SKA Phased Array Feed Consortium Update

SKA Engineering Meeting

15 June 2017

Steve Barker

Outline

- Consortium overview – membership, size & objectives
- R&D activities
- Science areas for PAFs
- PAF design considerations
- Challenges
- Future steps
- Conclusions

PAF Consortium Overview

SKA SQUARE KILOMETRE ARRAY
PHASED ARRAY FEED

Current Members:

MANCHESTER 1824
The University of Manchester

INAF
INSTITUT SUR LA NUTRITION ET LES ALIMENTS FONCTIONNELS

ASTRON

AVANCEZ 1829
CHALMERS

University of Malta

CSIRO

Max Planck Institute for Radio Astronomy

Joint Laboratory for Radio Astronomy Technology (JLRAT)

Prospective Members:

INSTITUTO de ASTROFISICA de ANDALUCIA
CSIC
I·A·A

IEEC
INSTITUT D'ESTUDIS ESPACIALS DE CATALUNYA

Size & Objectives

In-kind contribution:

Approximately 24 FTE-years and 700k€; over 2 years

The consortium aims to:

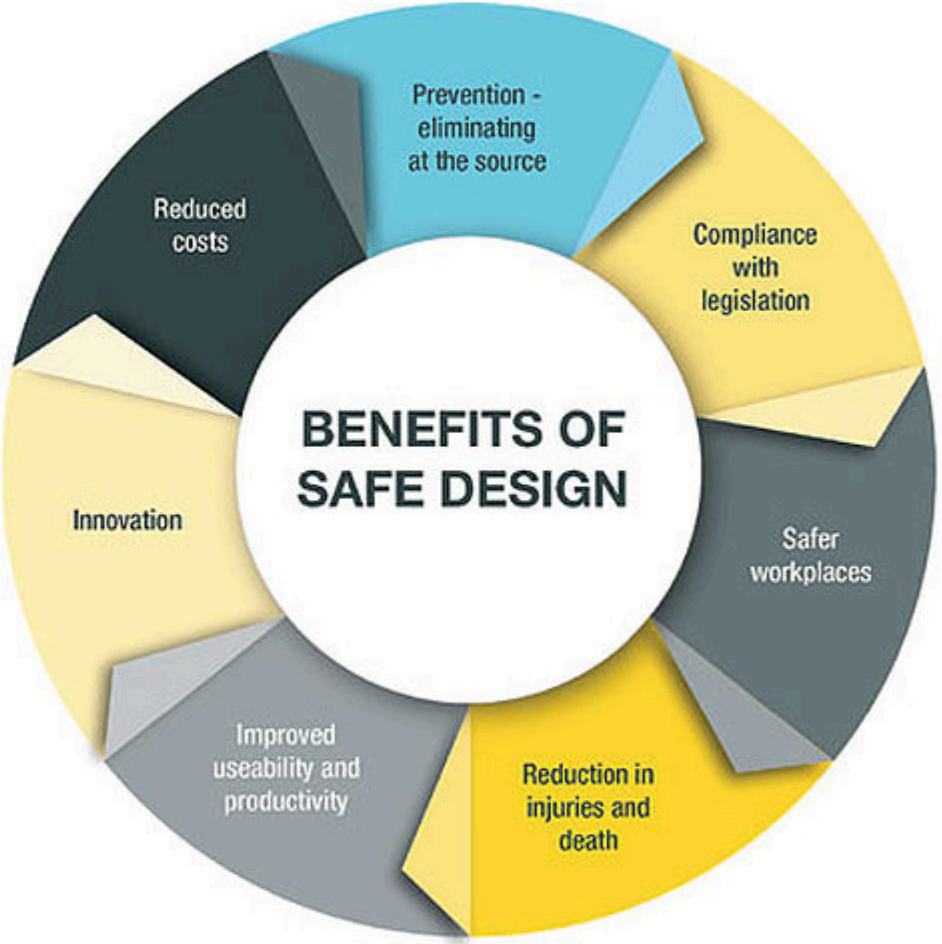
- Provide a vehicle for PAF R&D projects operating within the member institutes, and report on the work occurring in these projects to the SKA and broader PAF community.
- Review & verify requirements and performance metrics for SKA PAFs
- Progress toward PAF concept definition(s) leading into ODP.

Scope of Work being Investigated

- Room Temperature PAFs at low frequencies
- Cryogenic PAFs at low and higher frequencies
- Signal Chain Design / Digitisation
- Signal Processing / Beamforming
- Calibration
- RFI mitigation techniques
- Cost (manufacture & operating)
- Power consumption
- Manufacturability & maintainability
- Weight reduction

Safety

- Health & Safety is an integral part of workplace behaviour and attitudes.
- Designers aim to identify hazards which may create significant risks and seek to reduce them
- **Focus on Safety in Design**



R&D Activities

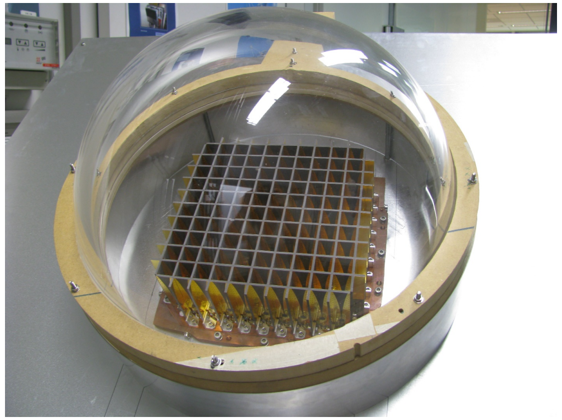
PHAROS2 (U.Manchester, INAF, ASTRON, Chalmers & U.Malta)

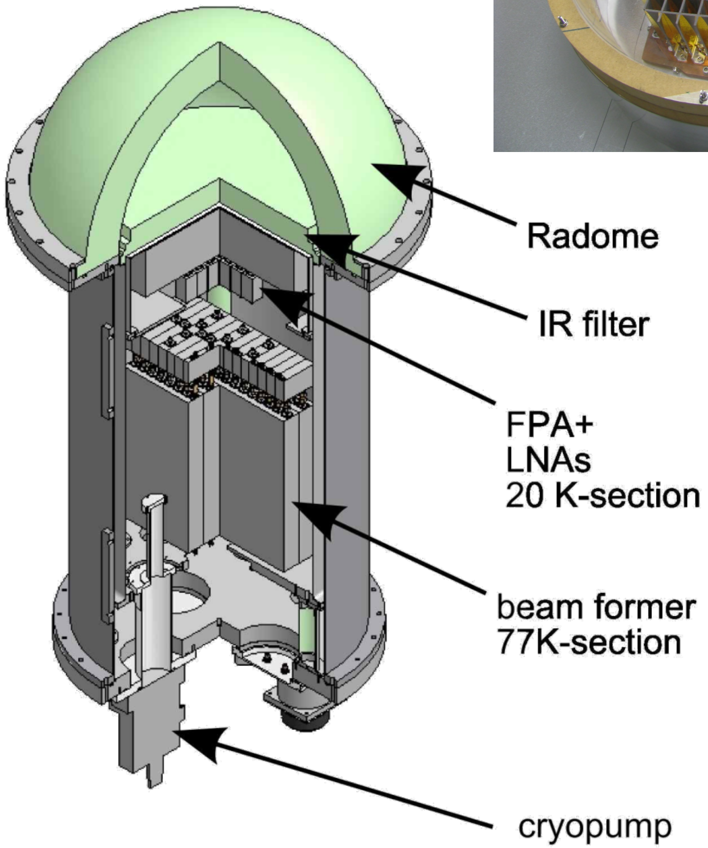
SKA SQUARE KILOMETRE ARRAY
PHASED ARRAY FEED

Upgrade of a 4 to 8 GHz Cryogenic PAF.

