Phased Array Feed Development for the SKA

SKA AIP Meeting

8 June 2017

PAF Consortium

Outline

- Consortium Overview
- R&D Activities
  - Pharos2
  - “Rocket Array” & ASKAP Commissioning
  - PAFs in China
  - MPIfR
- Science
- Design Constraints
- PAF requirements
- Future Steps
- Challenges
- Conclusions

PAF Consortium Overview

Eight Consortium Members

- ASTRON
- University of Manchester / Jodrell Bank
- INAF
- University of Malta
- Chalmers University / Onsala Space Observatory
- CSIRO Astronomy & Space Science
- JLRAT
- MPIfR

PHAROS2;
C-band Cryo PAF

L-Band Ambient
➔ Cryo PAF

L-Band Cryo PAF & modelling

PAF Science & RFI Mitigation

In-kind Contributions

- 21.6 FTE-year
- ~700k Euro

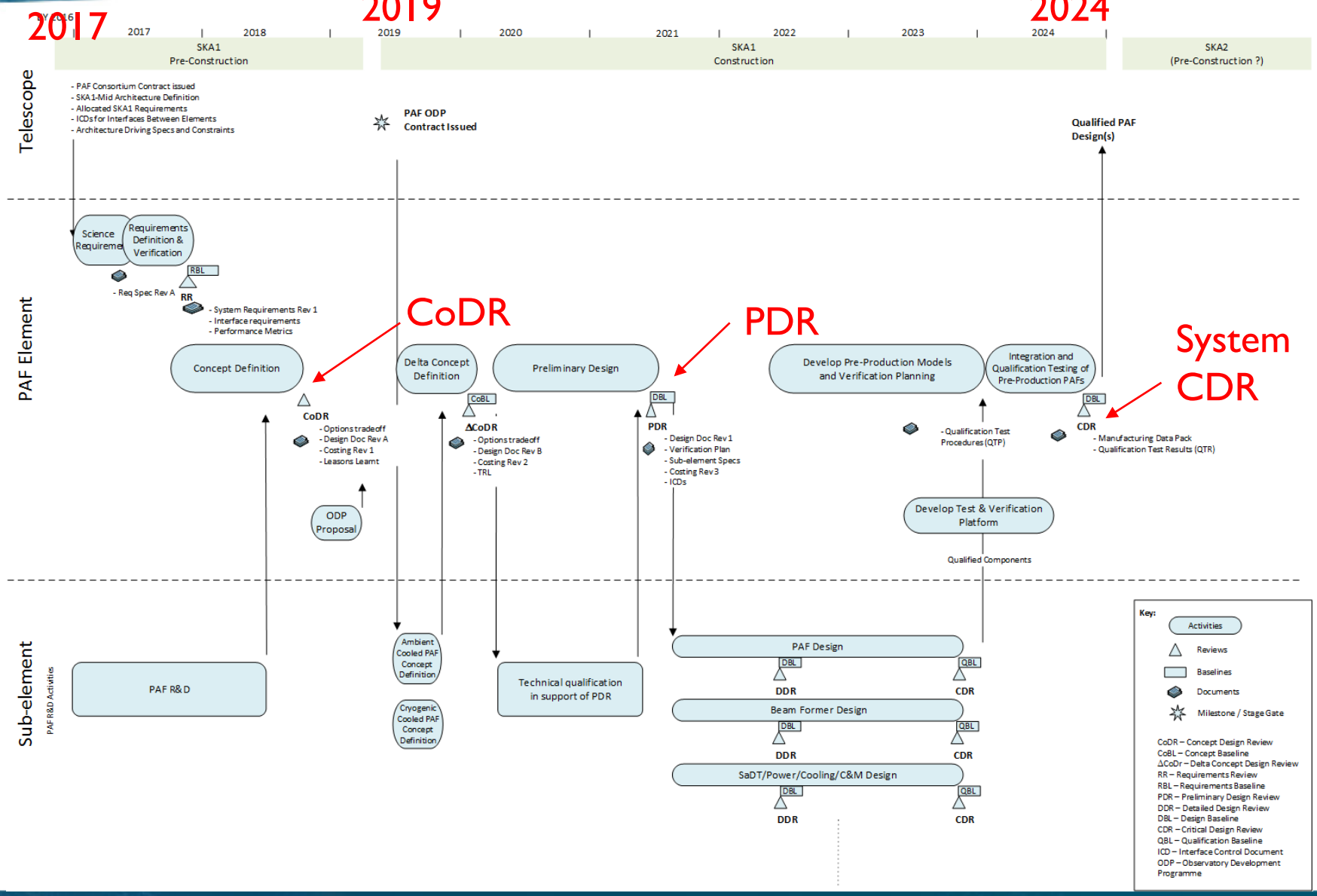
Objectives

The PAF Consortium aims to:

- Report on room temperature & cryo PAF R&D projects occurring within the member institutes
- Develop & verify requirements and performance metrics for SKA PAFs
- Progress toward possible SKA PAF Concept Designs and CoDR
- Develop a solid science & business case to support SKA PAF design work under the SKAP ODP.

