Radio telescopes for pulsar enthusiasts and PTA fanatics

Daniel Reardon (he/him)
(Swinburne/OzGrav)

Slides from Ryan Shannon (he/him)
(Swinburne/OzGrav)
Before that from **John Reynolds**?

About me

- My first visit to South Africa was **10 years ago**
  - 2016 IPTA meeting in Stellenbosch
  - Third-year PhD student at the student week
- Postdoc at Swinburne in Australia
- Member of the Parkes PTA (PPTA) and MeerKAT PTA (MPTA) collaborations
- Work interests: Pulsar timing and noise, gravitational-wave searching, and interstellar scintillometry
- Also interested in **trail running** and **triathlons**!

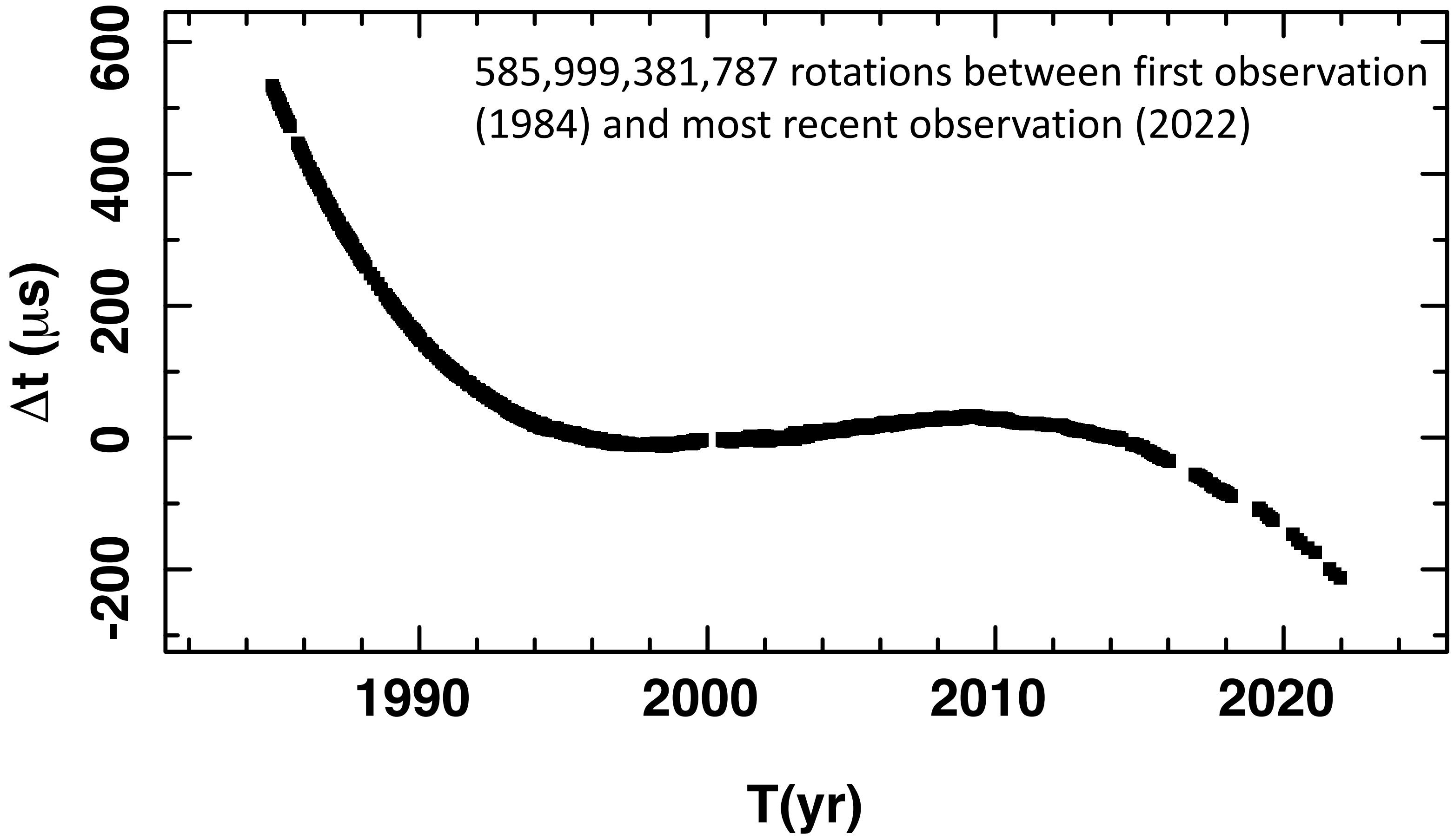
Hiking Table Mountain in 2016

The joy of pulsar timing

- **Phase coherent**: sensitive to effects that only manifest as small Doppler shifts