PHAROS2 will have:

- 24 active elements ➔ 4 single-pol beams
- 275MHz processed BW
- Tuneable LO down-conversion
- IF over Fibre (CWDM)
- Upgrade to new cryogenic LNAs
- Upgrade to digital beamformer





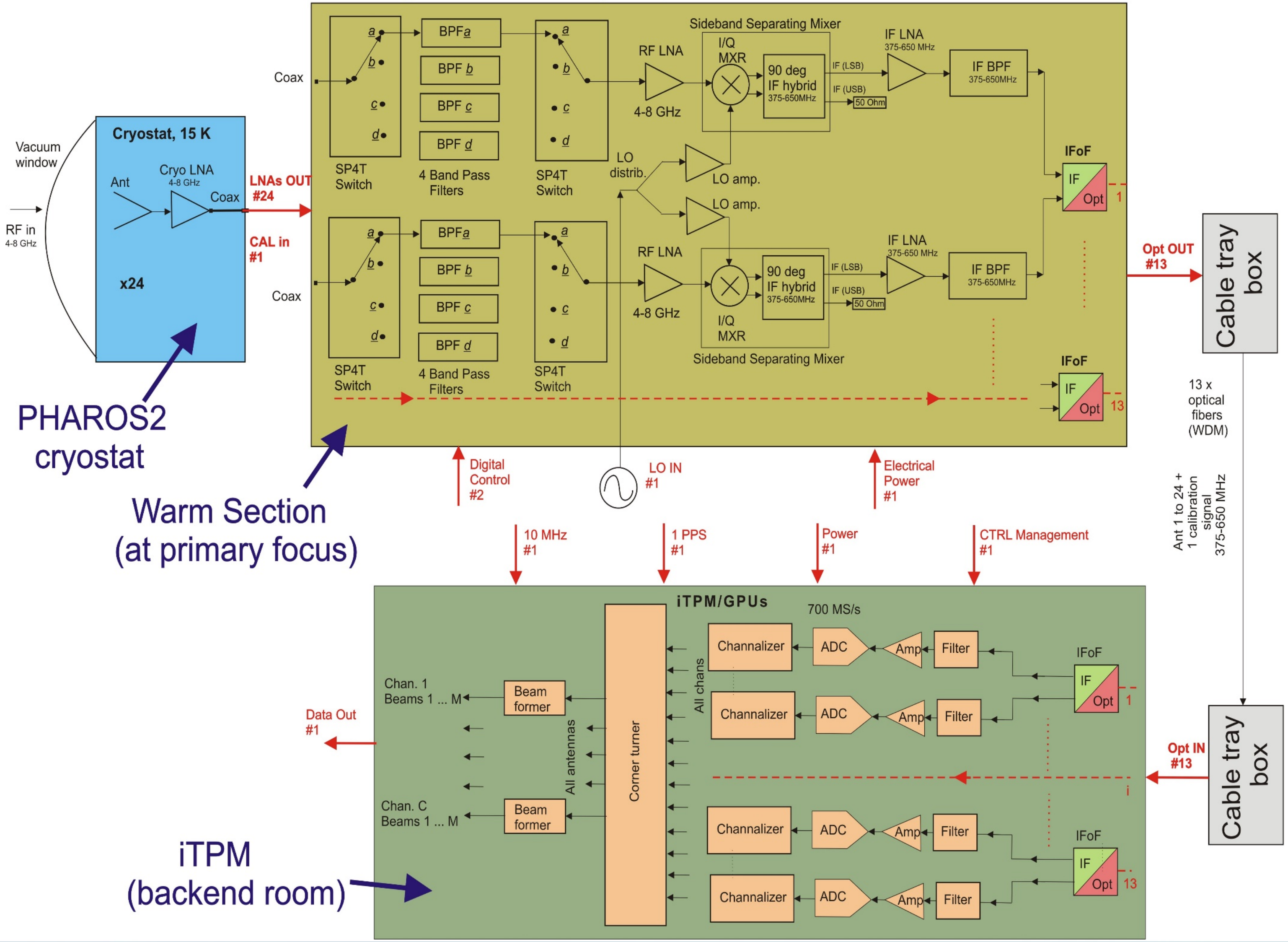
Aim is to install PHAROS2 on the 76m Lovell telescope at Jodrell Bank in Q2/Q3 of CY2018

PHAROS2 Work-package

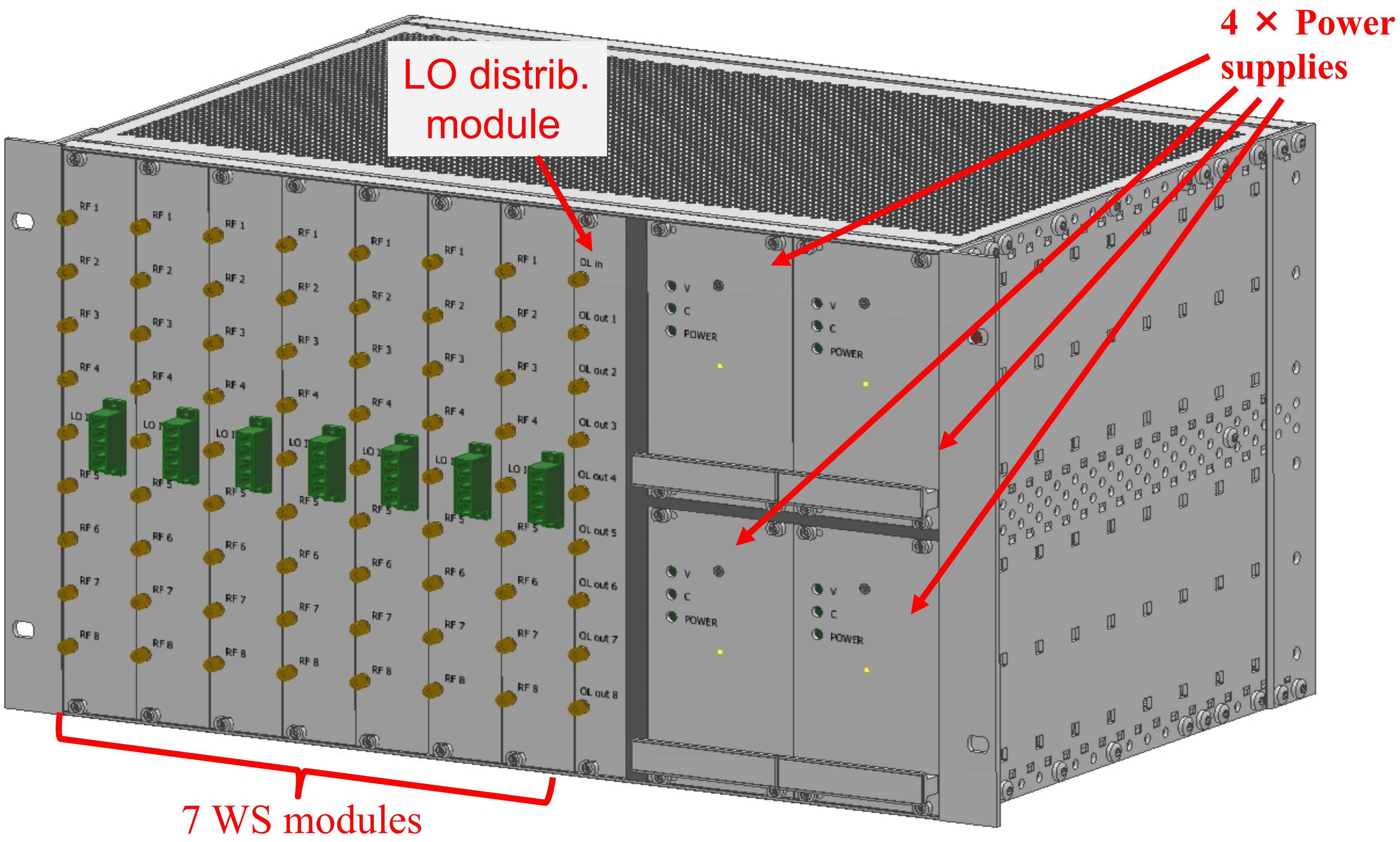
- ASTRON – Providing legacy PHAROS info & hardware; Reporting on APERTIF commissioning; Reviewing PHAROS2 design
- INAF – System Architecture of sub-assemblies; Down-conversion; RFoF signal transportation; Digitisation with iTPM; Beam-forming with PCs/GPUs & TPM-FPGA; field tests
- U. Manchester – Simulation of PHAROS on Lovell; acceptance testing; hardware integration & verification on Lovell
- Chalmers – Investigating technologies for EM & mechanical/cryo design; bias & protection circuitry for LNAs; modelling of receiver Noise Temp.
- U. Malta – Software for C&M of the digital signal processing; upload of beam-forming coefficients; calibration algorithms & calculation of co-variance matrix

