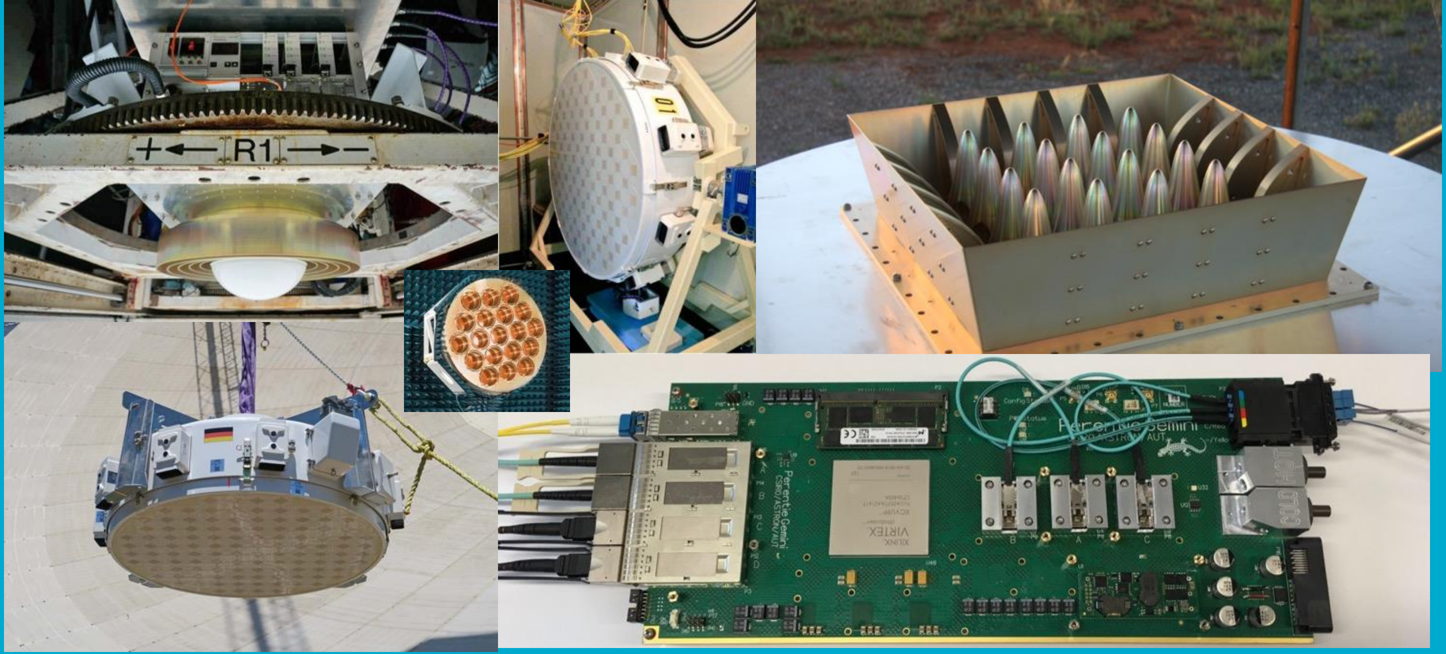


Trends in Radio Astronomy Technologies

Tasso Tzioumis | Program Director– Technologies for Radio Astronomy

ALMATY September 2024

- **CSIRO SPACE AND ASTRONOMY**

CSIRO

Outline

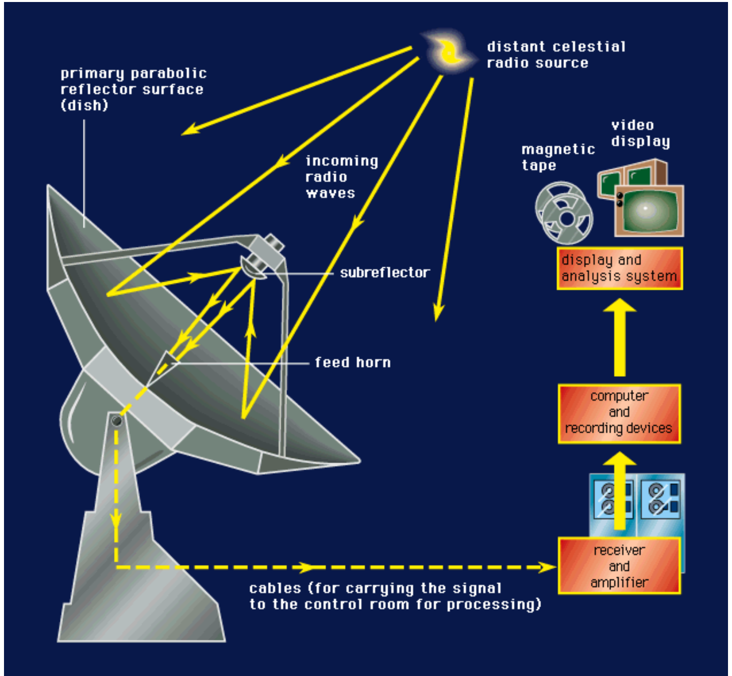
- Introduction to Radio Astronomy Instrumentation and Technologies
  - Concepts & Issues in current Radio astronomy Technologies
- Example: CSIRO ATNF Technology Capabilities & Projects
  - Ultra-Wide-Band (UWB) systems
  - Multi-beam systems
  - Phased Array Feed Systems (PAFs)
  - DSP systems (Back-ends)
  - Near Future Projects
  - Universal back-end & Compute systems
- Concluding remarks

Basics

- **Radio Astronomy:** Astronomy based on the reception of radio waves of cosmic origin *(ITU definition)*.
- Leverages antenna technologies developed for radio communications and other radio wave uses (e.g. radar, medicine, broadcasting....)

Radio Telescope systems:

- **Dish** (parabolic reflector) – collects & focusses the EM waves
- **Feed**: Detects the EM waves and coverts to electronic signals
- **Receiver**: Amplifies, filters and digitises signal.
- **Digital** systems: Digital signal processing (DSP)
- **Computer recording** systems (CPU, GPU)
- **Analysis** computer systems (HPC)



Sensitivity

- However, cosmic signals are extremely **faint**
  - Basic unit: Flux density 1 x 10^{-26} W/m²/Hz = 1 Jy (= -260 dB(W/m²/Hz).
  - And need mJy and even µJy.
  - ~ >100 dB fainter that communication signals (10 orders of magnitude = 10 billion times)
  - → RA systems very susceptible to spurious emissions from other services (RFI)
- Radio dish **sensitivity** ∝ Collecting area $A_{eff} \propto D^2$ (D= diameter of reflector)
  - → Need very large antennas. Usually, RA dishes from D=10m to 110m!
  - But cost of steerable dishes is $\propto D^{2.7}$ Becomes very expensive!
  - Non steerable (fixed) dishes up to D=500m (FAST). But limited tracking.
  - Balance cost vs flexibility.
- Alternative solution is to combine N smaller dishes (Arrays)
  - Save on mechanical costs
  - But multiple electronics costs (x N receiver systems)
  - Increased computing needs for effectively combining the array.

Resolution

- Angular resolution of dish antenna $\Delta\theta \approx {}^{1.22\lambda}/_{D}$ (wavelength λ, diameter D). Defines the telescope Beam.
- e.g. for $\Delta\theta$ = 1”:
  - At λ=500nm (optical)→ D=125mm; BUT at λ=20cm (radio) → D=50km!!
- Single radio dishes achieve ~arcminute resolution (primary beam)
- Arrays can achieve up to better than milliarcsecond (mas) for VLBI
- However, high resolution limits the field of view to the primary beam of the telescope → time consuming for widefield surveys
- Need multi-beaming capability for fast surveys e.g.
  - Multiple feed horns in a fixed pattern at the dish focus
  - Phased array feeds capable of independent multiple beams

Noise and Tsys

- Electronics components produce electrical noise $\mathbf{P_\nu = kT}$ where T is temperature in degrees Kelvin & k= Boltzmann’s constant.
- For **noise**, we must want as little as possible. In radio astronomy we describe noise in terms of temperature, and for a radio receiver the system temp, **Tsys.**
- To minimize Tsys, must keep the early stages of electronic amplifiers (LNAs) cold, and use cryogenic systems to achieve Tsys ~10K. Bulky and expensive systems using liquid He.
- **Radio sensitivity ∝ Aeff / Tsys**

Ideal Radiometer Equation

- For band-limited signal in bandwidth $\Delta\nu$
- And integrated for time τ
- The RMS error on the measured noise temperature of a signal (i.e. T_{sys}) is:

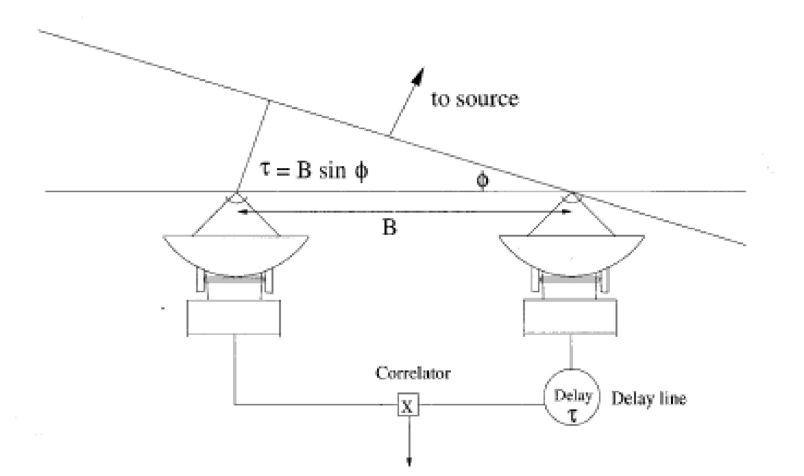
$$\sigma_T \approx \frac{T_s}{\sqrt{\Delta\nu\,\tau}}$$

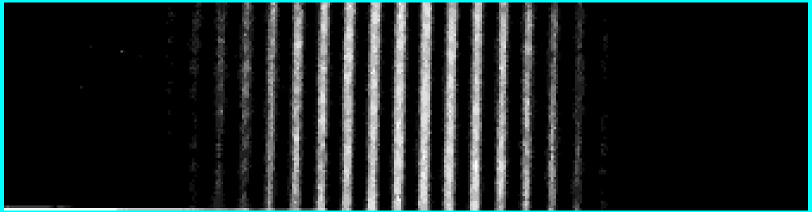
- Note that $\Delta\nu\tau$ is often very large, 10^8 or more

With a stable-enough system we can measure *anything* by waiting (and integrating) long enough!