- **Millisecond pulsars** sensitive to the smallest of perturbations

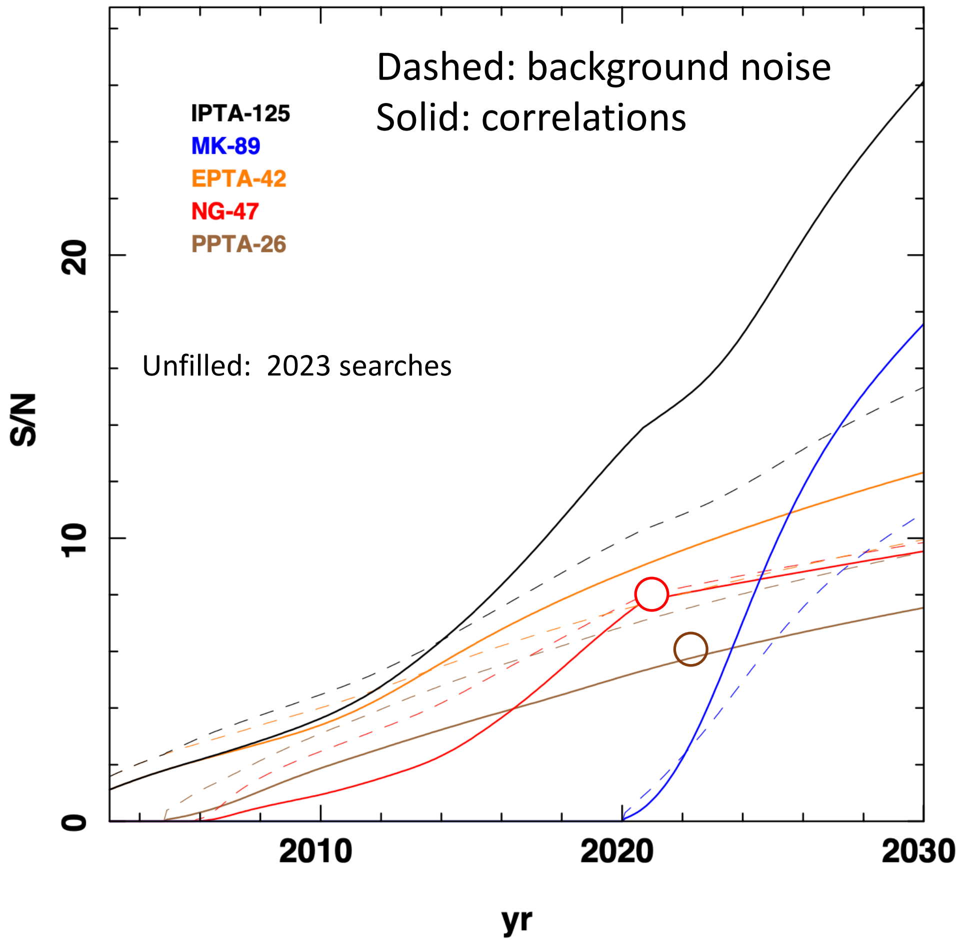
- Path length variations
  - Best timing: ~10 ns precision?
  - 1 ns = 1 foot = 30 cm



Motivation for talk

- What properties of radio telescopes affect the precision of arrival time measurements?
  - Timing precision set by signal-to-noise
- How can we make better telescopes/instruments for an even better IPTA?

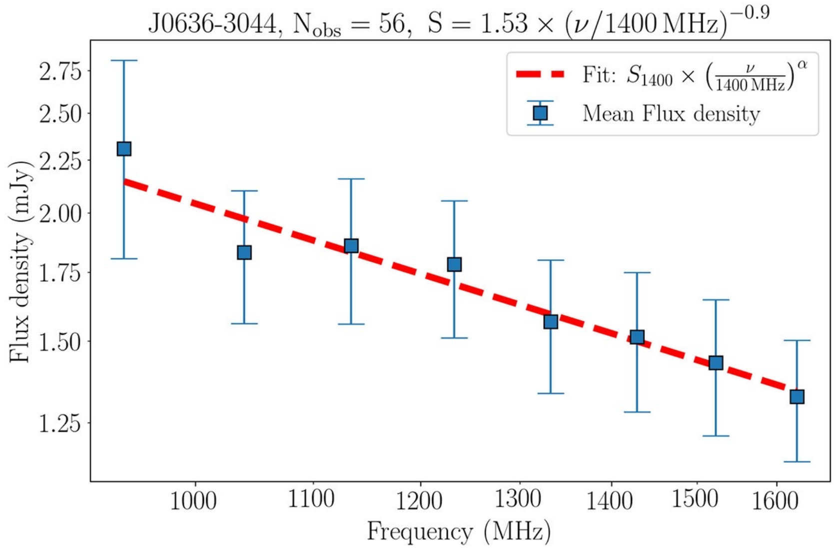
Forecasted sensitivity

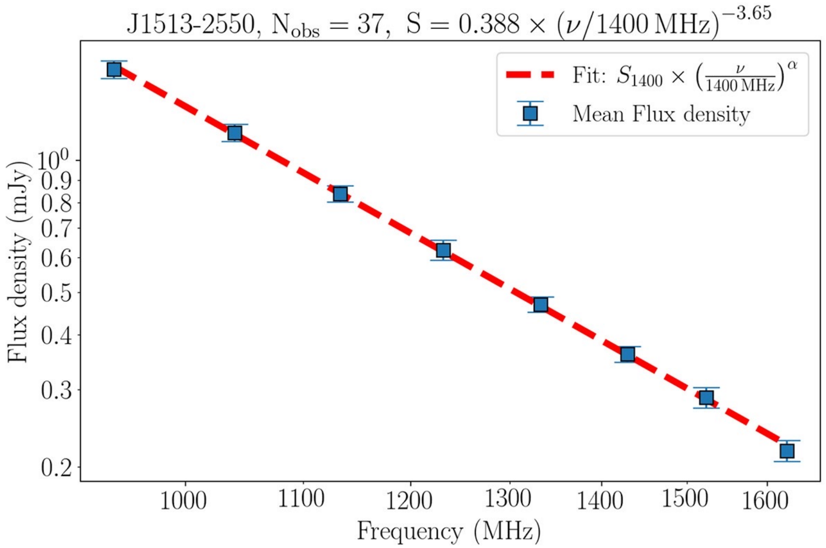


Based on Spiewak et al. (2022)