PHAROS2 System

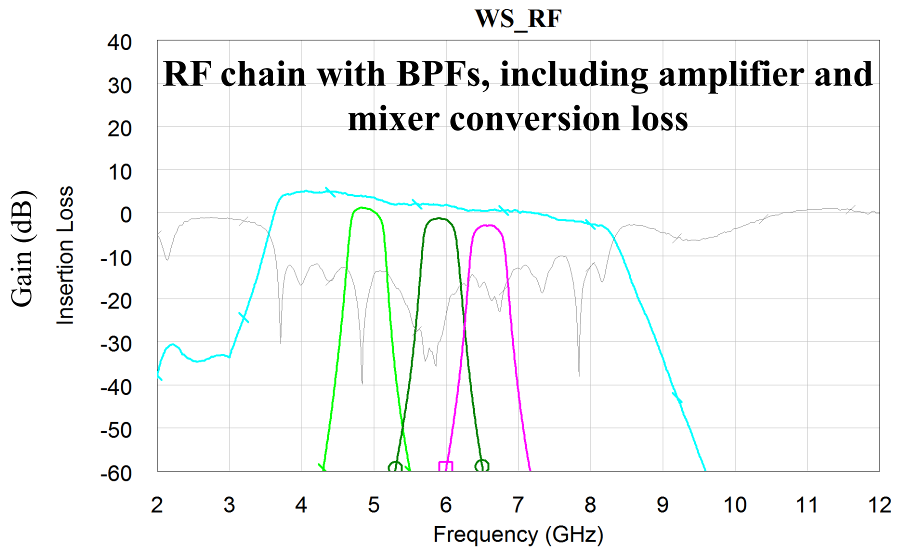
Schematic diagram of single-polarization PHAROS2 PAF

