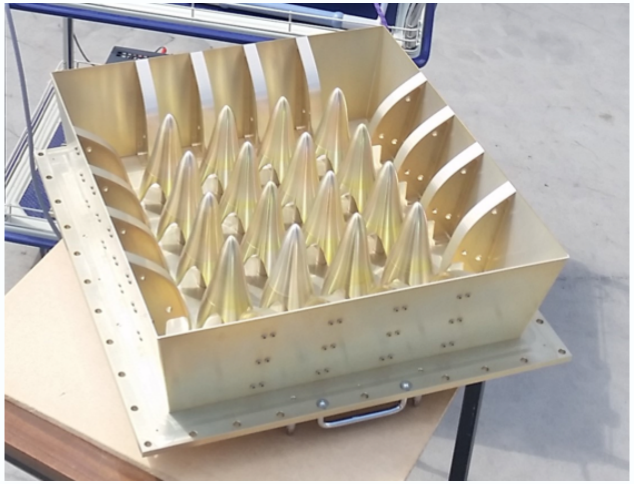



- Measurement using max SNR beamweights, using the Parkes Test Facility – BETA digital backend.
- Measurement “calibrated’ using ASKAP (Mk. II) reference array.
- Gaps in the measurements are caused by RFI whilst the vertical displacement is due to the measurement system.