Key challenges

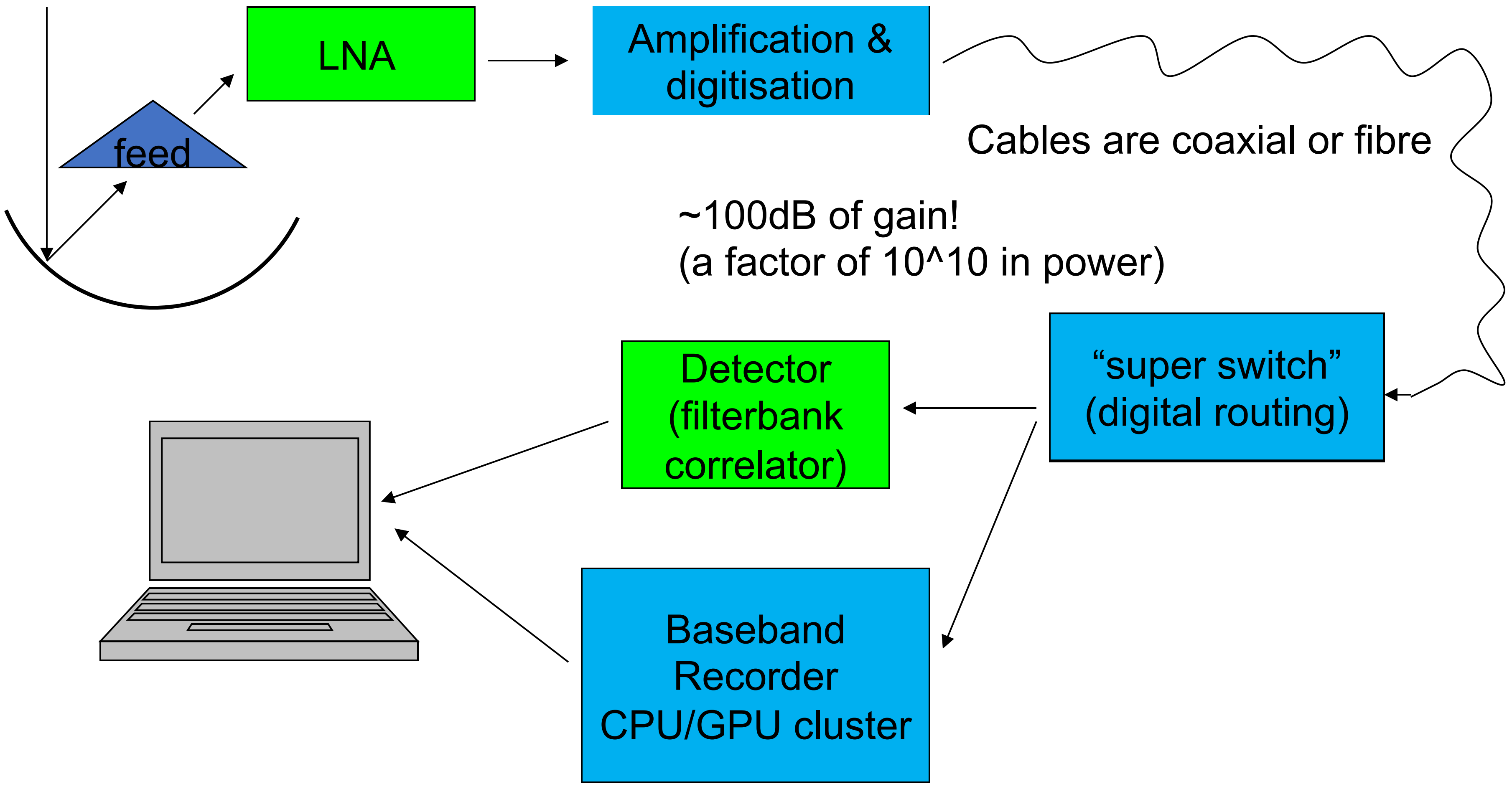
- Pulsars are faint
  - Newly discovered millisecond pulsars are likely to be even more faint
- Pulsars have steep spectral indices
  - Nearly always brighter at lower radio frequencies
  - Interstellar medium effects low frequencies more
- Solution:
  - Observe with large telescopes with a wide bandwidth
  - Measure high precision arrival times





Gitika et al. (2023)

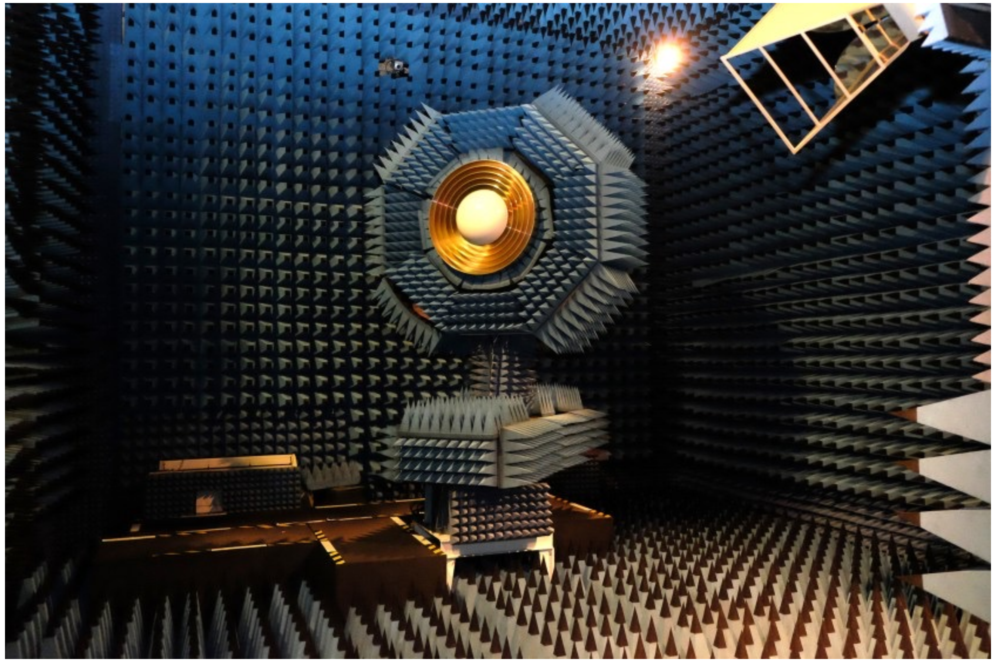
Elements of telescope observing system



Timing pulsars

- Radio waves focused to receiver/frontends
  - 100 MHz – 5 GHz radio frequency for PTA obs
  - 50 - 3000 MHz instantaneous bandwidths
  - Converted into an electrical signal/amplified
  - Kept cold - we don't want to amplify noise!