Radio Interferometry

Simple Interferometer

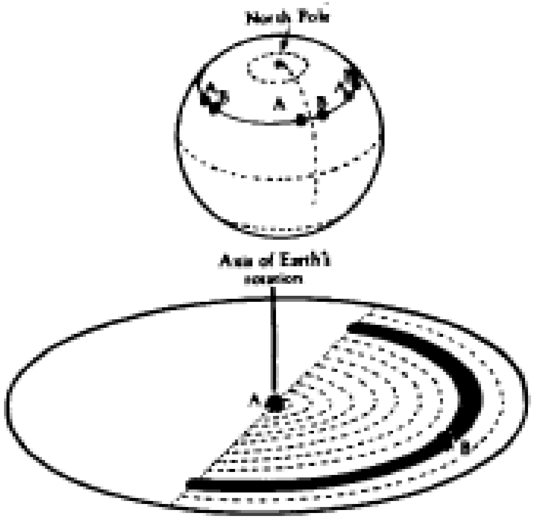




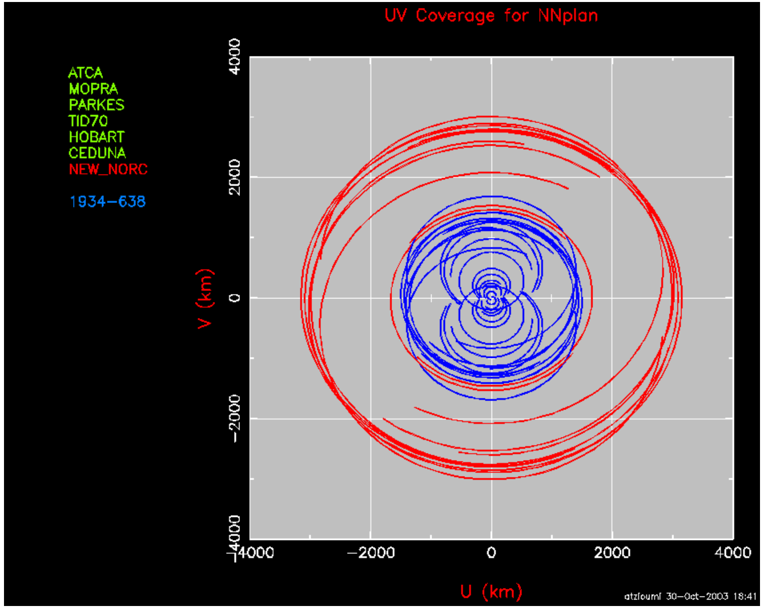
Fringe Pattern

- **Baseline B**: Distance between antennas
  - "Virtual" telescope of diameter **B.cos ϕ** *(projected baseline)*
- Fringe pattern provides information on structure and position of the radio source

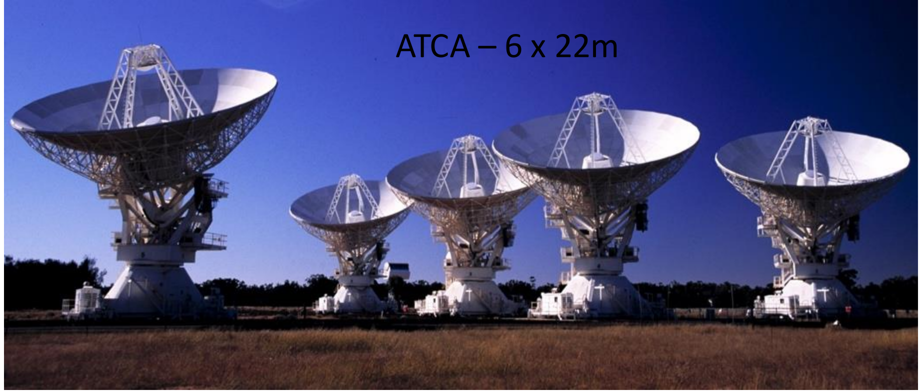
Earth Rotation Aperture Synthesis

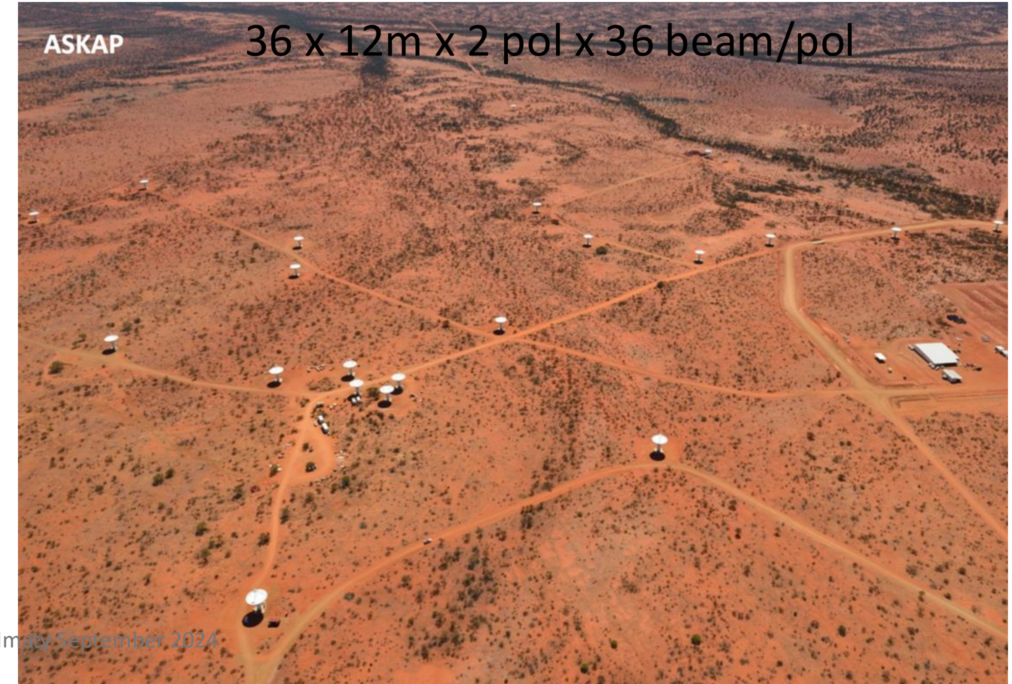


uv- diagram



- Baseline length and orientation (as viewed from the source) changes as the Earth rotates ⇒ new information on source structure.
- **uv-diagram** - an indicator of imaging "quality" of an array of antennas
    - more antennas ⇒ filled uv ⇒ better image fidelity