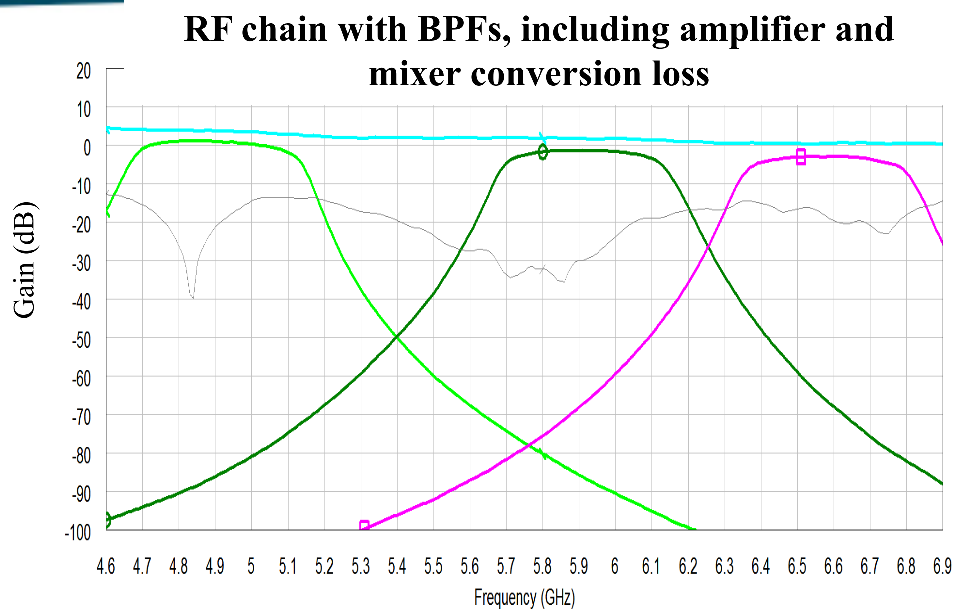


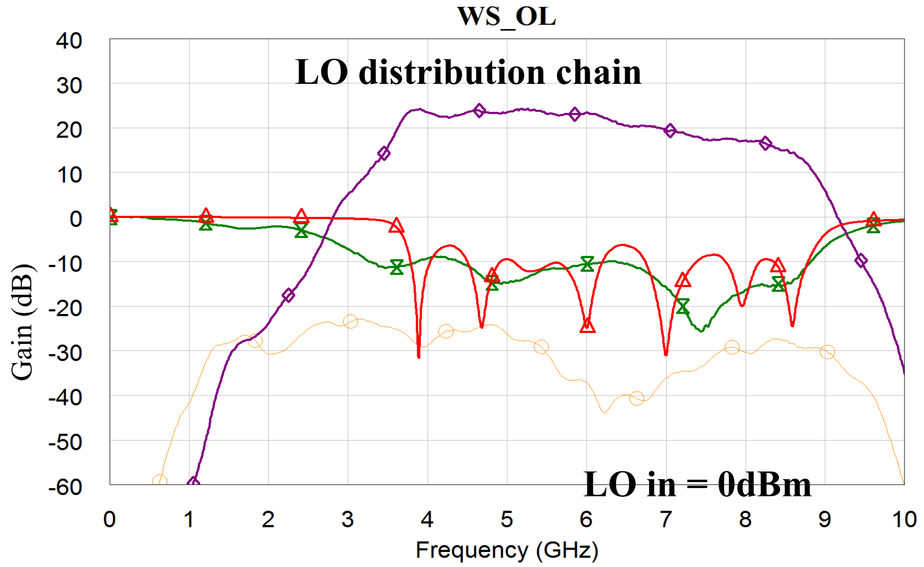
PHAROS2 Warm Section Rack

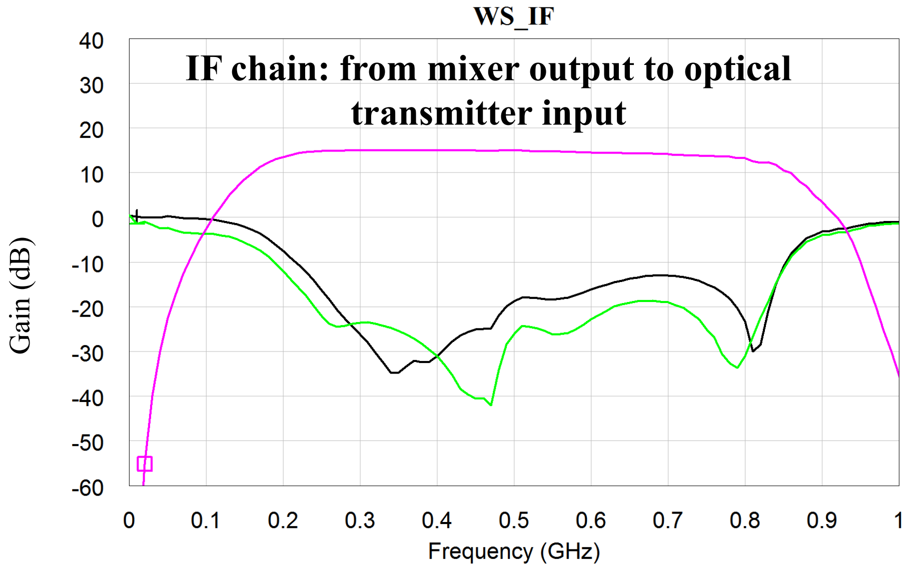


Electromagnetic simulation results of WS module



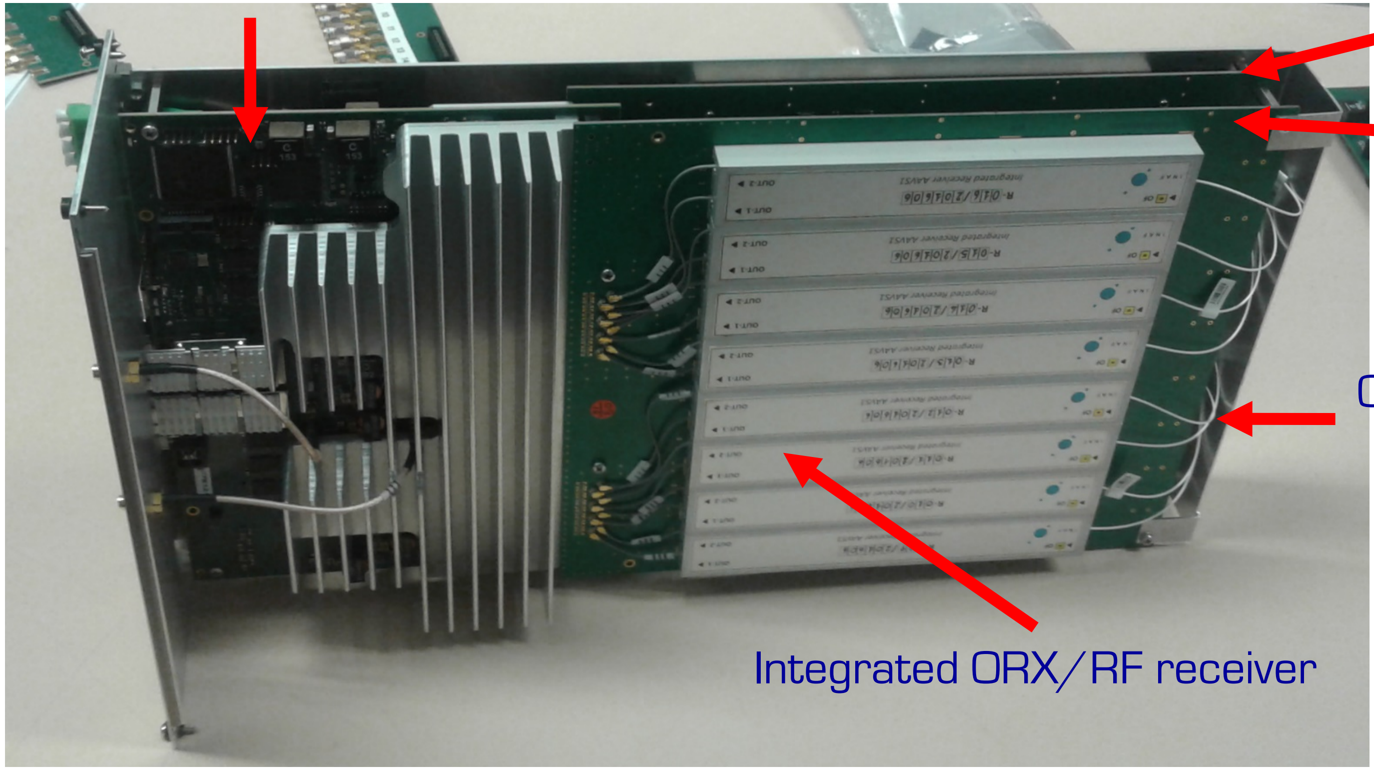






iTPM

- Includes one ADU and two preADUs
- One preADU has 8 fiber optics receivers

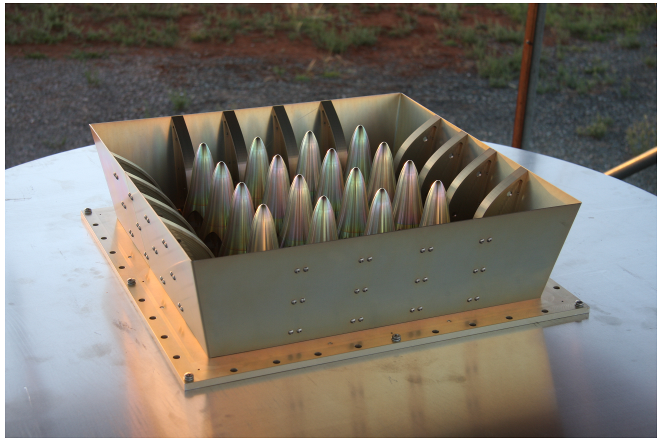


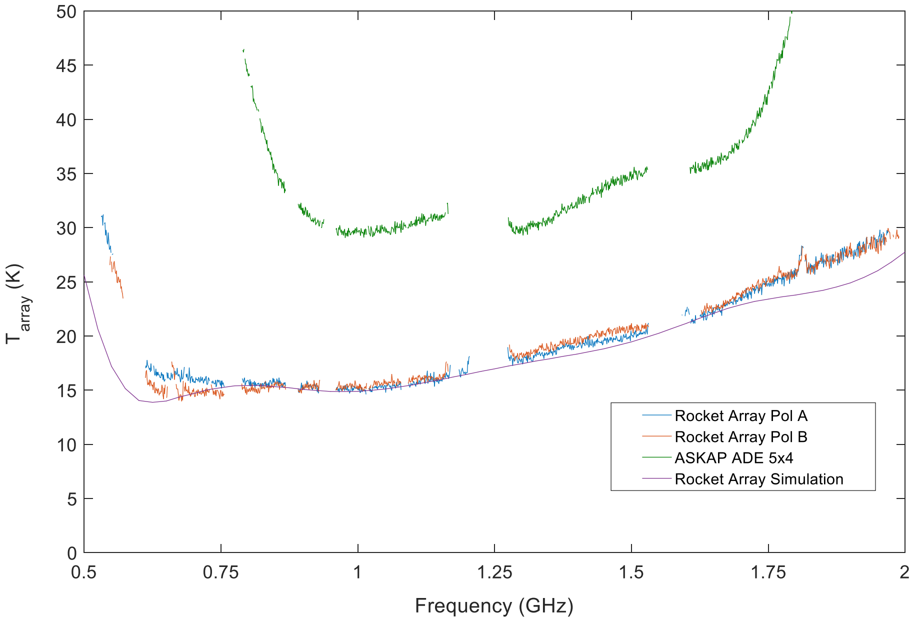
"Rocket" PAF (CSIRO)

SKA SQUARE KILOMETRE ARRAY PHASED ARRAY FEED

Mk. III PAF

- Optimised for 650 – 1650 MHz (3:1)
- Element based on a conical solid of revolution
- 5 x 4 array constructed as proof-of-concept
- Measured at Parkes on the 64m Telescope, but compromised by RFI
- Aim to remeasure using narrow band receiver later in 2017/18
- Plan to develop a full-size L-band cryogenic PAF in 2018 for the Parkes 64m telescope.