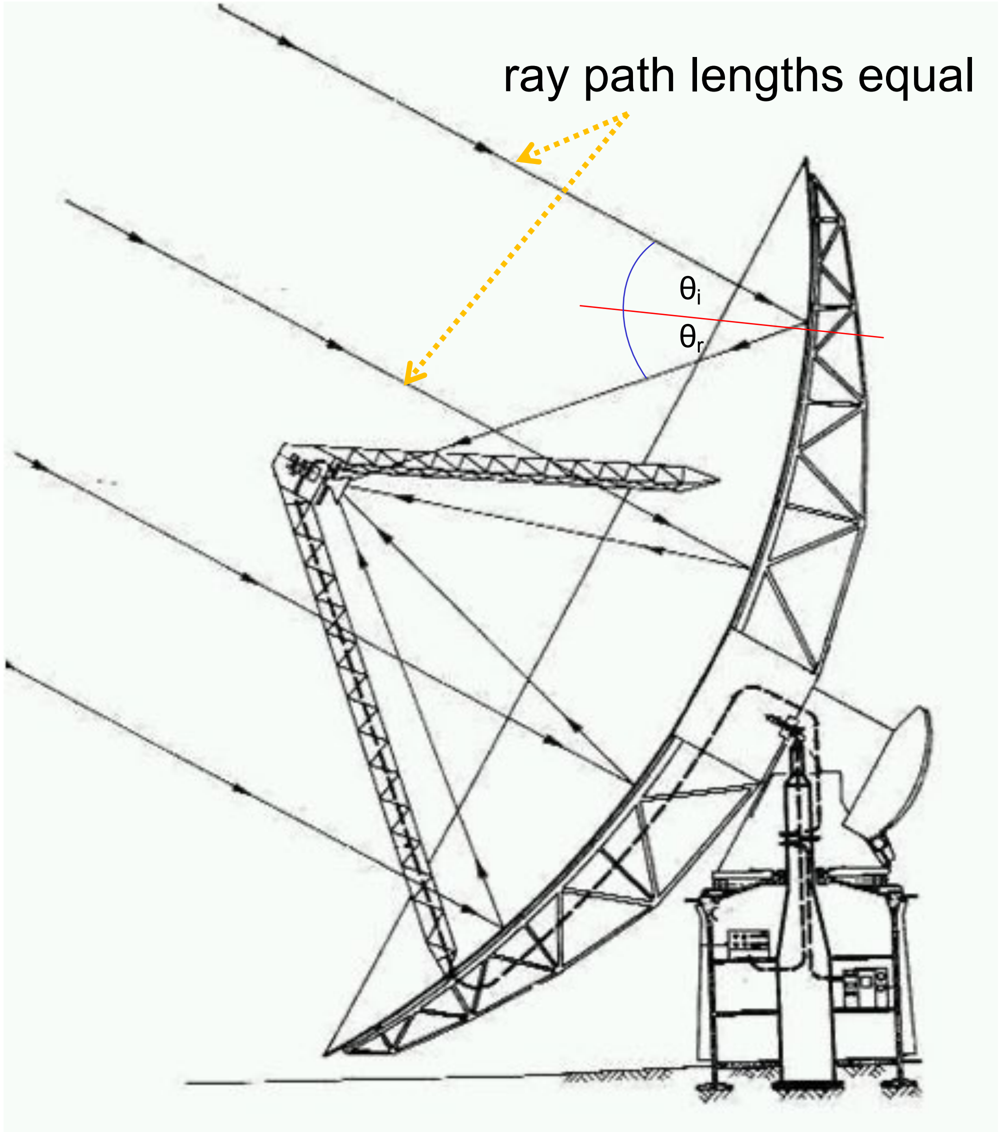
- Signal is received
- Signal is digitised/channelised
- Digital signal is processed by backend
  - Graphical Processing Unit (GPU)
  - Field Programmable Gate Array (FPGA)



Parkes UWL in anechoic chamber in Sydney, Australia

The parabolic reflector

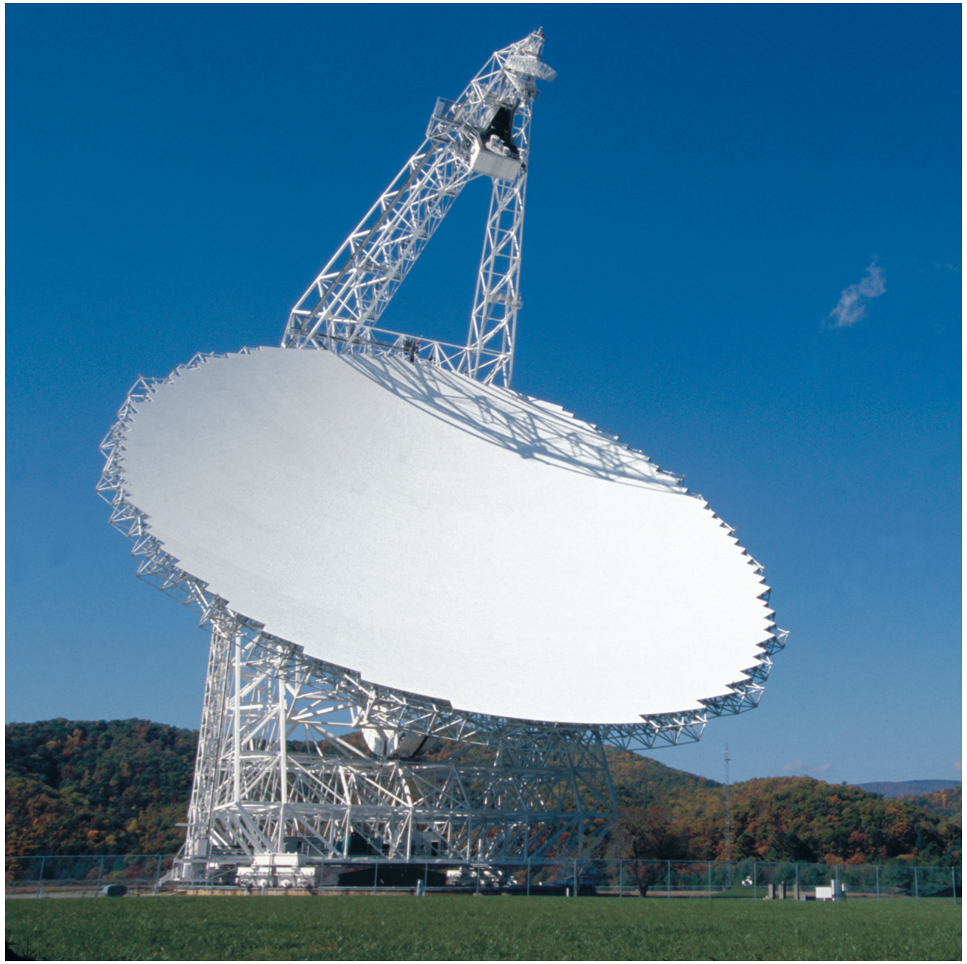
- In-phase addition at the focus
- Murriyang (Parkes) 64-metre antenna
  - Prime-focus: f/D ~ 0.4
  - 74 MHz – 26 GHz
    - (2.5 decades in frequency)
    - Optical band (one octave)