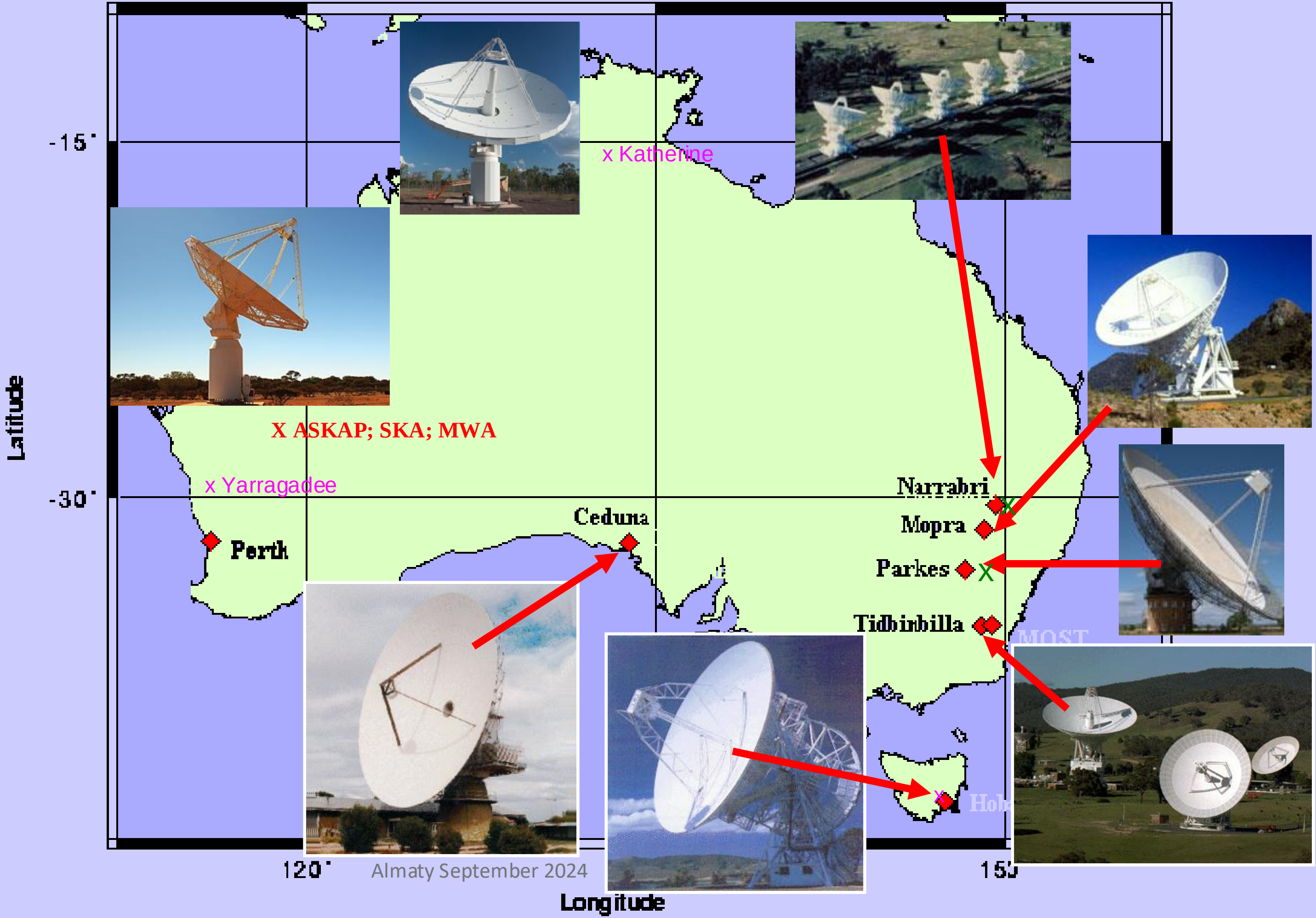


ATNF

Australia Telescope National Facility

CSIRO

LBA + AuScope + ASKAP



Technologies for Radio Astronomy ATNF Program

Example of a modern Radio Astronomy Development Laboratory

CSIRO S&A - ATNF Technologies Capabilities

- **Antennas & Receivers (Front-end) (~20):** RF technologies (Feeds; OMTs; LNAs; RF Electronics; Cryogenic systems; Mechanical design; …)
  - **Workshop (~5):** Mechanical systems (Machining; Fitting; Production;…)
- **Signal Processing (Back-end) (~25):** Digital technologies (RFoF; Samplers/Digitisers; Timing systems; Beamformers; Correlators;…) - Digital Signal Processing: FPGAs; ALVEOs; GPUs
- **Scientific Computing (~10):** Control and monitoring systems; calibration strategies and algorithms; data processing (e.g ASKAPsoft).
- **Engineering Generalists (~5):** System Scientists/Engineers; System integrators; Radio Spectrum; New Ideas; …

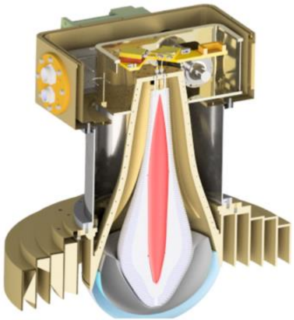
**** Produce fully integrated radio telescope systems!**

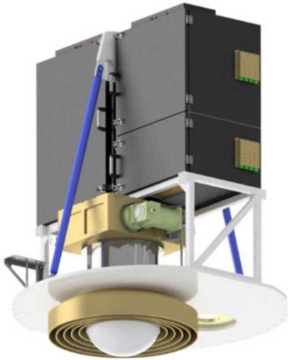
– **Concept; design; construction; testing; commissioning; operation; science.**

Ultra WideBand systems

UWBs

Ultra-Wideband Systems (UWB)





Low
‘UWL’

Mid/High
‘UWM/H’

UWB Low (UWL)@Parkes - Operational since 2018

- 700MHz - 4 GHz – **BW 6:1** Full illumination at all frequencies!
  - ~20 K Tsys, Linear polarization feeds. **– Main PKS system**
  - Digitisation at focus; critical shielding
  - Very high data rates → GPU cluster
- Installed in 2018 – main low-freq system at Parkes
- Supports all main modes of observing
  - Pulsars searches and timing;
  - Continuum; Spectral line; VLBI; Transients; FRBs; SETI
- Further Technical Developments: (underway)
  - Calibration schemes (pseudo-random noise etc.)
  - **RFSoC** upgrade (Jimble) – leverage new systems
  - Oversampled filterbanks

UWB Mid/High - Funded. Start construction in 2025

- 4 GHz - ~25 GHz, ~20 K Tsys, Linear polarization feeds
- Shares digitisers and backend infrastructure with UWL
- Single feed for entire range has sub-optimal feed illumination
  - preference for 2 feeds, 4-15 & ~15-27 GHz, or ~4-18 &~18-32 GHz
- Replace high-freq feeds → **All systems available on the antenna**

- UWB systems developed for other telescopes
  - Effelsberg 1.2-6 GHz delivered in 2022;
  - ngVLA 3.4-12.3 GHz; design complete; prototypes within 2024.

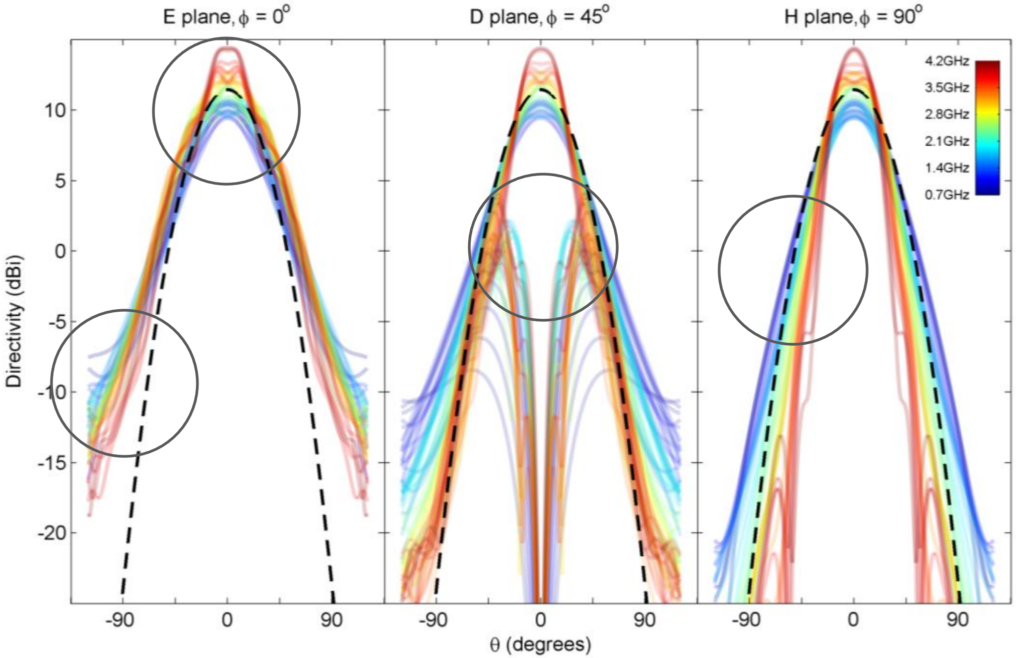
A Simple Quad-Ridged feed with a 6:1 bandwidth

Positives:

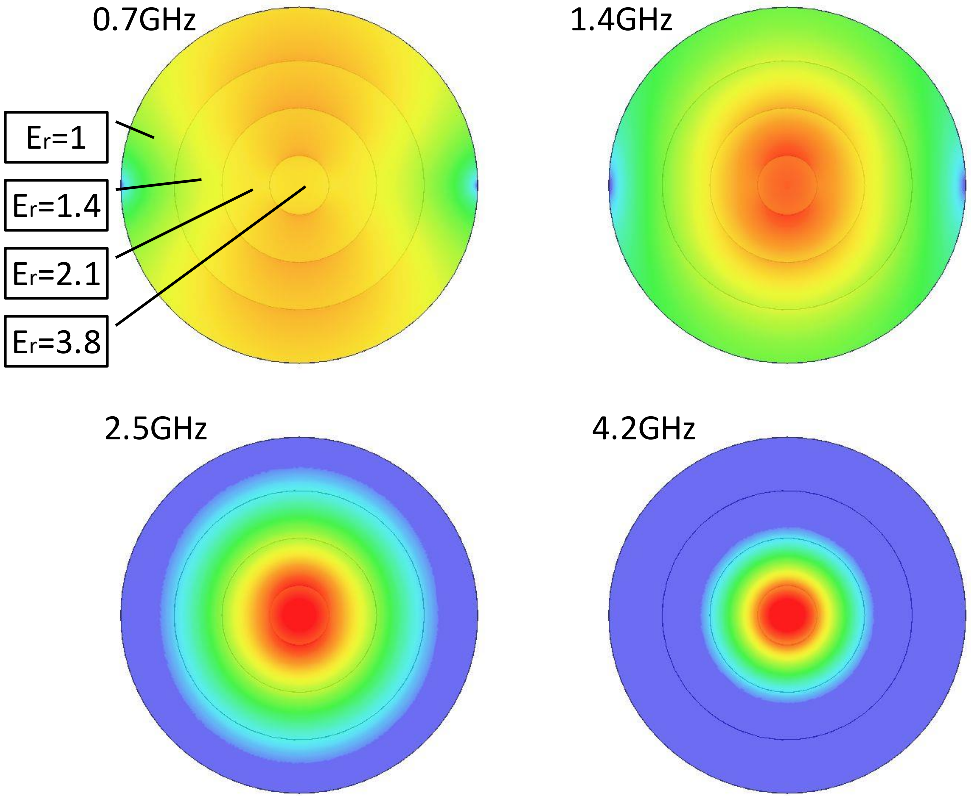
- Low loss
- High return loss

Negatives:

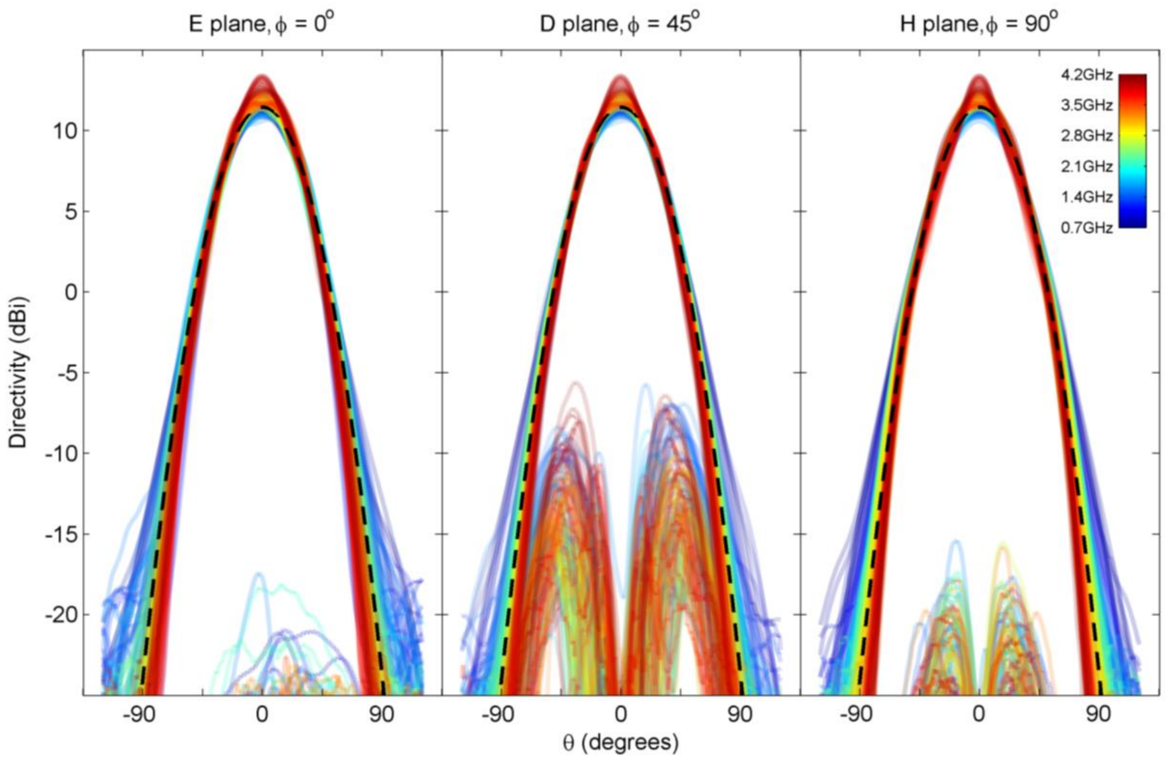
- High spillover
- High cross polarisation
- Beam narrows at high frequencies