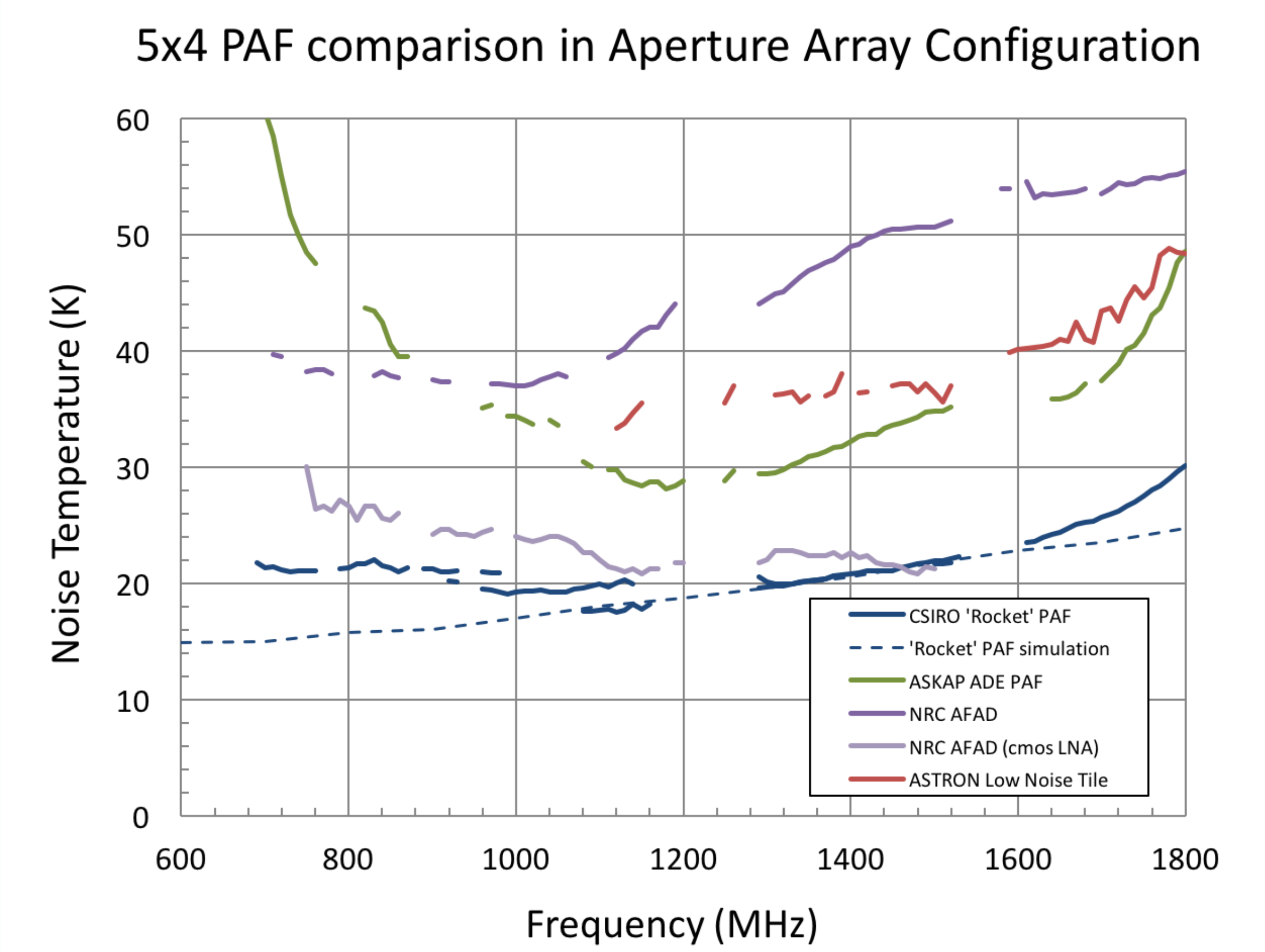
# Future Work

- Hot/Cold load testing ($LN_2$) – ASKAP Mk. II digital backend (Mar 2016)
- Installation on Parkes 64m antenna – Bonn PAF backend (Sep 2016)
- LNA development – Parkes Ultra-Wideband Receiver
- Investigate cryogenic system issues
    - Cooled elements
    - Vacuum window
    - Hermetic feedthrus
- Sampling at the Focus





# Performance – Room Temperature PAFs

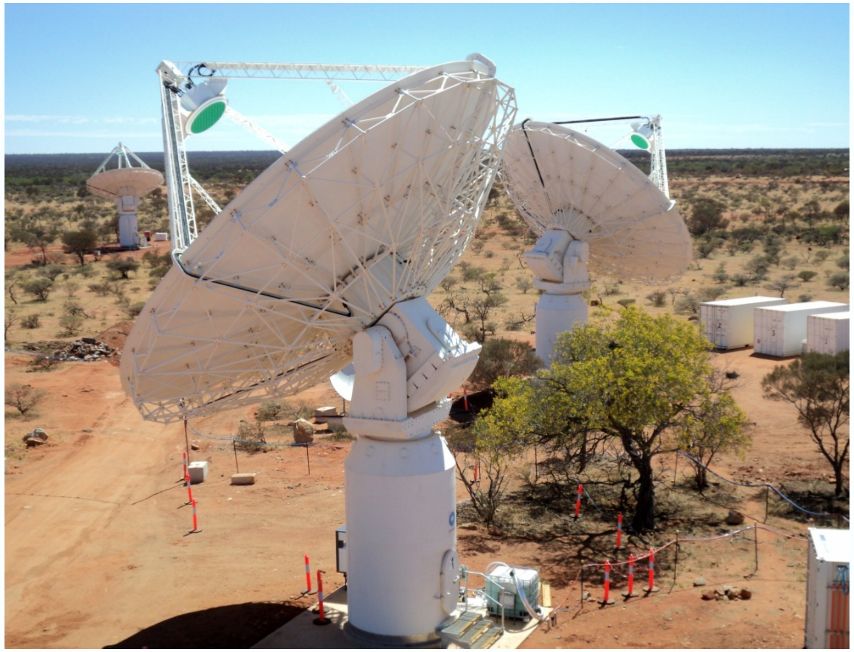



- Measurements “calibrated’ using ASKAP (Mk. II) reference array.
- Gaps in the measurements are caused by RFI.

# The Future

## CSIRO Strategic Development

- Enhance existing Australia Telescope National Facility (ATNF) Instruments
- Reduction in PAF Tsys achieved in SKA work incorporated into ASKAP
- Participate in SKA PAF AIP
- Continue collaborative measurement program (NRC, ASTRON, JBCO, INAF)
- Engagement with broader PAF community



- Cryogenically cooled PAF for Parkes
  - Rocket array element geometry
  - RFI/EMI considerations
  - Sampling at the focus
- Increase bandwidth >2.5:1
- High frequency PAF – 22GHz
- Design for manufacture
  - Cost, Mass
  - Power consumption



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# Radio Astronomy in General

- PAFs on large single dishes – Parkes, Effellsberg, Lovell, SRT, Arecibo & GBT
- Cryogenic PAFs
- High frequency PAFs (2GHz – 20GHz)
- Continue collaborative programs (NRC, ASTRON, JBCO, INAF, CSIRO, NRAO)
- PAFs on the SKA

*We acknowledge the Wajarri Yamatji people as the traditional owners of the Murchison Radio Observatory site.*

**CSIRO Astronomy and Space Science**

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www.csiro.au

# References

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