- Antennas can have a variety of focuses: Prime focus vs Gregorian/secondary etc.
- MeerKAT uses Gregorian offset – it folds the optics to put the receivers in a convenient place

The parabolic reflector

Five hundred metre aperture spherical telescope (FAST)

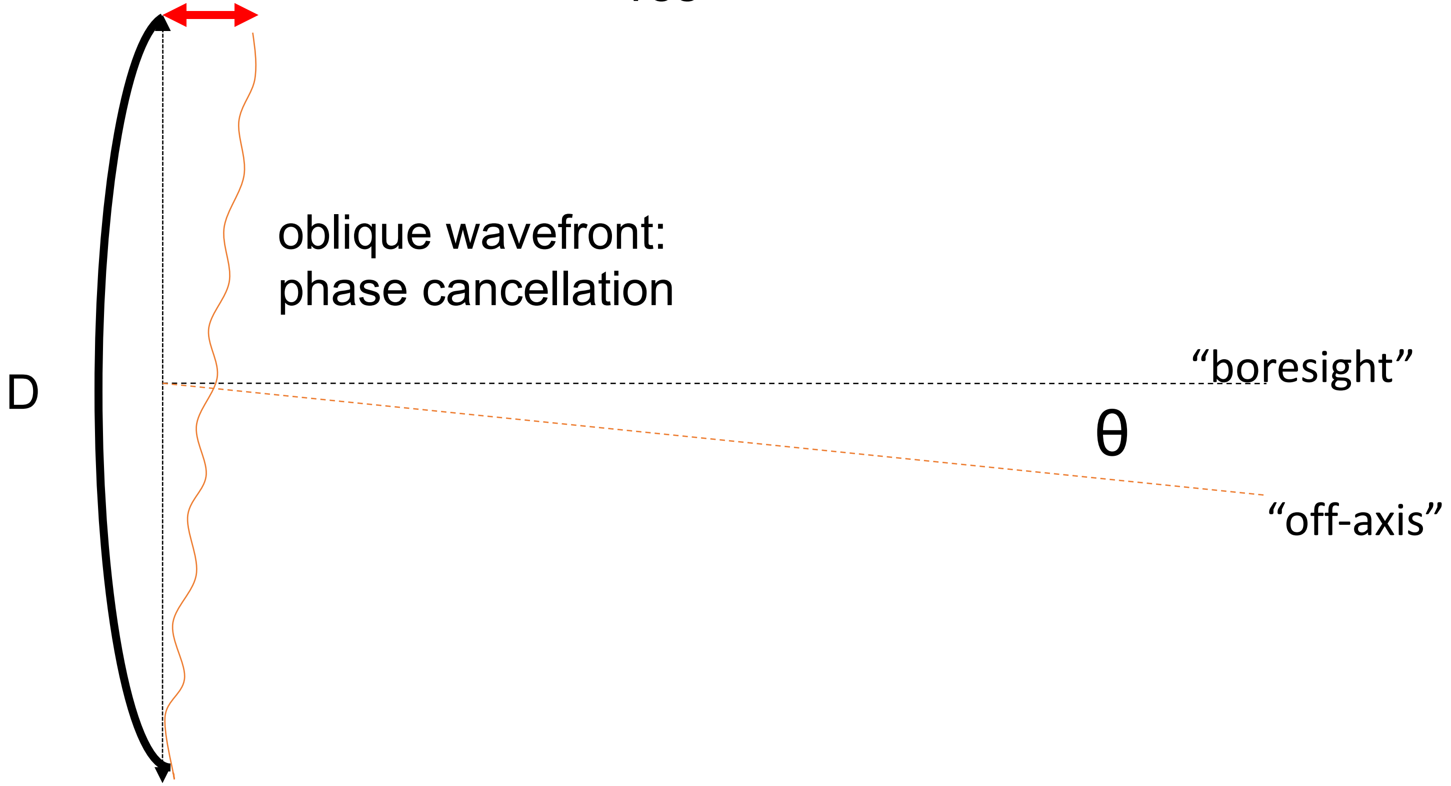


Green Bank Telescope (GBT)