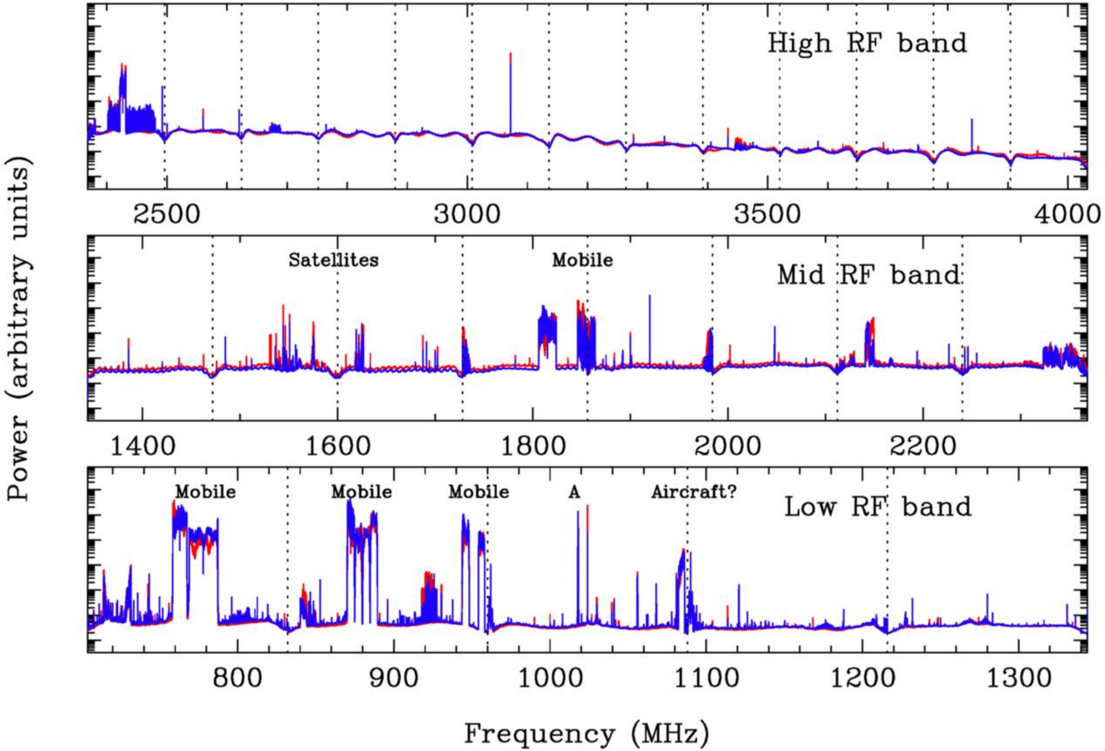
Graded Dielectric Waveguide



Measured Feed Radiation Patterns



Cont ations



Currently critically sampled filterbank. Will upgrade to oversampled filterbank later

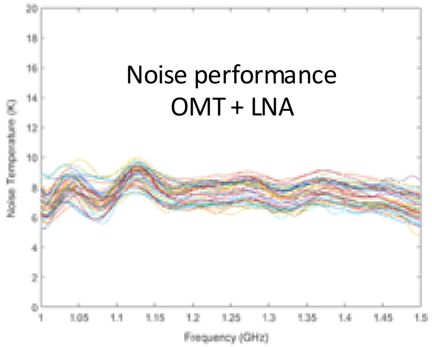
Multibeam Systems

Parkes – Arecibo – FAST L-band Multibeams

- The FAST receiver is bigger, better and smaller than its predecessors
- 19 beams to 7 (Arecibo) and 13 (Parkes) – bigger

- Lower noise and wider band – better performing
- OMT and feed more compact – smaller

FAST 19-beam receiver

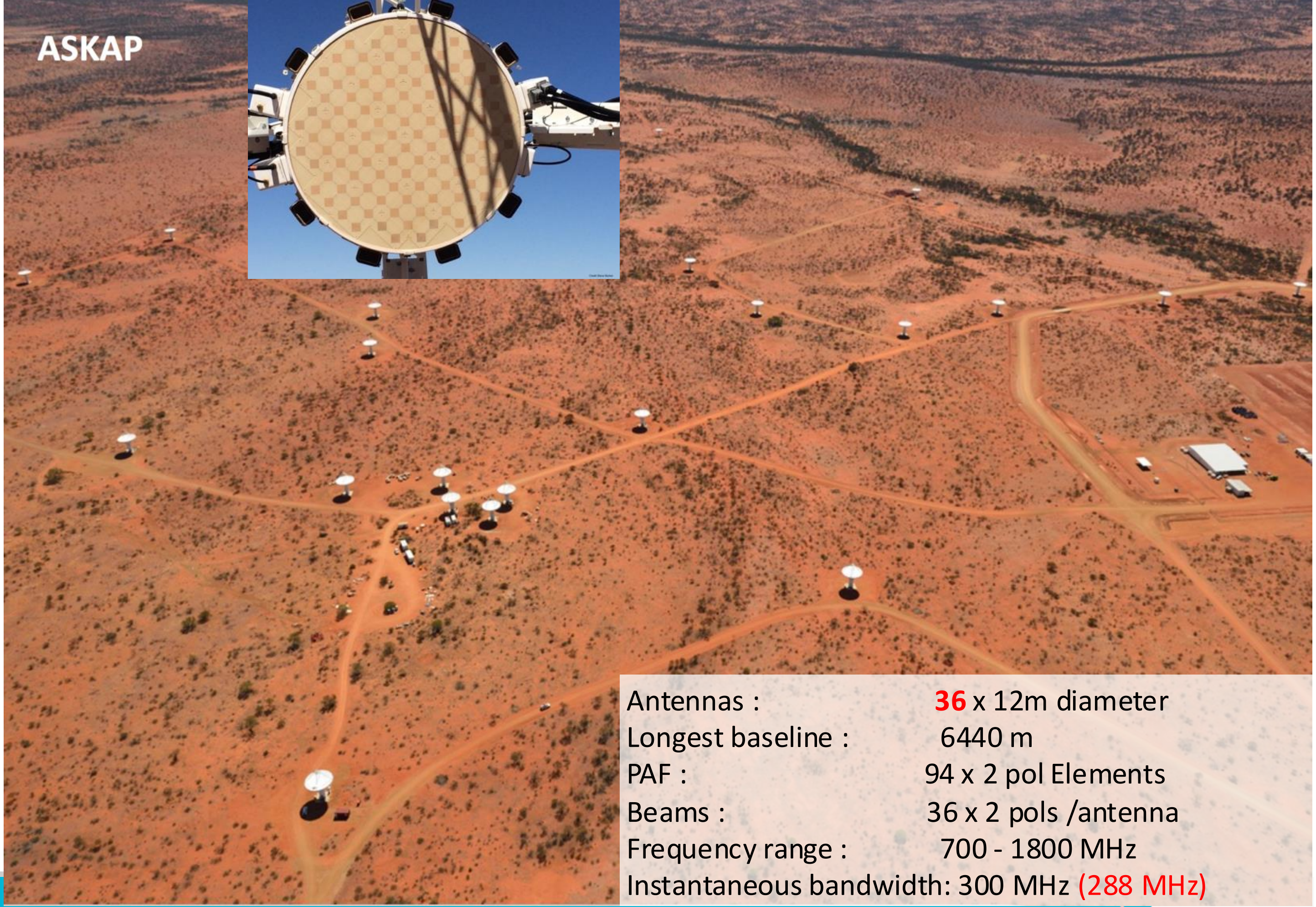


“Exceeded expectations”