Analogue Beamformer Noise Temperature

ASKAP Commissioning (CSIRO)

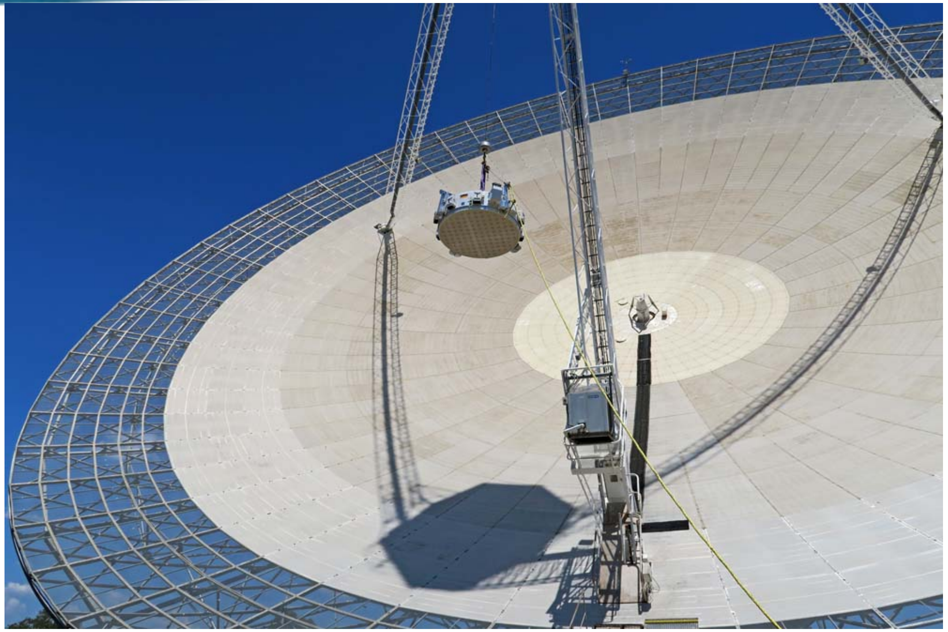
SKA
SQUARE KILOMETRE ARRAY
PHASED ARRAY FEED

Current Focus:

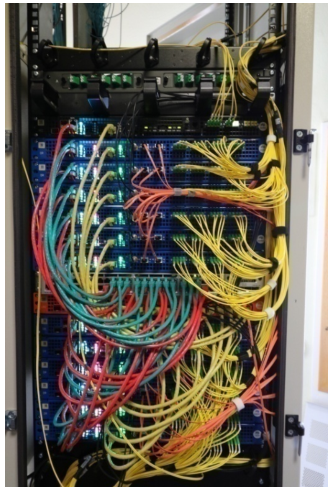
- Beamforming – generalised beamforming approaches including beam metrology & characterisation, beam-shape and calibration
- Sensitivity Assessment – goal to automate the evaluation of System Equivalent Flux Density (SEFD) every time ASKAP observes its primary flux calibration source
- Astrometry – to understand position offsets in known sources due to possibly the ionosphere, instrumental effects, un-modelled structure in the calibration field and/or cell size of the image
- Data Validation – exploring how to qualify data with known deficiencies
- Metadata – reviewing the information that is archived with the data

ACES Memo Series:
http://www.atnf.csiro.au/projects/askap/ACES-memos

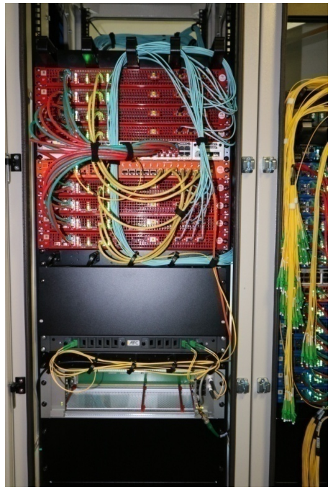
PAF on Parkes (CSIRO, MPIfR)



PAF: 600 MHz



DRX: 600 MHz



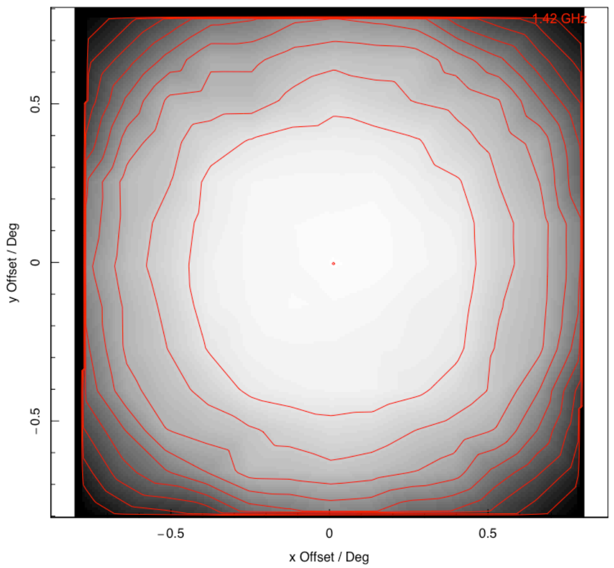
BMF: 384 MHz

14 GPU nodes

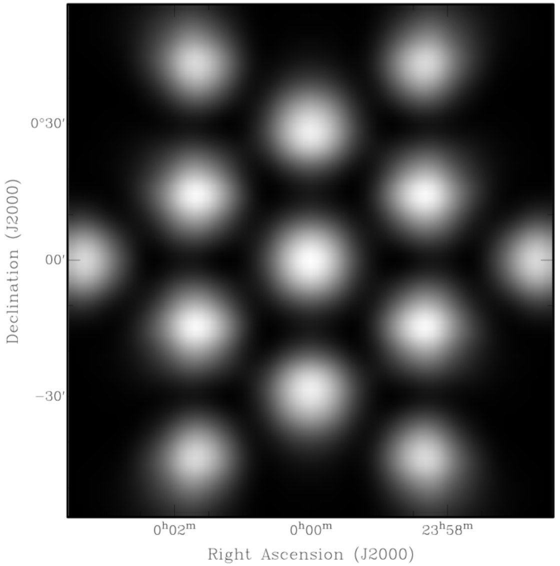
PAF System at Parkes

- 188 ports, 94 ports each polarization, 4 spare ports
- 36 beams x 2 pol x 336 MHz voltages streamed to GPUs (1 MHz resolution)
- 16 beams x 2 pol x 384 MHz spectra download (18 kHz resolution)
- Tested 18 beams in streaming mode and 16 beams in spectral-line mode