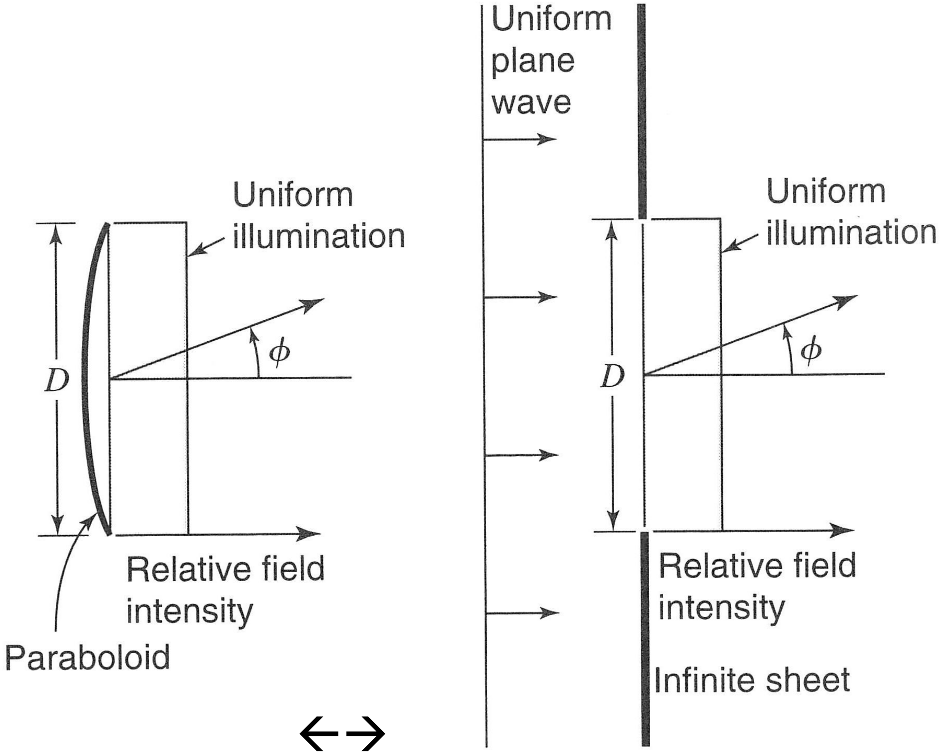
Diffraction limit – simplified

$\theta D = \lambda$

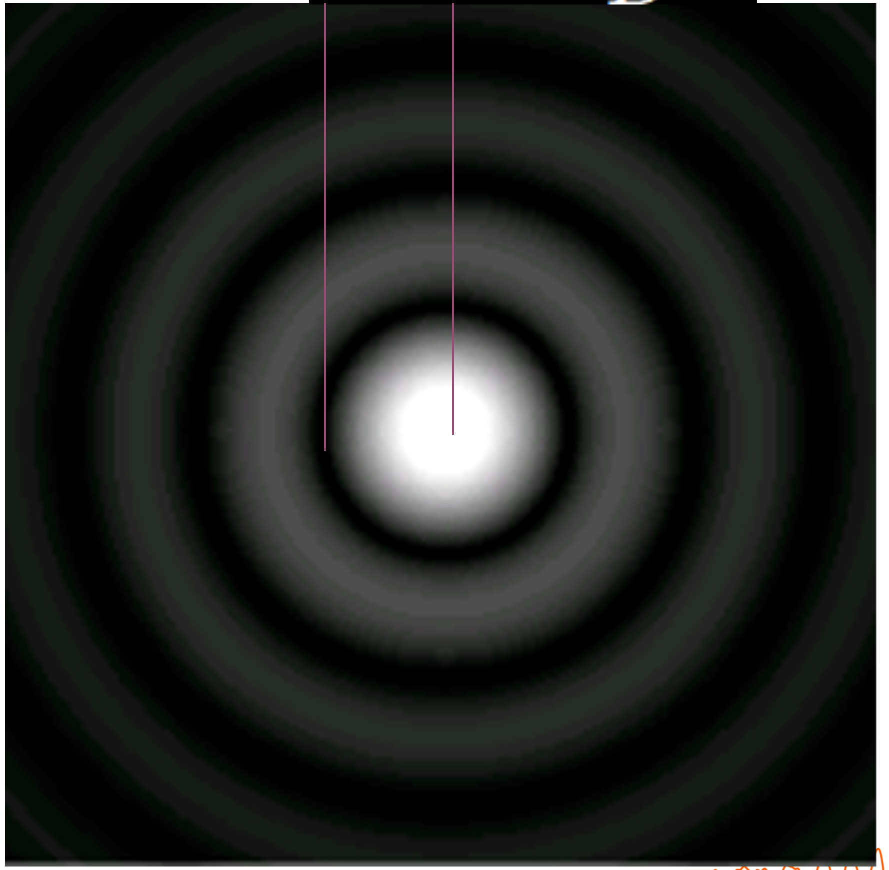
(small-angle approx.) $\rightarrow$ $\theta_{res} = \lambda / D$