Phased Array Feeds

PAFs

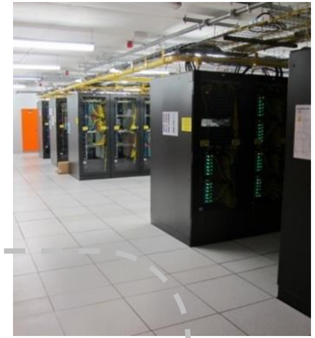
Field of View and Survey Speed

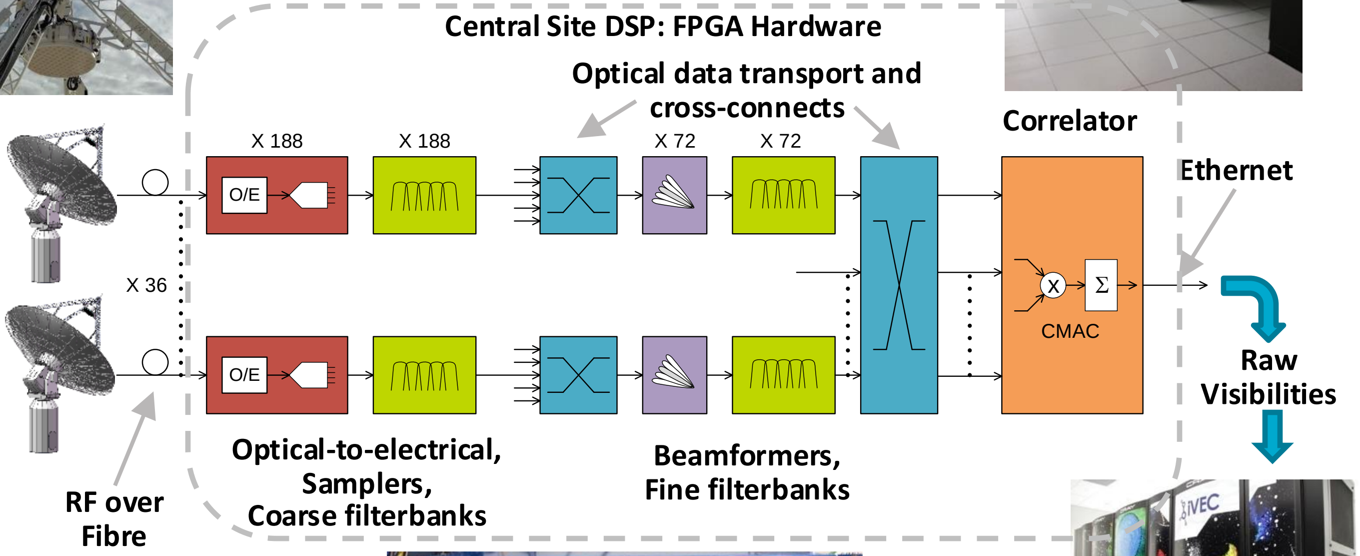


Antennas :	**36** x 12m diameter
Longest baseline :	6440 m
PAF :	94 x 2 pol Elements
Beams :	36 x 2 pols /antenna
Frequency range :	700 - 1800 MHz
Instantaneous bandwidth:	300 MHz (288 MHz)

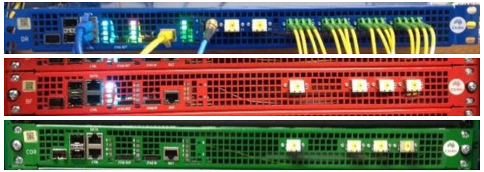
ASKAP DSP Signal Chain

Mk-II PAF: checkerboard array, LNAs, RF filters, laser drivers





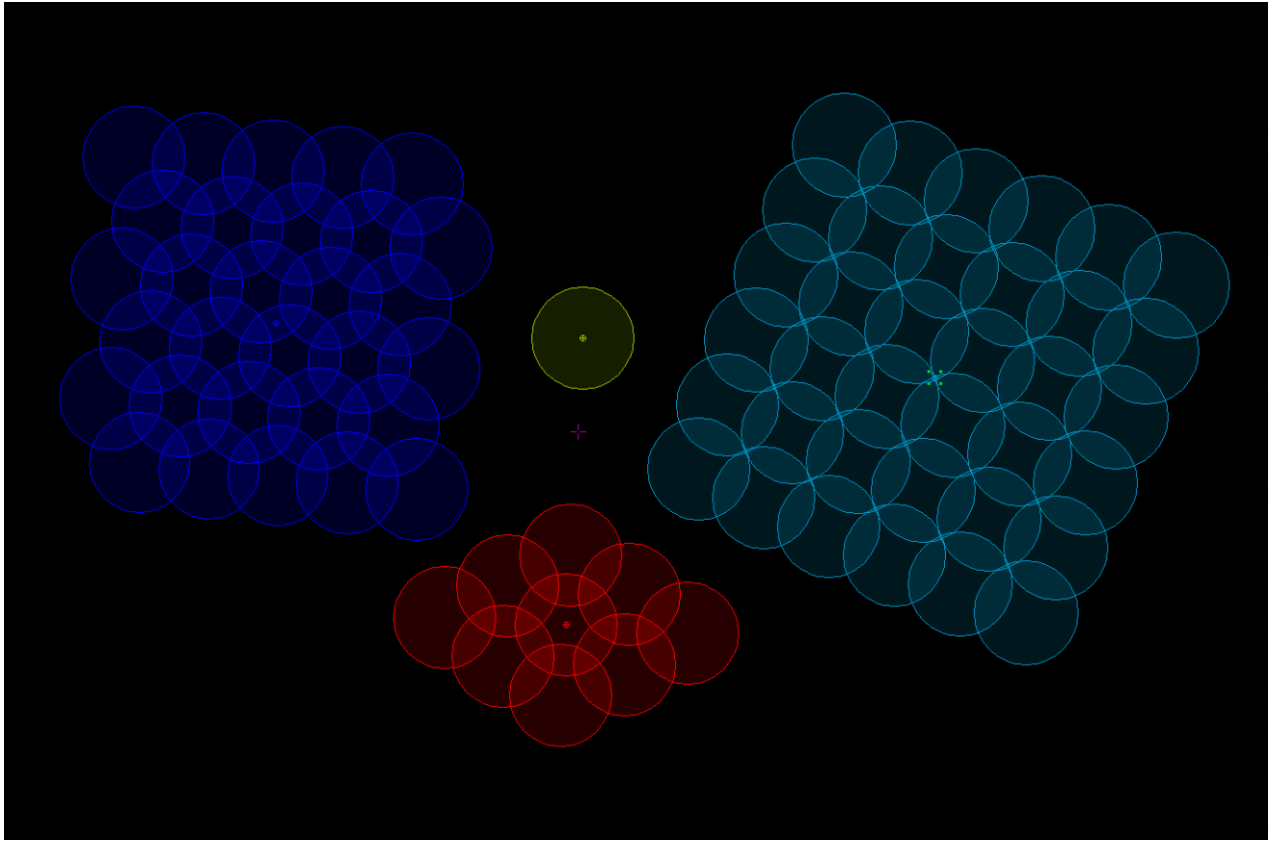
FPGA Hardware



Sampler

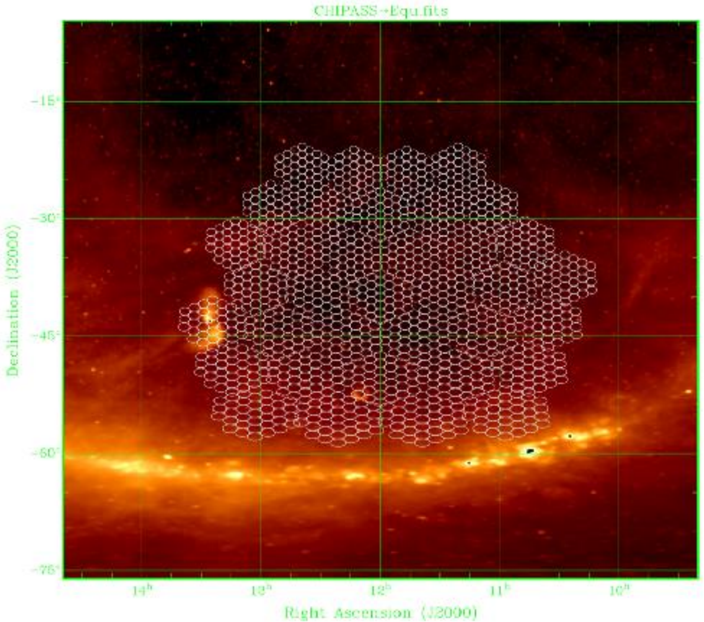
Beamformer

Digitally formed Beams



FRBs: ASKAP – Fly's Eye mode

Ryan Shannon
J-P Macquart
Keith Bannister
CRAFT team

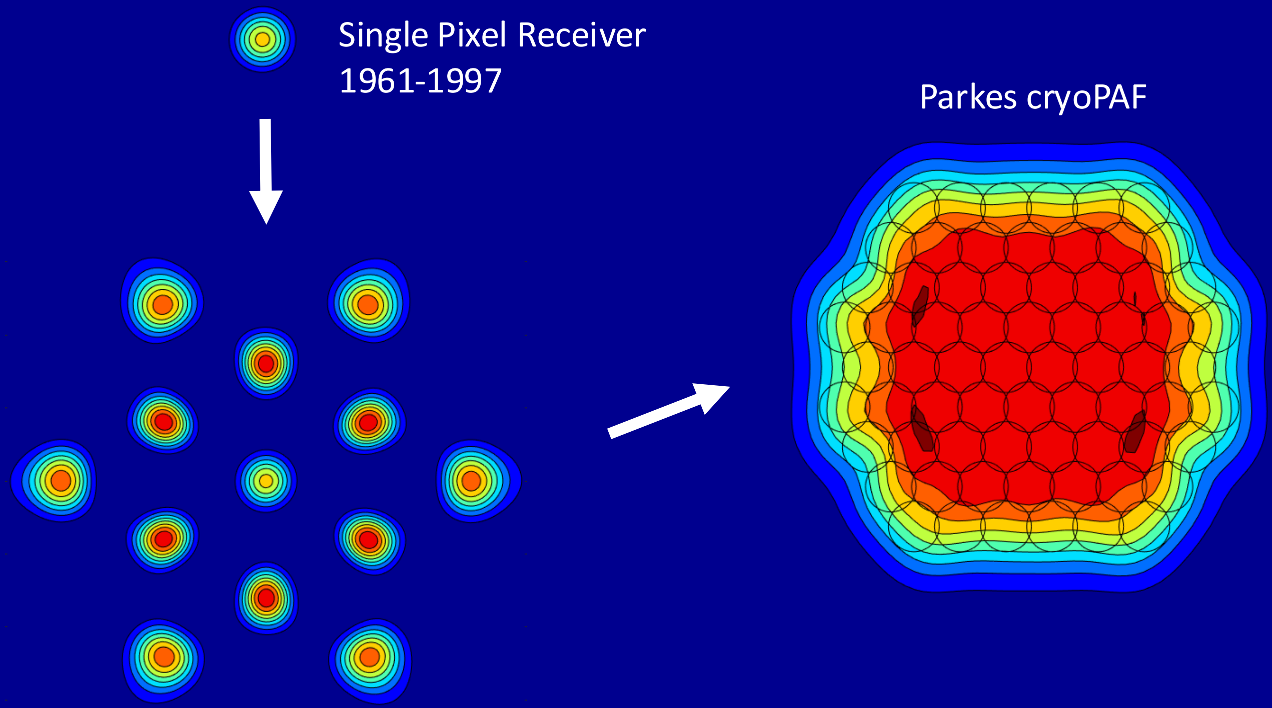


- 36 x 12m antennas
- 36 beams – 30 deg^2 per antenna
- Total Fly's eye Fov – 1080 deg^2
- 0.7 to 1.8 GHz; Very low rfi
- 336 x 1 MHz channels
- 1msec Autocorrelations
- → 26 FRBs discovered (Nature)
  - ~1 per 2 weeks with ~7 antennas