PAF sensitivity envelope

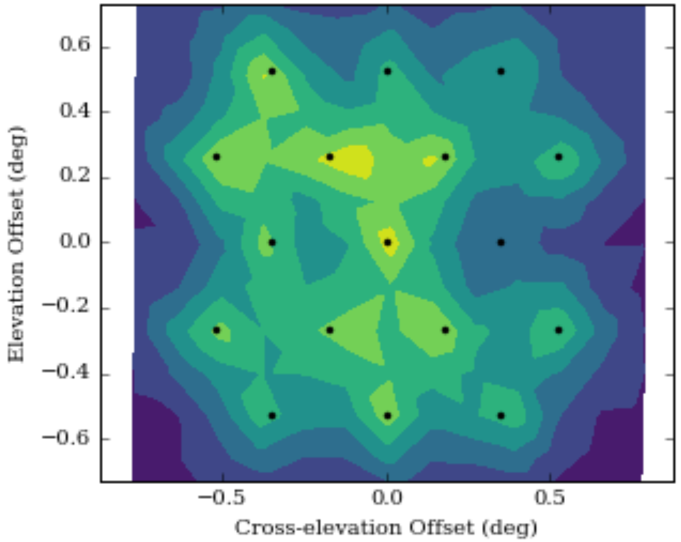


Multibeam sensitivity



13 beams

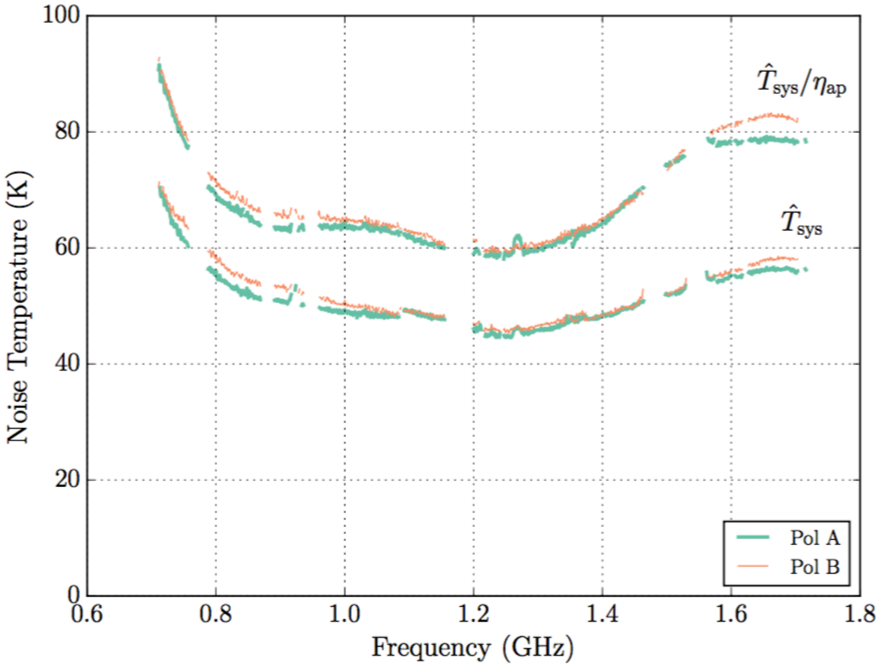
MPIfR PAF beam sensitivity

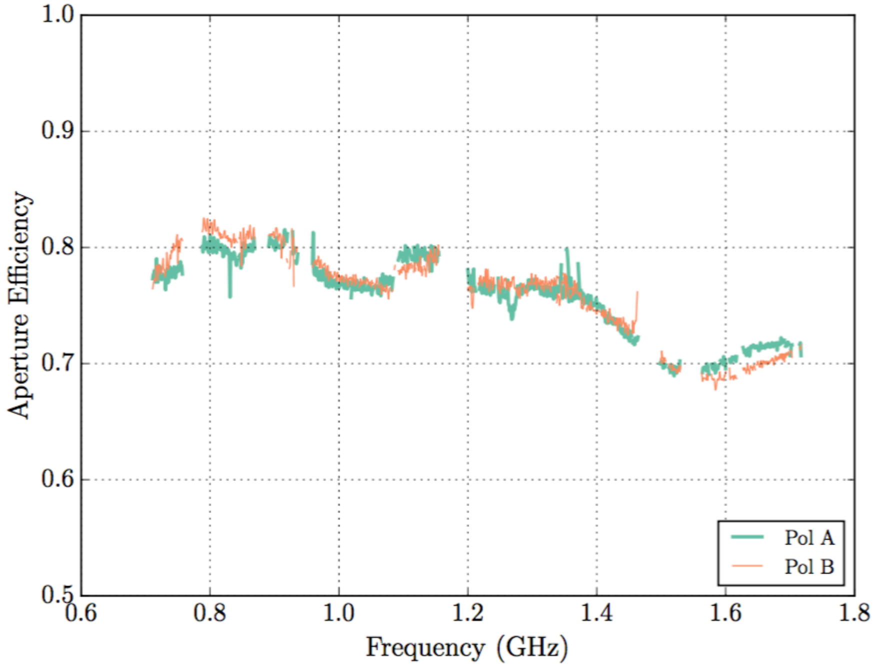


17 beams

Noise temperature of on Parkes 64 m

- System temperature is around 50 K from ~ 800MHz to 1400MHz
- It is significantly better than ASKAP (around 90 K)
- Efficiency is around 0.8 across these frequencies
- Temperature over efficiency is around 60 K across these frequencies



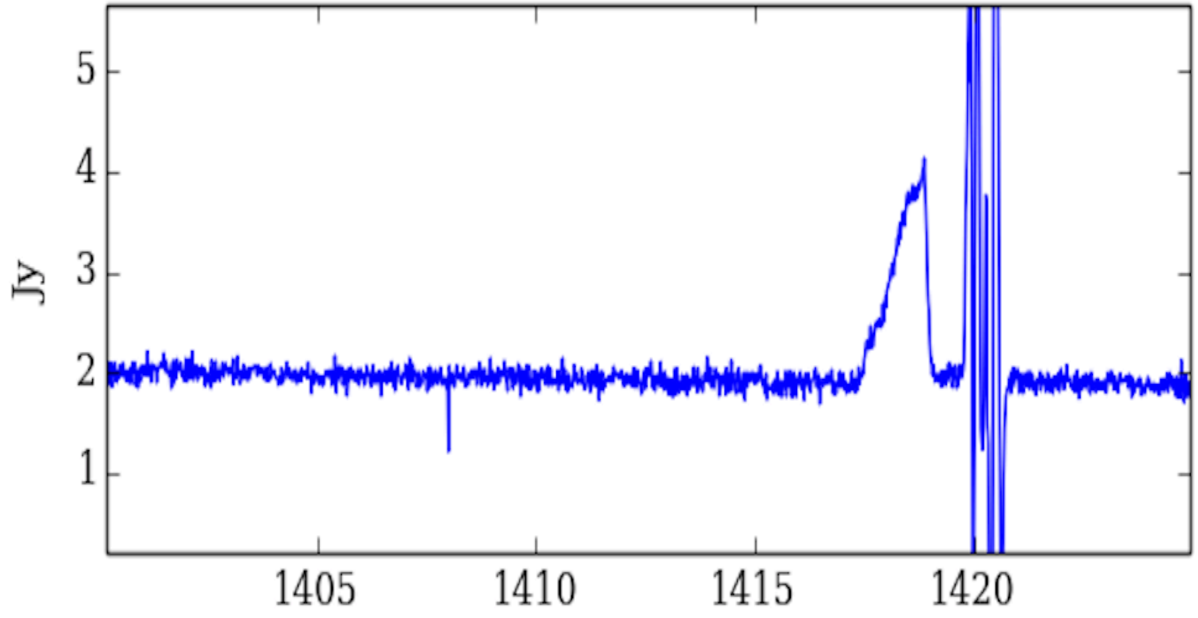


(Chippendale et al., ICEAA 2016 arXiv:1606.03533)

PAF on Parkes HI astronomy

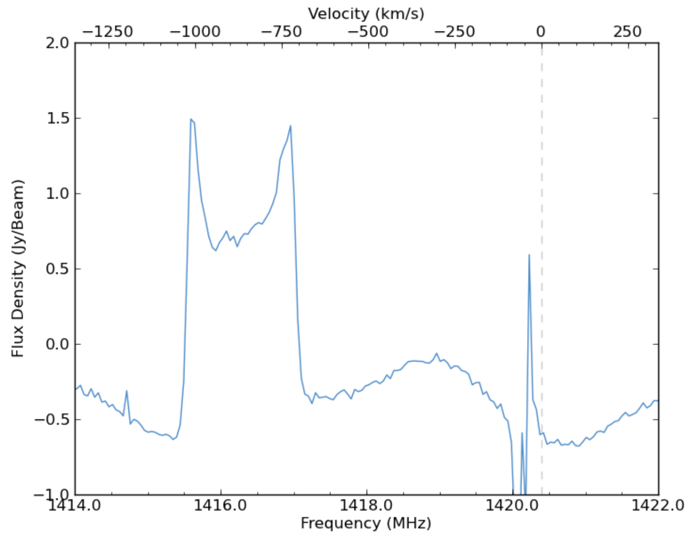
PHASED ARRAY FEED

MPIPAF@Parkes: August 2016 No standing wave!



(credit: L. Staveley-Smith and J. Rhee)

HIPSR first light: Oct 2011



PAF on Effelsberg (MPIfR)

- In April/May, MPIfR installed a CSIRO Mk II chequerboard PAF on the 100m Effelsberg Telescope
- First tests occurring in the telescope focus.
- Backend hardware installed, software still in progress.
- Survey of spectra for RFI vs. elevation have been taken.
- Plan to use the PAF for pulsar and FRB searches and for wide-field imaging *

Photo credit: Michael Kramer

* X. Deng, et al, "Observing Pulsars with the PAF at the Parkes Telescope", Publications of the Astronomical Society Australia 2017

PAFs in China (JLRAT)

- JLRAT is working on developing a cryogenically cooled 19 dual-pol (dipole) element PAF for the FAST telescope operating from 1050 – 1450 MHz.
- The motivation is to produce high-performance beams to achieve better sensitivity and continuous sky coverage over the FOV.
- JLRAT is also looking at a PAF with 31 dual-pol elements for the SKA DVAC.
- A simulation study of the PAF on the SKA DVAC is proposed to investigate the gain and sensitivity. This is in addition to previous modelling of a PAF and SKA dish during the optimisation of the SKA dish optics.