Diffraction limit

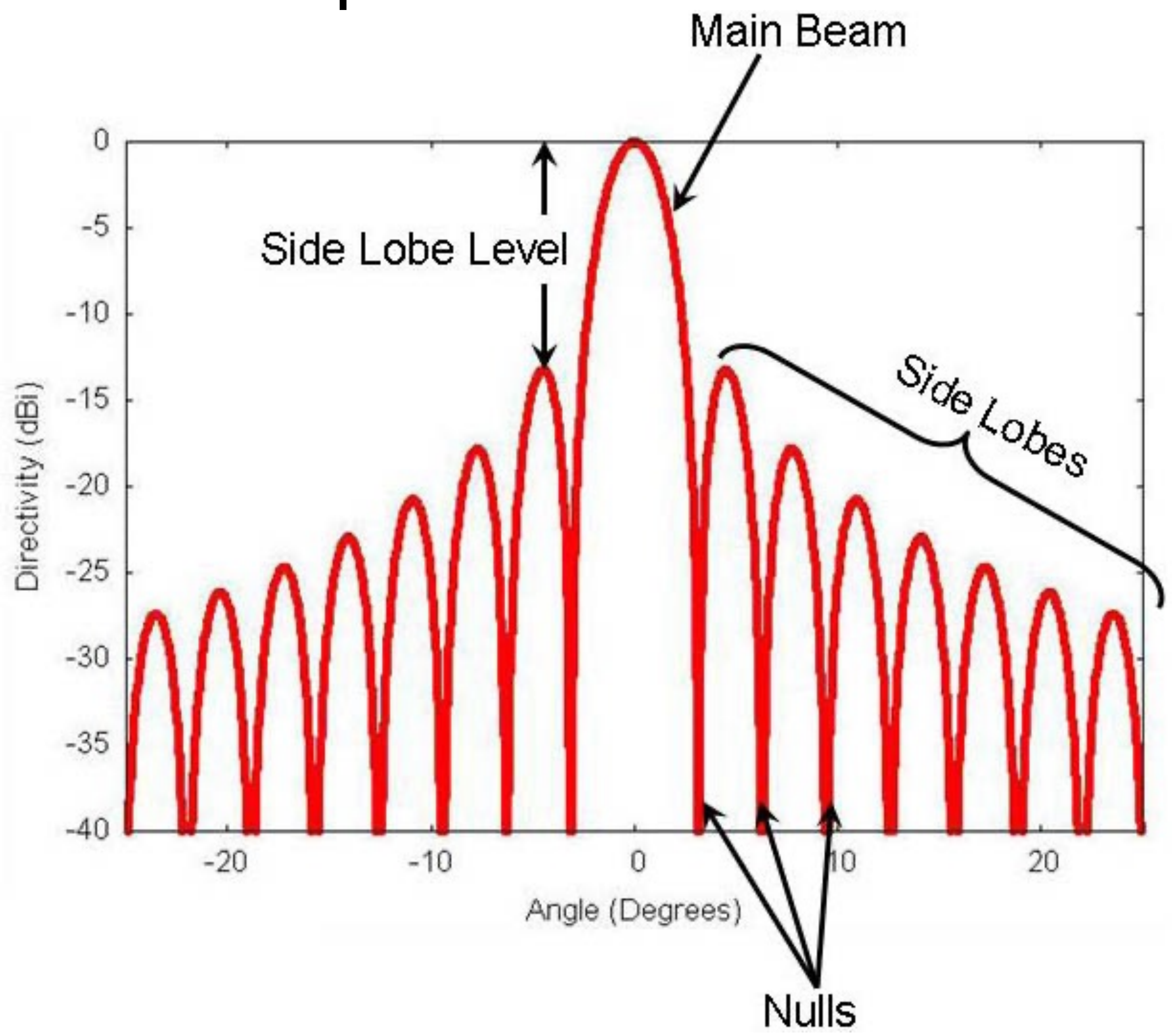


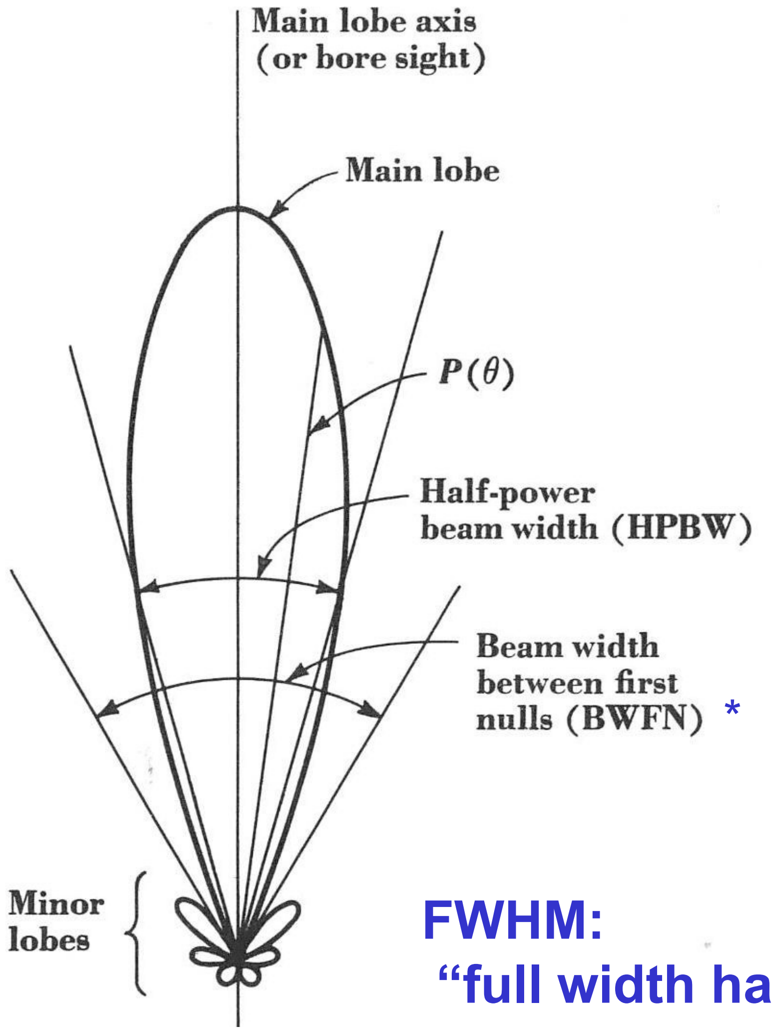
$$\Delta\theta \approx \frac{1.22\lambda}{D}$$