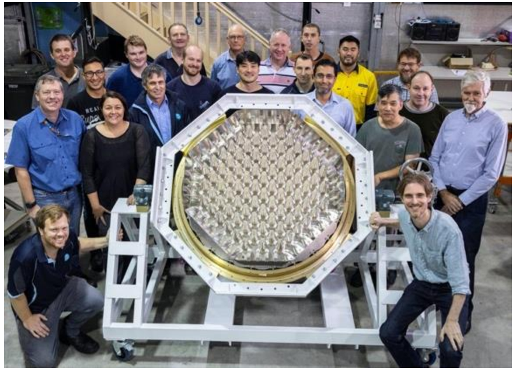
- New FRB processing with voltage dump and correlation
  - Discovered 3 FRBs with <1" localisation
  - New GPU-based system planned

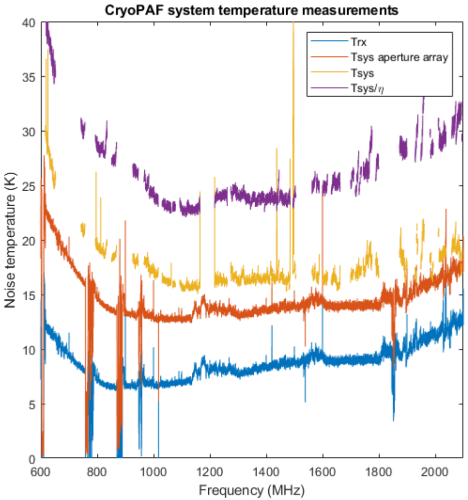
CryoPAF

Parkes Radio telescope field of view



Parkes cryo-Cooled Phased Array Feed





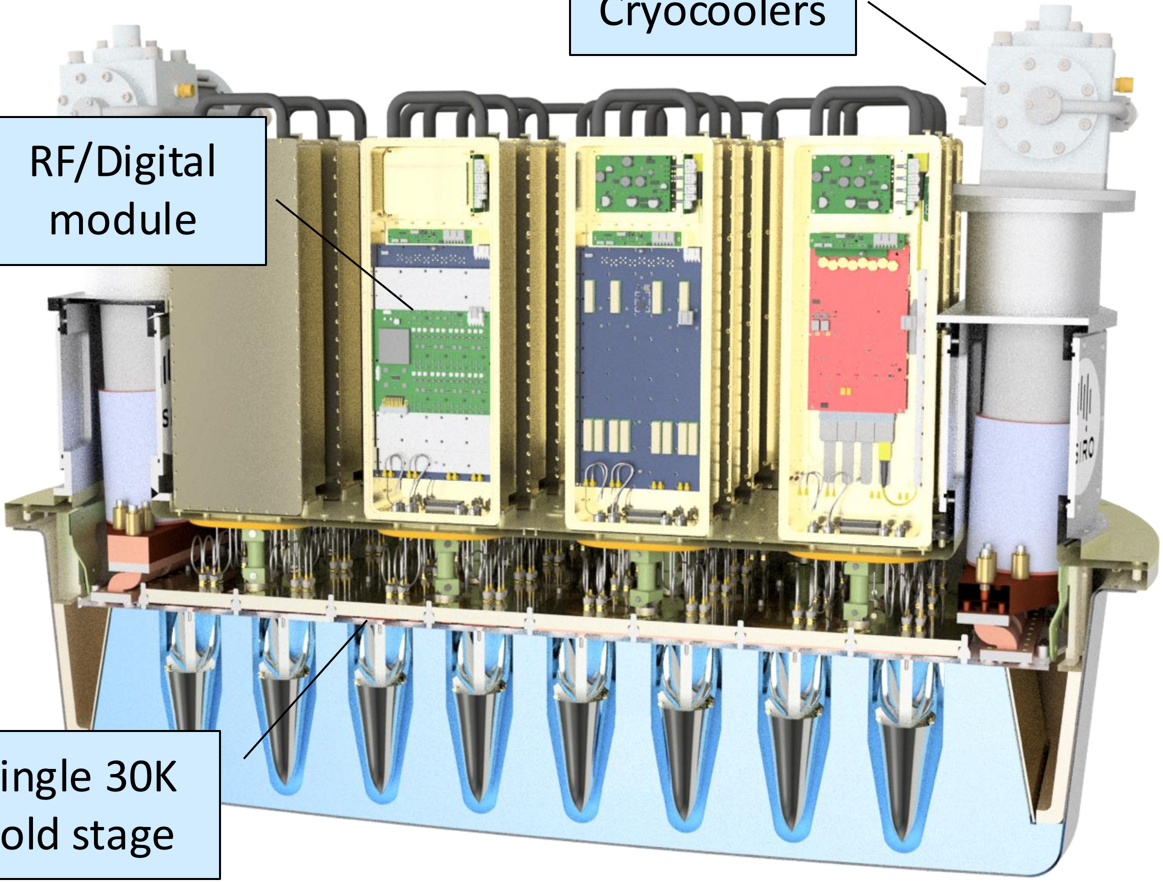
Installed & in Commissioning – Aug-Sept 2024

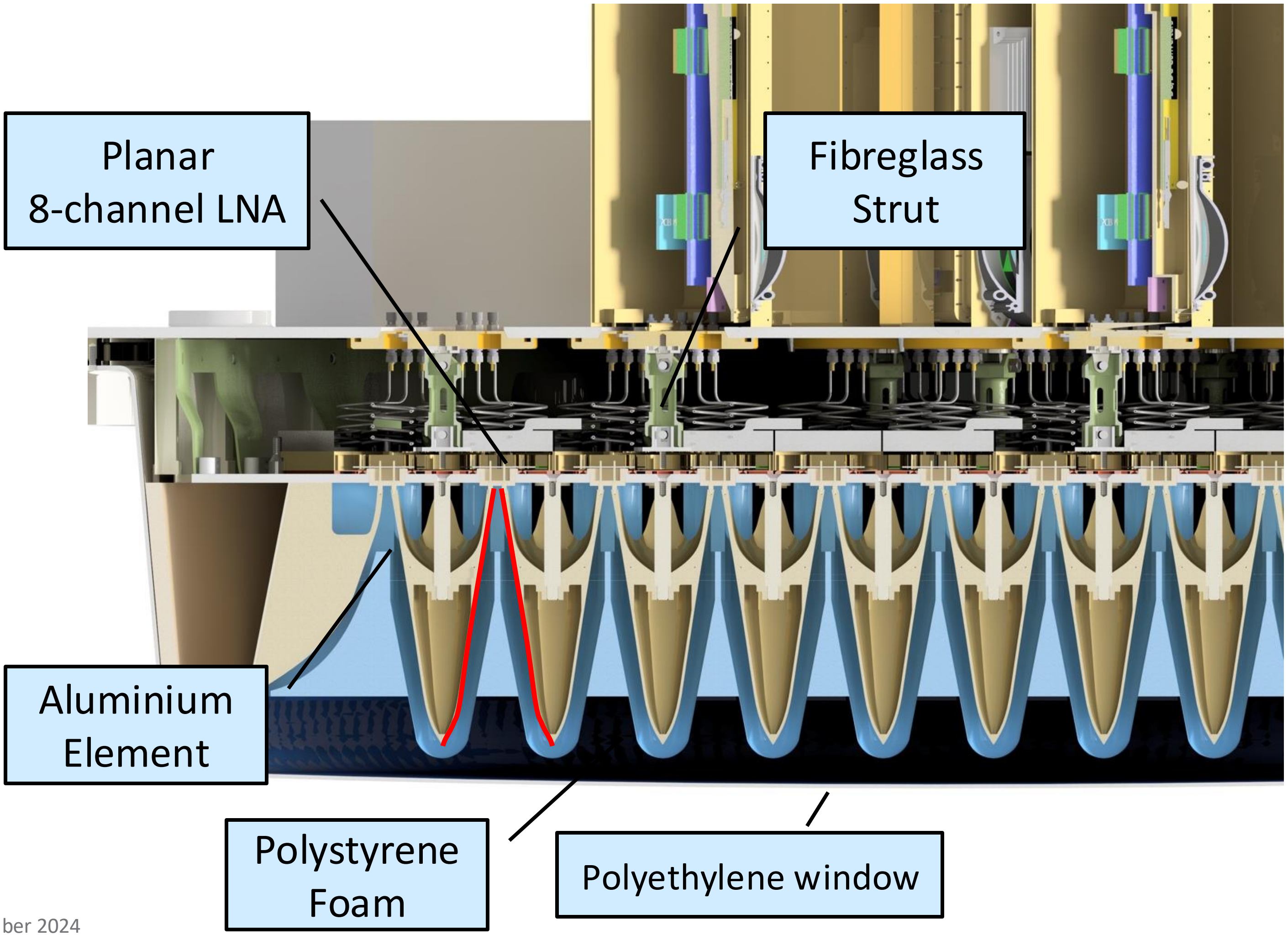
- Range: 700-1950 MHz (~3:1); Bands: 700-1220 & 1100-1950 MHz
- Tsys ~20-25 K ; BW 600 MHz . Up to 912 MHz possible.
- ~3 x Multibeam footprint; ~1.5 deg^2 FoV → 10-30 fold survey speed
- Up to 70 x 2 pol beams (less needed at low frequencies)
- Multiple modes – many commensal
  - Pulsars; Continuum; Spectral line; VLBI; Transients; FRBs; SETI

- **PAF – H/W** Construction complete & tested
  - All RF systems completed. Narrow band Tsys measured.
  - RFSoC "Jimble" board installed. Firmware in commissioning.
    - RF & RFSoC in one shielded module. At the focus cabin.
  - **COTS beamformer** – ALVEO + P4 Tofino switches
    - Firmware development in commissioning
  - **GPU cluster** (share with UWB system) for data processing
    - New GPU cluster operational (100 Gbps links)
    - Software nearing completion (Fourier Space)
- Issues: Mechanical (foam) in Dewar. Under repair.