Associated R&D work

- Chalmers plans to investigate ambient LNAs for L-band PAFs with the Low Noise Factory
  - includes transistor design, wafer processing in the clean room, on-wafer characterisation with a probe station, and single device characterisation.
- U. Manchester have bought an ASKAP Mk II PAF and plan to install it on the 76m Lovell later this year.
- Discussions have commenced around putting a PAF on the SKA-MPI verification antenna when it might be available – probably in several years from now.

Science

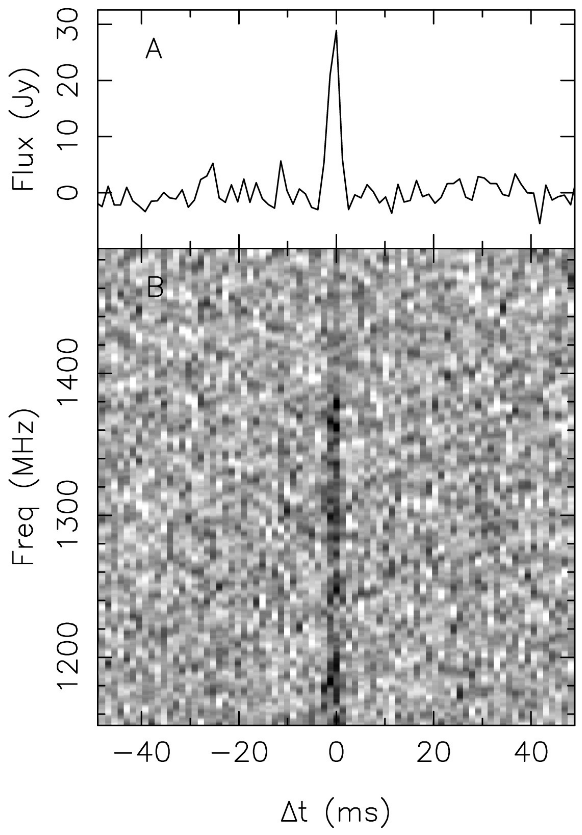
Science

With Low Frequency PAFs ≤ 1.6 GHz

- HI emission surveys
  - “A billion galaxy survey” to investigate Dark Energy
  - Study of Baryonic Acoustic Oscillations to shrink error bars on dark energy parameters
  - Intensity Mapping Survey to determine expansion and growth history of the Universe
  - Study of the Milky Way ISM ➔ Galaxy evolution

Science

- Continuum Surveys & Polarisation
  - Precision Cosmology
  - Growth of super-massive black holes
  - Gravitational lens systems
  - High resolution imaging of weak lensing
  - Magnetic field studies & rotation measures
- Transients & Pulsars
  - Slow (imaging) transients
  - Pulsar survey ➔ test of gravity, equation of state of matter
  - Fast (sub-second) transient detection*



The signal of FRB 170107, found using CSIRO's ASKAP radio telescope in less than four days of looking. Credit: K. Bannister et al.

* K. Bannister, et al, "The Detection of an Extremely Bright Fast Radio Burst in a Phased Array Feed Survey", The Astrophysical Journal Letters

Science

With Higher Frequency PAFs ~ 4 - 8 GHz (PHAROS2)

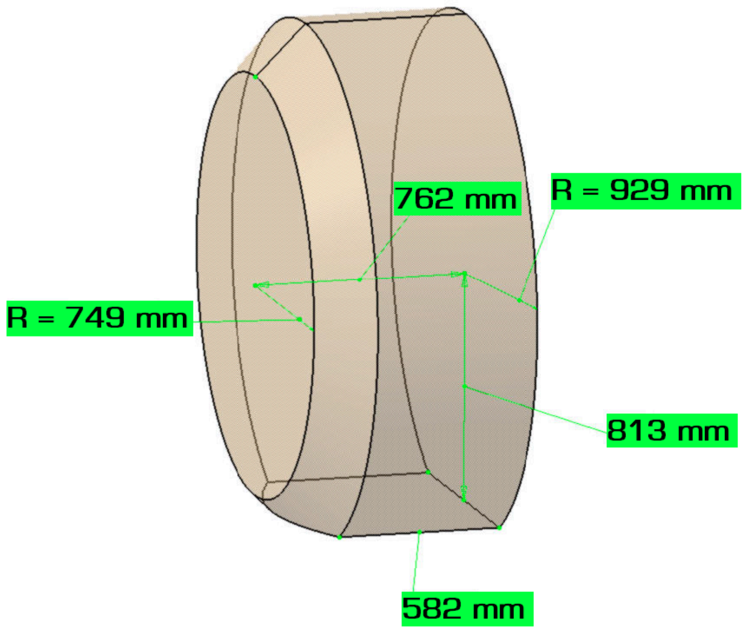
- Spectral lines studies
- Fast C-band continuum surveys, and polarization meas. in particular in the Galactic Plane (to improve existing surveys to ~2.5' resolution)
- Flat spectra transients/pulsars, (e.g. magnetars)
- Excited rotational states of OH near 6.03 GHz: Zeeman effect, star formation
- CH3OH (6.7 GHz): survey of methanol masers, gas kinematics, UC HII region
- Formaldehyde line emission at 4.8 GHz
- Confusion limited polarization mapping of Galaxy Clusters and Supernova Remnants
- Hydrogen recombination lines around 5 GHz
- High Dispersion Measure pulsar searches toward the Galactic Centre and inner Galaxy

PAF Design Considerations

Constraints

SKA Dishes have allowed for inclusion of a PAF in their design:

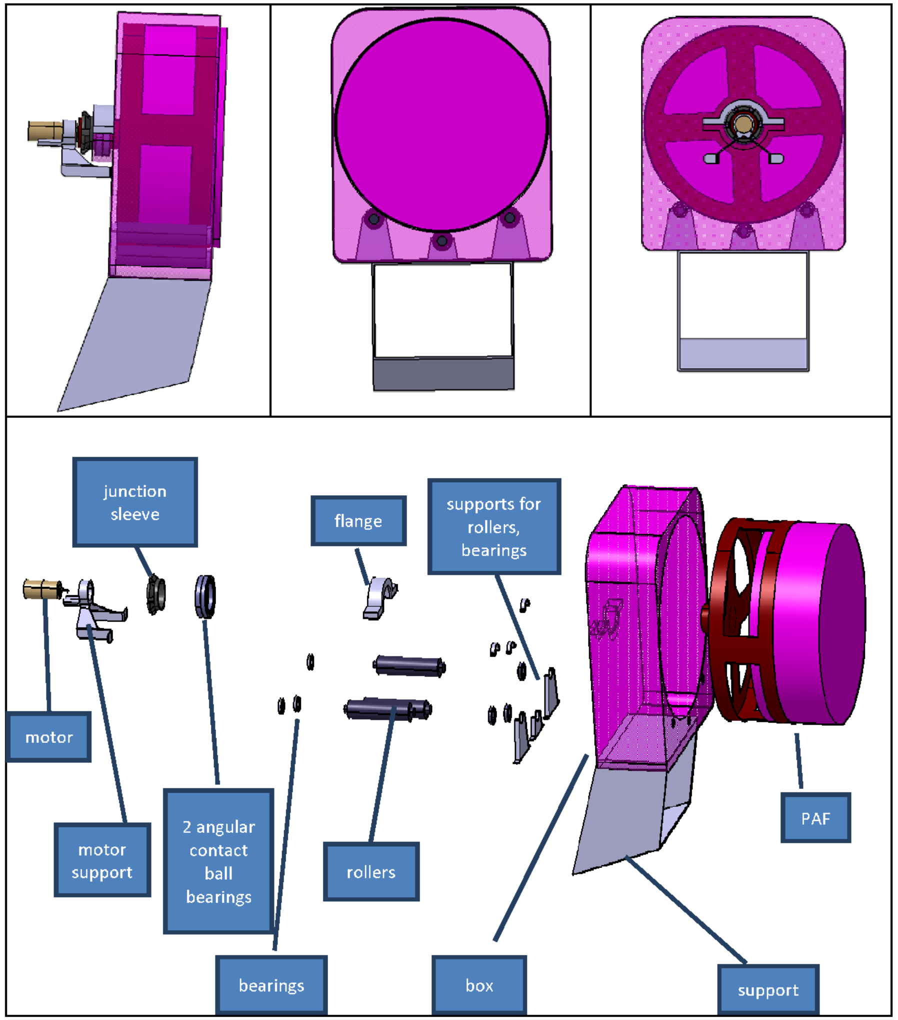
- PAF to use SPF Band 1 location on feed indexer
- ≤ 1.6m diameter x ~500mm deep (TBC)
- Weight up to 250kg (TBC)
- Power 1150W (TBC) on indexer; 2600W (TBC) for digitiser & beamformer – current ICD assumes 100% PSU efficiency
- Digitiser & beamformer located in separate RFI shielded bunker
- Sky de-rotation required with an Alt-Azimuth mount