- ❖ System Requirements Review (SRR) – November 2017
- ❖ Conceptual Design Review (CoDR) – November 2018

Proposed Roadmap



R&D Scope

Room Temperature or Cryogenic PAFs operating up to 20 GHz with:

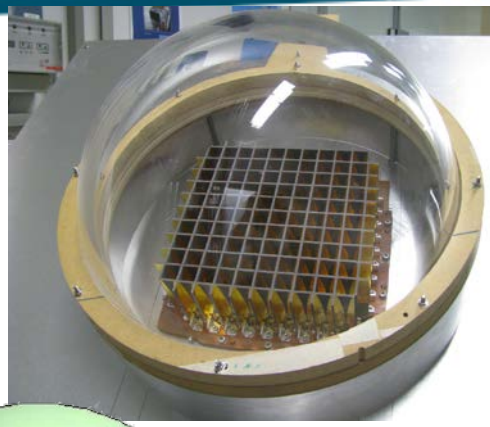
- Improved system temperature
- Increased/wide bandwidth (observed and processed)
- Digitisation, real-time beam-forming, calibration and data-processing
- Cryogenic cooling
- Lower power consumption
- RFI mitigation techniques
- Low cost to manufacture & operate
- Ease of manufacturability & maintainability
- Weight reduction
- Heat dissipation

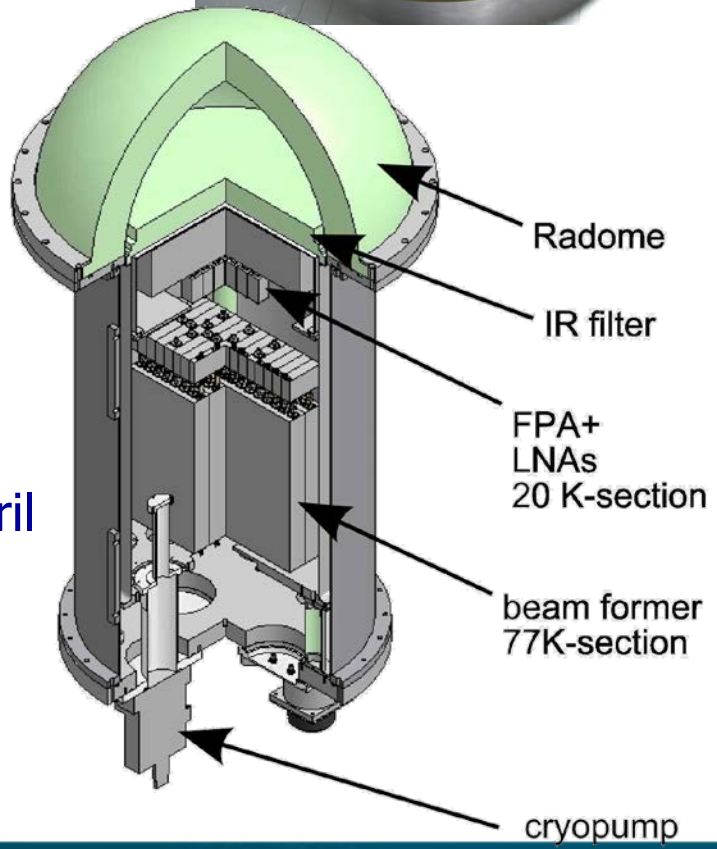
PHAROS2 (JBO, INAF, ASTRON, OSO & U.Malta)

A 4000 to 8000 MHz Cryogenic PAF with

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

Aim to install PHAROS2 on the 76m Lovell telescope at Jodrell Bank Observatory in April 2018