- Extensive Parkes infrastructure upgrades
  - He-lines; Optical fibres; Co-axial cables; GPU cluster update.

The phased array




Planar
8-channel LNA
Fibreglass
Strut
Aluminium
Element
Polystyrene
Foam
Polyethylene window

Quasar – Phased Array Ground Station Demonstrator

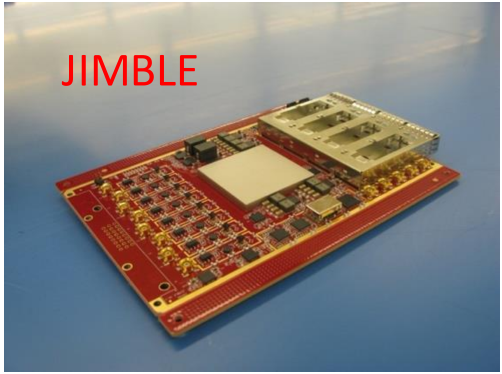
- Start-up company
- 2.1 – 2.6 GHz phased array receiver – construction complete (RFSoC & ALVEO)
- Tracking multiple satellites (10) demonstrated.
- Further development & demonstration continuing in 2024
- Deployment early 2025.

Digital Signal Processing

DSP systems

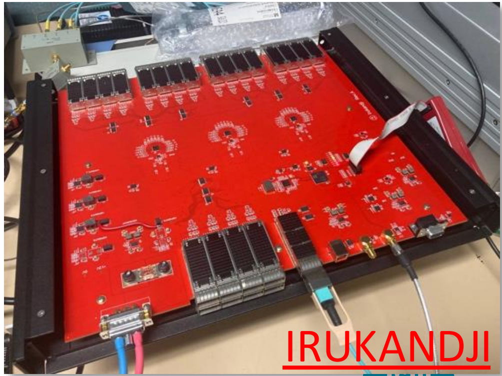
RFSoC – disruptive new technology

RF System on Chip (RFSoC) – more than an FPGA
- Digital-RF subsystem (ADC/DAC)
- Programmable logic (FPGA core fabric)
- Processor System (ARM Cortex + DDR)
- SerDes interfaces (high speed serial IO) on fiber.



"JIMBLE" board
- 8 x 2 GHz inputs; 12 bit outputs (optical 3x @100 Gbps channels)
- Designed to be screened - install near feed.
- Adopted for cryoPAF, UWB, BIGCAT, (Quasar)

"Irukandji" board – synchronization board (up to 32 systems)



("**Bluering**" board: RFSoC with 16 x 1 GHz inputs; Developed).

COTS digital back-ends (ALVEO & P4 Switch)

Xilinx ALVEO - FPGA-based accelerator boards

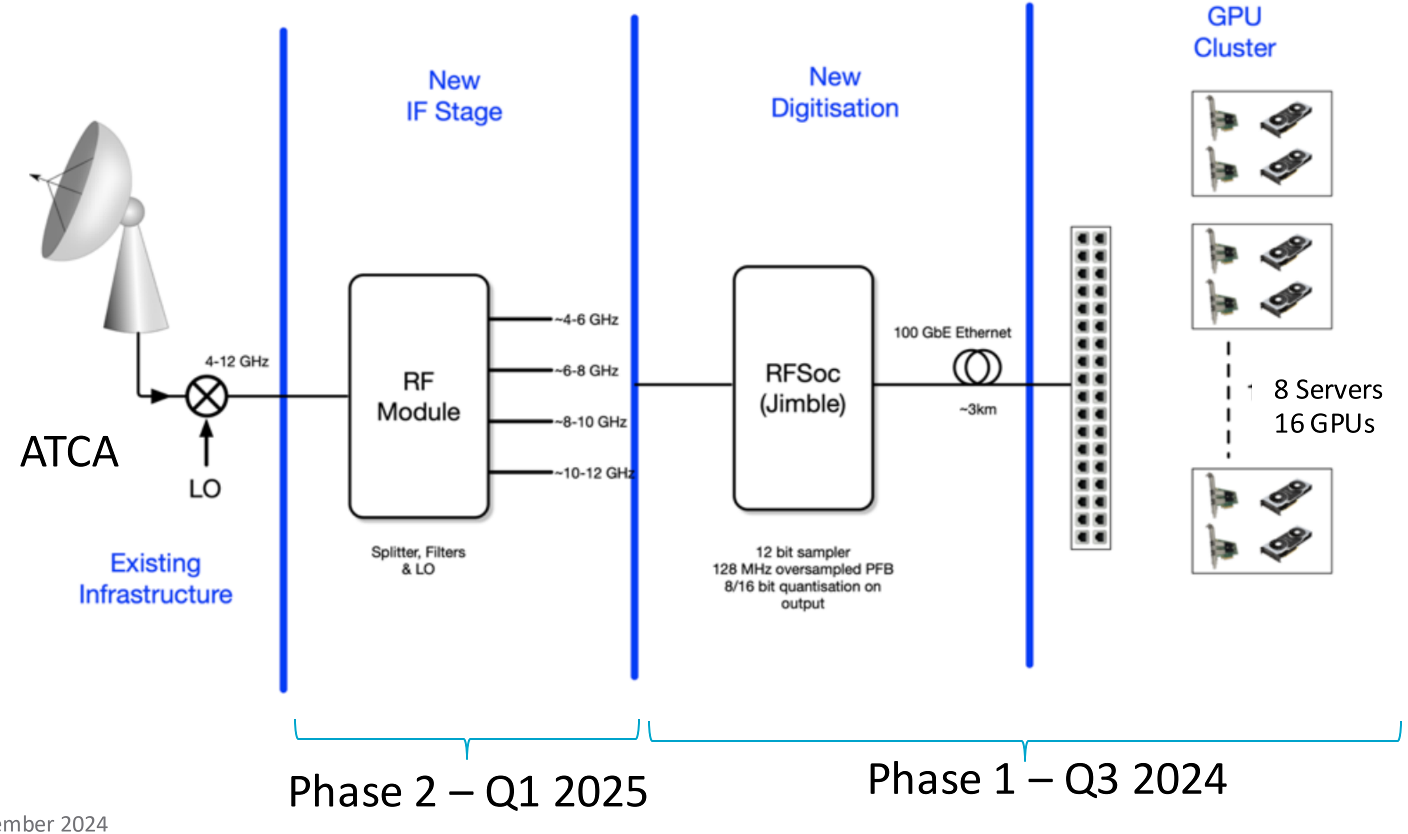
- E.g. - U50 HBM Board; -- 8GB HBM; 5952 DSP; 1x100GbE
    - Very small & low power – 20 in server!
- Faster and cheaper than own FPGA boards
- Many variants, with prices cheaper than FPGA chip!
- U50 implemented in cryoPAF & Quasar
- Newer U55 board adopted for SKA1-LOW BF-Cor
- U55 also for ASKAP coherent FRB detector (CRACO)

P4 Tofino - Bare metal h/w switch

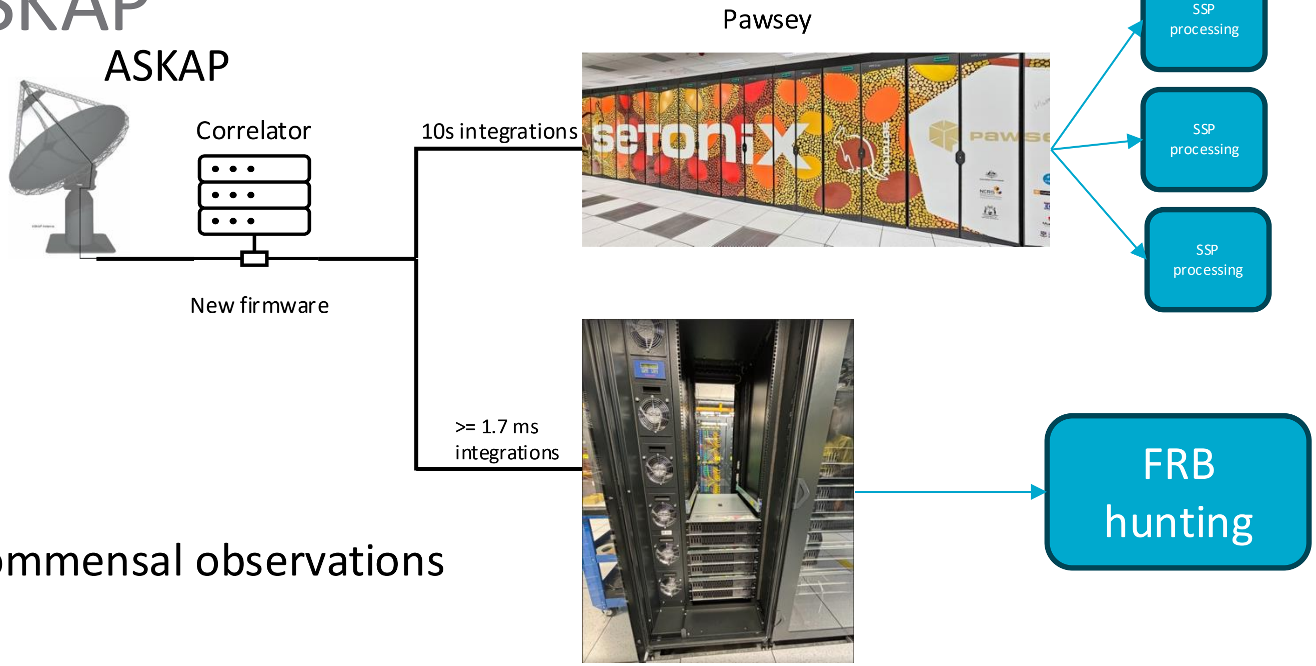
- Fully user programmable
- Versatile for one-way traffic
- System in SKA1-Low, cryoPAF, Quasar

**** Synergies & leveraging developments.**

Broadband Integrated GPU Correlator for the Australia Telescope



CRACO - Coherent FRB detection @ ASKAP



New cluster ‘SKADI’ (on-site)
Using U55 ALVEO

* Fully commensal observations

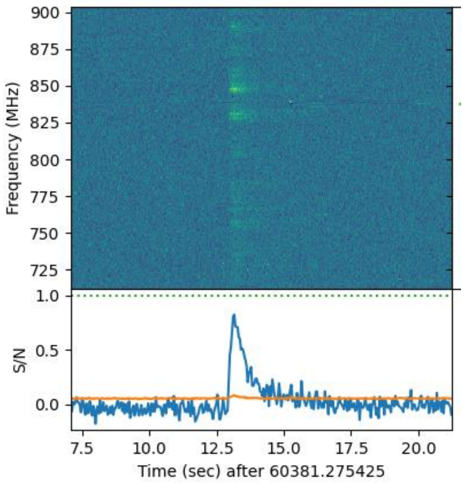
** CRACO system installed and operating since end 2023.