Many of these parameters need to be verified.

Sky De-Rotation

- The SKA-Mid antenna with an alt-azimuth mount will require sky de-rotation.
- Provision for mechanical de-rotation is planned, but beam weights will still require frequent updating.
- Electrical de-rotation will most likely be needed instead via software updates to the beam weights.



Mechanical De-rotator

Low Frequency PAF

Potential Design Parameters

- 475 – 1425 MHz (3:1)
- Large processed BW
- T_{sys} ~ 15K - 30K
- 30 beams @ 1 GHz
- ~100 dual-pol elements
- ~ 200 ports (channels)
- Beam-form using both polarisations and most of the elements

High-frequency PAF - scaled in frequency ??

Roadmap considerations

- SKA2 construction planned to start ~2027, so it probably won't be running until ~2037+.
- PAFs could be installed on SKA1 sooner than this, if their price is right!
- PAF's can't be installed on the 64 MeerKAT antennas due to their optics.
- With only 128 SKA1-mid dishes a L-Band PAF would need to be cryogenically cooled to offer a significant improvement over SKA1-mid.
  - Estimate a L-band PAF with 15 K Tsys, 950MHz processed BW & 30 beams @ 1GHz would provide approximately a 10x improvement on survey speed over the full (128 + 64) SKA1-mid. Is this a worthy objective??

Best Case Estimate of System Temperatures

	T_{sys} components at L-band	
	Cryo PAF	Ambient PAF
Sky	5	5
Spillover*	5	5
Element loss	1	3
LNA	3	12
Beamforming loss	1	3
Backend	0.5	0.5
Cryogenic Window	1	0
Total	**16.5**	**28.5**

- Prototype CSIRO Rocket array was not too far off the ambient numbers
- Some degradation in the noise performance expected at the band edges (of a 3:1 system)

Challenges

SKA SQUARE KILOMETRE ARRAY
PHASED ARRAY FEED

- Noise performance & bandwidth need to be competitive with traditional feed horn based systems ➔ cryogenically cooled?
- System cost – needs to be as low as possible – drives design choice & manufacturing, include life cycle cost
- Power – total required & efficiency
- Cryogenics – power required, PAF topology, maintainability
- Cooling – PAF & backend; power, low RFI, robust, cost
- Sky de-rotation – mechanical, electronic, software
- System size & weight
- Data transport & processing
- Beamforming algorithm development
- Calibration

Future Steps

- Review and refresh the system requirements

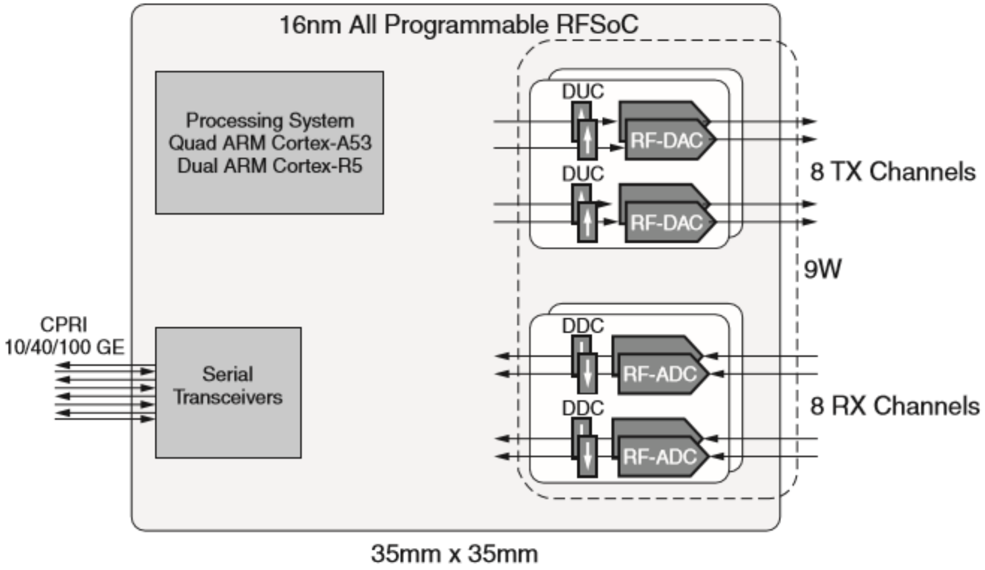
- Develop a technology roadmap for PAFs (Q4/2017)
  - Articulate the goal for PAFs on SKA
  - Describe likely technology development paths and milestones
  - List the current gaps and barriers
  - Establish action items, priorities and timelines for on-going technology development under the ODP.

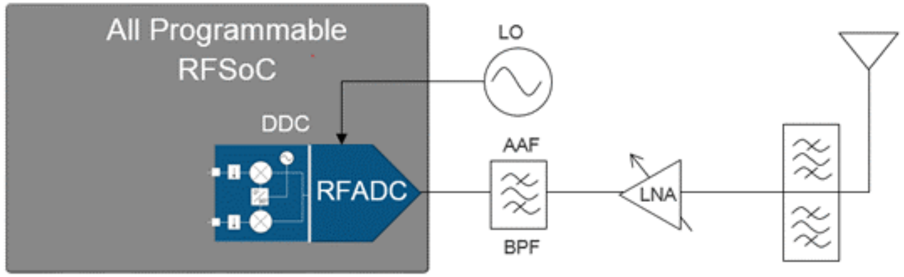
- Draft a PAF Concept White Paper (Q4/2018)

Future Steps

… and time & resources permitting …

- Investigate methods for cryo-cooling a SKA PAF wrt. to cost & power
- Prepare the way to put a PAF on SKA-MPI
- Investigate direct digitisation – Xilinx RFSoC





Conclusions

- SKA Science
  - “require observational statistics on a very large scale” *
  - case for PAFs is strongest in SKA Band 1 and Band 5

- PAFs on SKA1-mid should probably be considered with the SKA2 timeline – this would most likely require a cryogenically cooled PAF for a significant performance increase.

- Power will be a major constraint, even without cryogenics.

- New 16nm FPGAs will help to reduce cost of the data processing. Need to understand this technology’s roadmap.

- System cost is a major driver

* Torchinsky, S.A., “The Questions that Drive the Specifications”, SKADS Conference 2009

Thank You!

Questions?

2017 International PAF Workshop, CSIRO Sydney – November 14-16
http://www.pafworkshop.org – call for abstracts