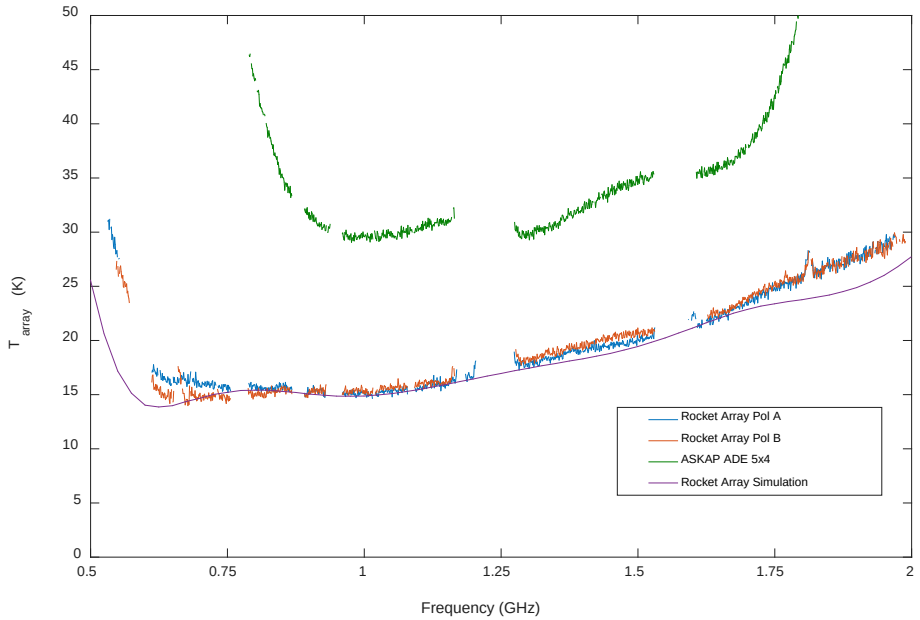




“Rocket” PAF (CSIRO)

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)

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

PAF on Effelsberg (MPIfR)

- In April/May, MPIfR installed a CSIRO Mk II chequerboard PAF on the 100m Effelsberg Telescope
- Initially MPIfR will investigate and evaluate noise-minimisation and specific nulling techniques in an non-optimal RFI environment
- Ultimately MPIfR 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.
- Initially JLRAT will complete a theoretical study on the maximum achievable sensitivity for a given array

- 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.

Science with Low Frequency PAFs

Frequencies ≤ 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 with Low Frequency PAFs

- 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*

* 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 High Frequency PAFs

Frequencies ~ 4 – 8+ GHz

- 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

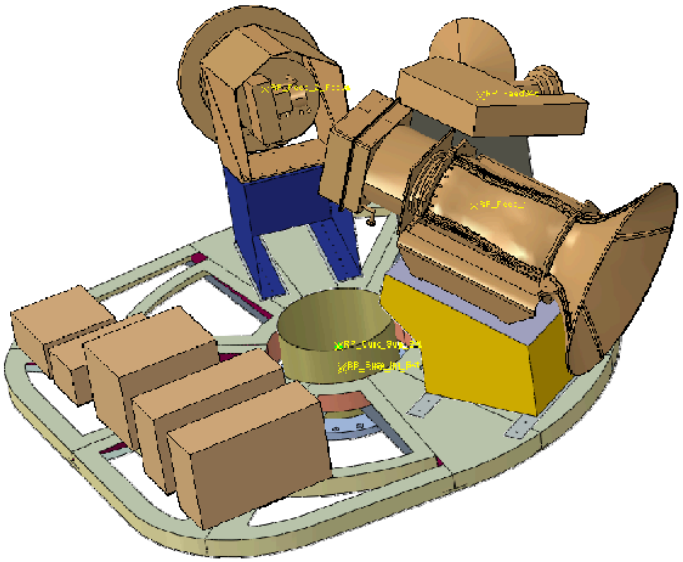
Dish Design Constraints

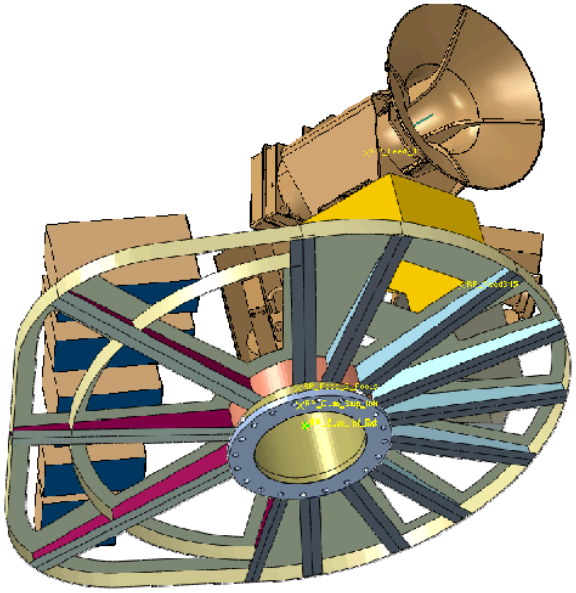
Dish have allowed for inclusion of a PAF in their design:

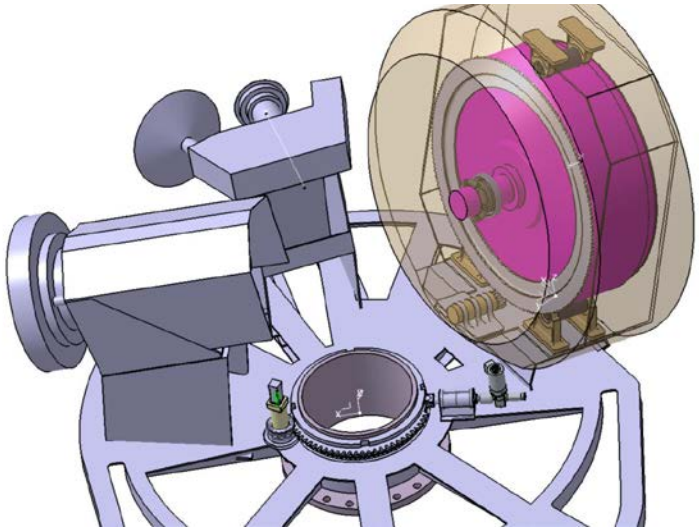
- PAF to use SPF Band 1 location on feed indexer
- ≤ 1.6m diameter x ~500mm deep (TBC)
- Weight up to 250kg (TBC)
- Axial mechanical de-rotation
- Power 1150W (TBC) on indexer; 2600W (TBC) for digitiser & beamformer ➔ Too Low??
- Digitiser & beamformer located in separate RFI shielded bunker

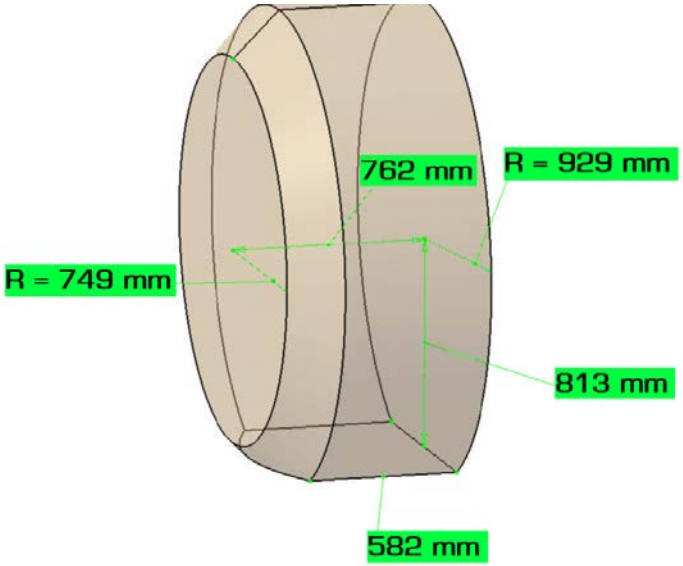
Many of these parameters need to be verified ➔ ECPs ?