CRACO science

* Transient survey at 15 ms underway since 25th Dec 2023

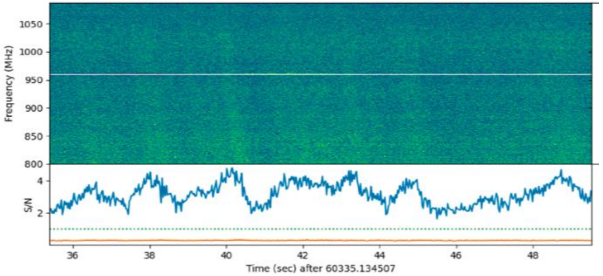
FRBs

- 14 FRBs – with localisations
- 1 repeating FRB; 1 highly scattered FRB



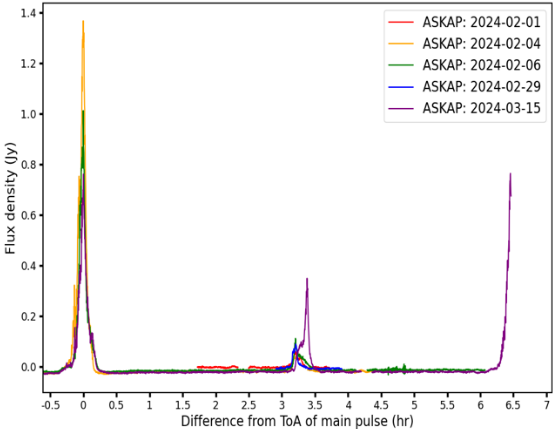
New galactic sources – Excellent sensitivity at low DMs

- Intermittent pulsar
- RRATs (~5)
- Slow pulsars (40 s)
- Ultra-long period sources (2)



ULPs

- Periods - 44 min, 6.5 hours!
- Intriguing pulse morphology, polarization and periods
- Follow-up obs underway



Joshua Lee

Future

Projects?

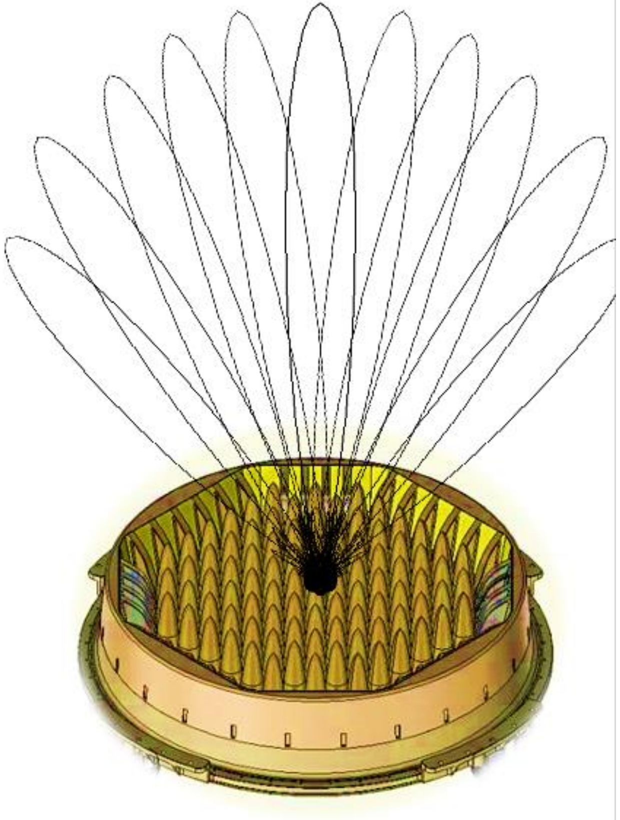
Future ATNF technology developments?

- **RFI mitigation for all ATNF observatories – ongoing -** R&D difficult but critical.

- **Upgrade of ASKAP** beyond current surveys? –
  - Future decision & funding
  - Prototype room-Temp PAF development
  - improve sensitivity x2-3.
  - Funded! (next 2 years)

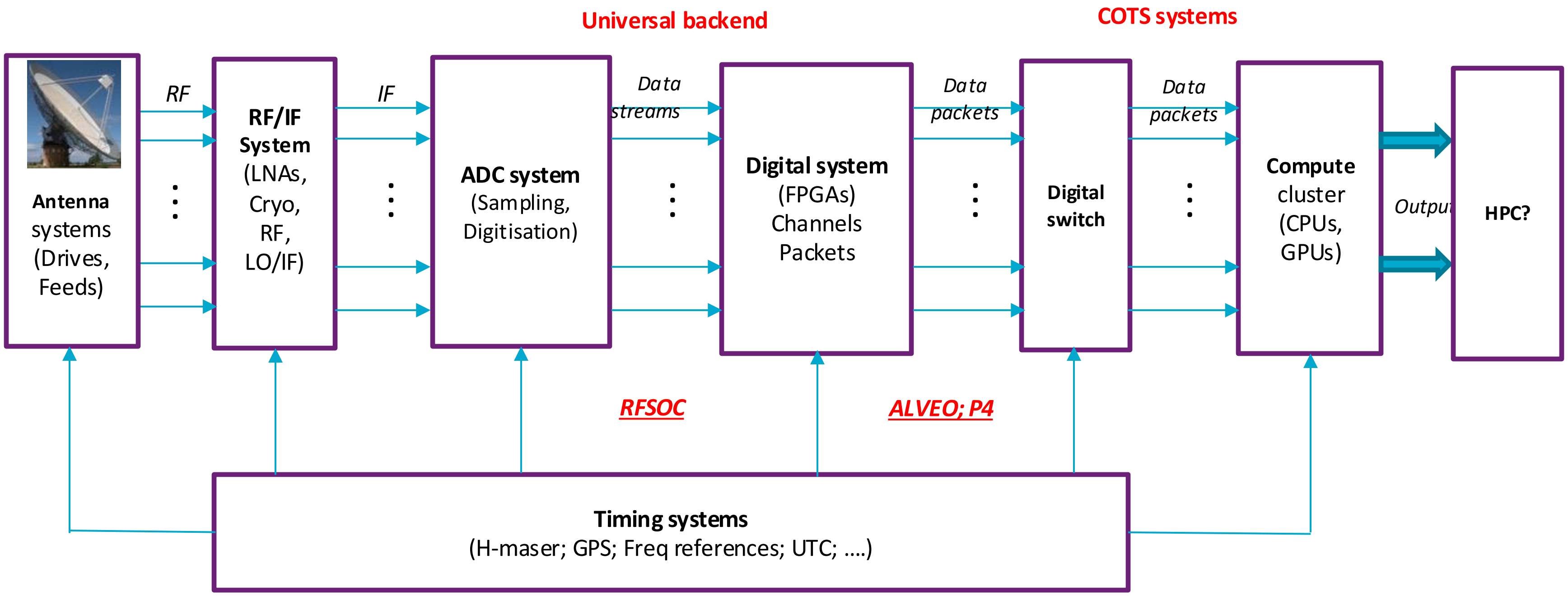
- Aperture arrays: PAF all-sky dishless monitor
  - FoV ~25% of sky;
  - → 3 PAF all-sky VLBI for astrometry
  - – FRB positions -1-10 FRB/week
  - + SETI detection & confirmation!

- New disruptive technologies? R&D
  - E.g. AMD/Xilinx "Versal" –
    - ARM CPUs, FPGA, "AI engines",
    - Network-on-Chip (NoC) interconnect!



Universal Back-end & Compute Systems

Radio telescope signal flow block diagram



NO need for Special VLBI h/w or Firmware !!

Concluding remarks

- **RFI impact** is getting worse →
  - Need **robust** systems tolerant to RFI
  - Need **RFI mitigation** strategies.
- Radio telescope systems age and evolve rapidly
  - Mechanical (dishes, motors, feeds, …) can me maintained for decades!
  - RF systems 10-15 years to replace; Digital systems ~10 years; Compute transferable
  - → Need **continuous development** for replacement and renewal.
- More of the RX systems are **integrated** and becoming **digital** very early in the chain
  - More flexible and maintainable. Need to plan for quick obsolescence of h/w.
- Many functions in computers – need firmware & software skills
  - Flexible but effort still large
  - Supercomputers are needed to deal with huge increase in data rates!
- Critical to maintain & evolve **capabilities** & skills

Conclusions from G. Siringo (ALMA) talk at FM5 IAU GA

CSIRO

Technology of present and future receivers

A look at the future

Recommendations:

- Minimize the opportunities for RFI by better design –> minimize the number of elements that can be subject to RFI
- Invest in RFI monitoring and prevention strategies: more than ever before, today we need a strong RAS community to protect the RAS spectrum
- Move to new technologies trying to convert as much as possible of the receiver design from analog electronics to digital, convert to digital as early as possible
- Go for a compact, simple and modular design that facilitate the production of large multi-beam receivers

Thank you

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