SKA-MID Feed Indexer



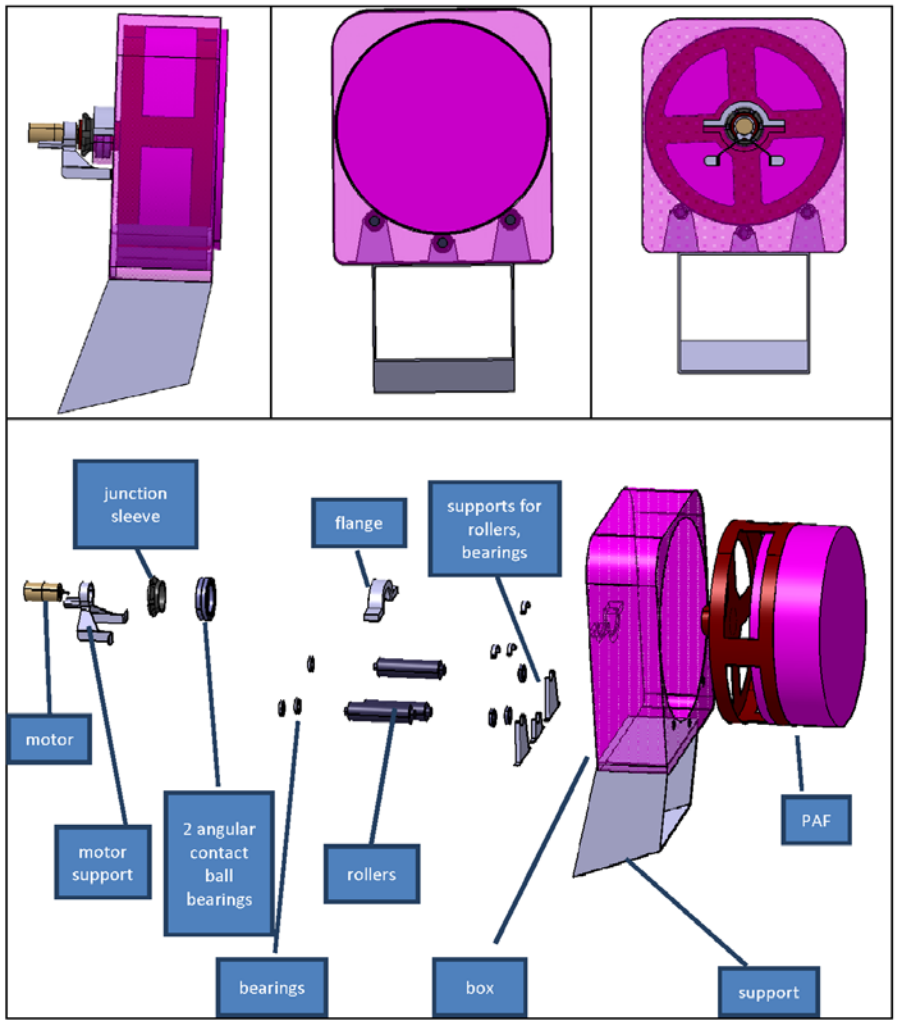






SKA-Mid PAF De-Rotation

- The SKA-Mid offset Gregorian antenna will require beam de-rotation
- A system for mechanical de-rotation is planned on the indexer, but its not clear that this is a viable since the beam weights will still require constant updating.
- Electrical de-rotation will most likely be needed instead.



Concept Mechanical De-rotator

Low Frequency PAF

Preliminary Requirements

- 475 – 1425 MHz (3:1)
- 950 MHz processed BW
- T_{sys} ~ 15K
- 30 beams @ 1 GHz
- 128 x 15m SKA-MID dishes

10 times increase in Survey Speed on SKA-MID

- ~200 ports (channels) or ~100 dual-pol elements (TBC)
- N ports/beam with N $\rightarrow$ 200, i.e. beam-forming using both polarisations

High Frequency PAF

Preliminary Requirements (TBC)

- 4600 – 13800 MHz (3:1)
- 950 MHz processed BW (TBC)
- T_{sys} ~ 15K
- 30 beams @ 13 GHz
- 128 x 15m SKA-MID dishes

Possible Band 5 replacement?

- ~200 ports (channels) or ~100 dual-pol elements (TBC)
- N ports/beam with N → 200
- RF down-conversion ➔ distributed LO?

Future Steps

- Refresh the system requirements from the updated Science cases
- Verify all requirements and update relevant ICDs with SKA-MID
- Develop metrics for verifying the requirements

And Investigate …

- methods for cryo-cooling a SKA PAF with consideration to power
- cost drivers
- direct digitisation – Xilinx RFSoC
- a PAF on the MPI SKA-Mid verification antenna in 2-3 years from now (TBC)

International PAF Workshop, CSIRO Sydney – November 14-16

Challenges

- Noise performance & bandwidth competitive with traditional feed horn based systems ➔ cryogenically cooled
- Sky de-rotation – electronic, software
- System cost – component, manufacturability, signal processing, maintainability, installation
- Cryogenic cooling
- System size & weight
- Power – total requirement, RFI, efficiency
- Cooling – power, weight, RFI, robust, cost
- Data transport & processing
- Beamforming algorithm development
- Calibration

Conclusions

- SKA Science
  - "require observational statistics on a very large scale" *, which is best done with a large field-of-view survey instrument.
  - cases appear strongest in SKA Band 1 and Band 5
- If the SKA1 cost control cuts Band 5 SPF, this may improve the case for Band 5 PAFs
- Cryogenically cooled PAFs hold the key!
- Advances in FPGAs (& GPUs) will help to reduce complexity and cost of the data processing, but it is not yet clear whether this will be enough. ASIC's should also not be ruled out.
- There is still much to learn and R&D to be done.

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

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Thank You!