Diffraction theory results in the Airy pattern →

Telescope beams

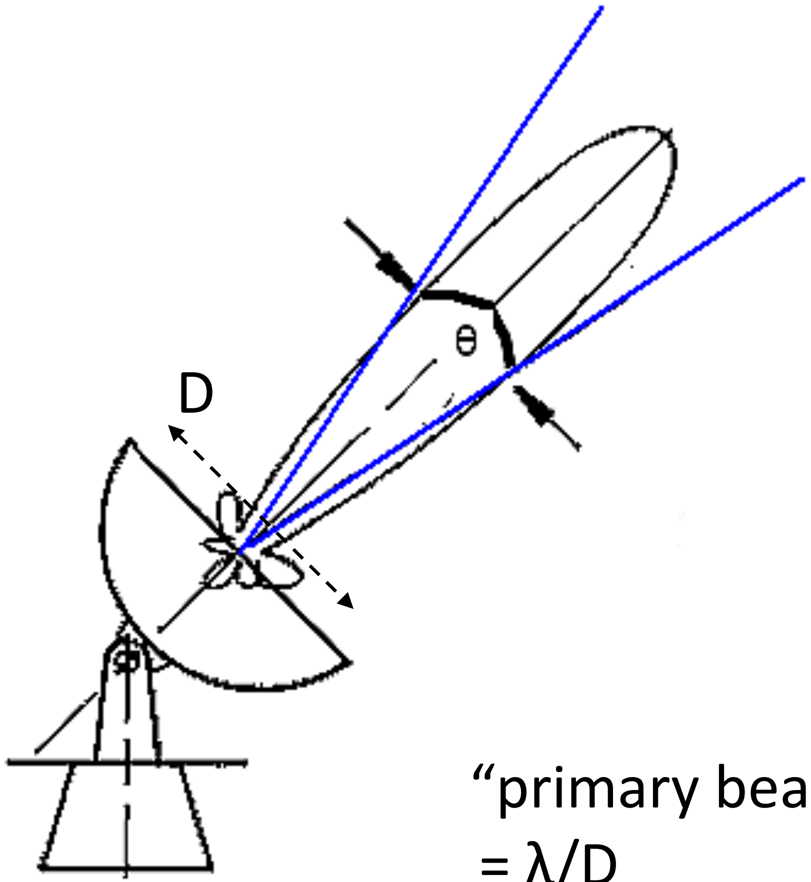




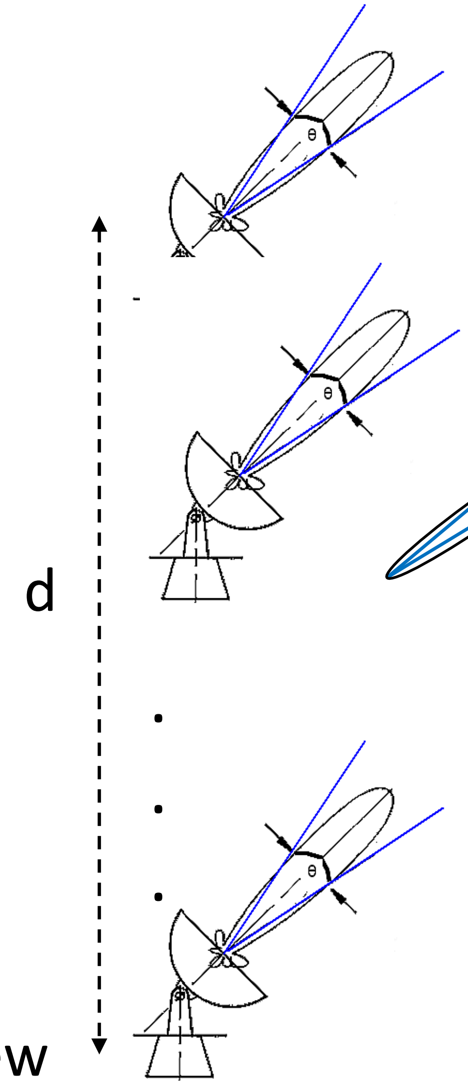
FWHM:
"full width half maximum"

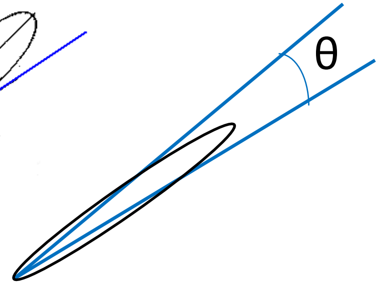
Radio telescopes: sensitive to sources in primary beam and in sidelobes

Primary Beam = “field of view”



“primary beam”
= λ/D
= FWHM
Is the field of view





“synthesised beam”

$$\theta_{FWHM} = \lambda/d$$

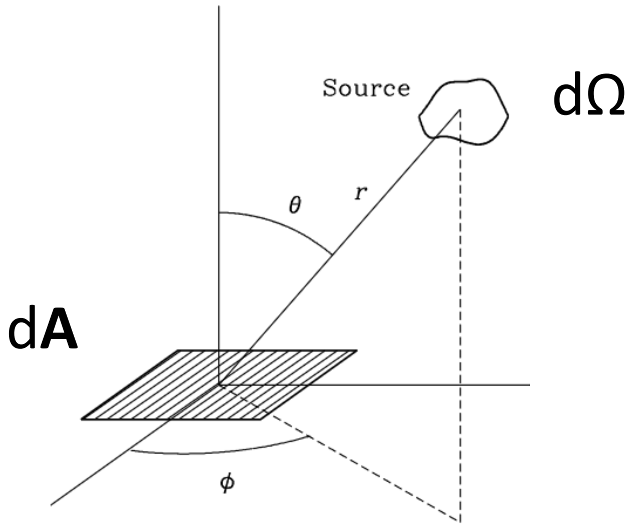
An array of small dishes has a wide field of view (small ***D***) but sharp resolution (big ***d***)

Intensity vs Flux Density

- Astronomers measure power per unit collecting area per unit bandwidth

Sky Intensity / Brightness:

$I_\nu(\theta, \varphi, \nu)$: W Hz^{-1} sr^{-1} m^{-2}



dP = $I_\nu \cos(\theta)\, dA\, d\Omega\, d\nu$

Flux density (W Hz^{-1} m^{-2})

$$S_\nu \equiv \int_{\text{source}} I_\nu(\theta, \phi) \cos\theta d\Omega$$

$$S_\nu \approx \int_{\text{source}} I_\nu(\theta, \phi) d\Omega$$

Jansky: 1 Jy = 10^{-26} W Hz^{-1} m^{-2}

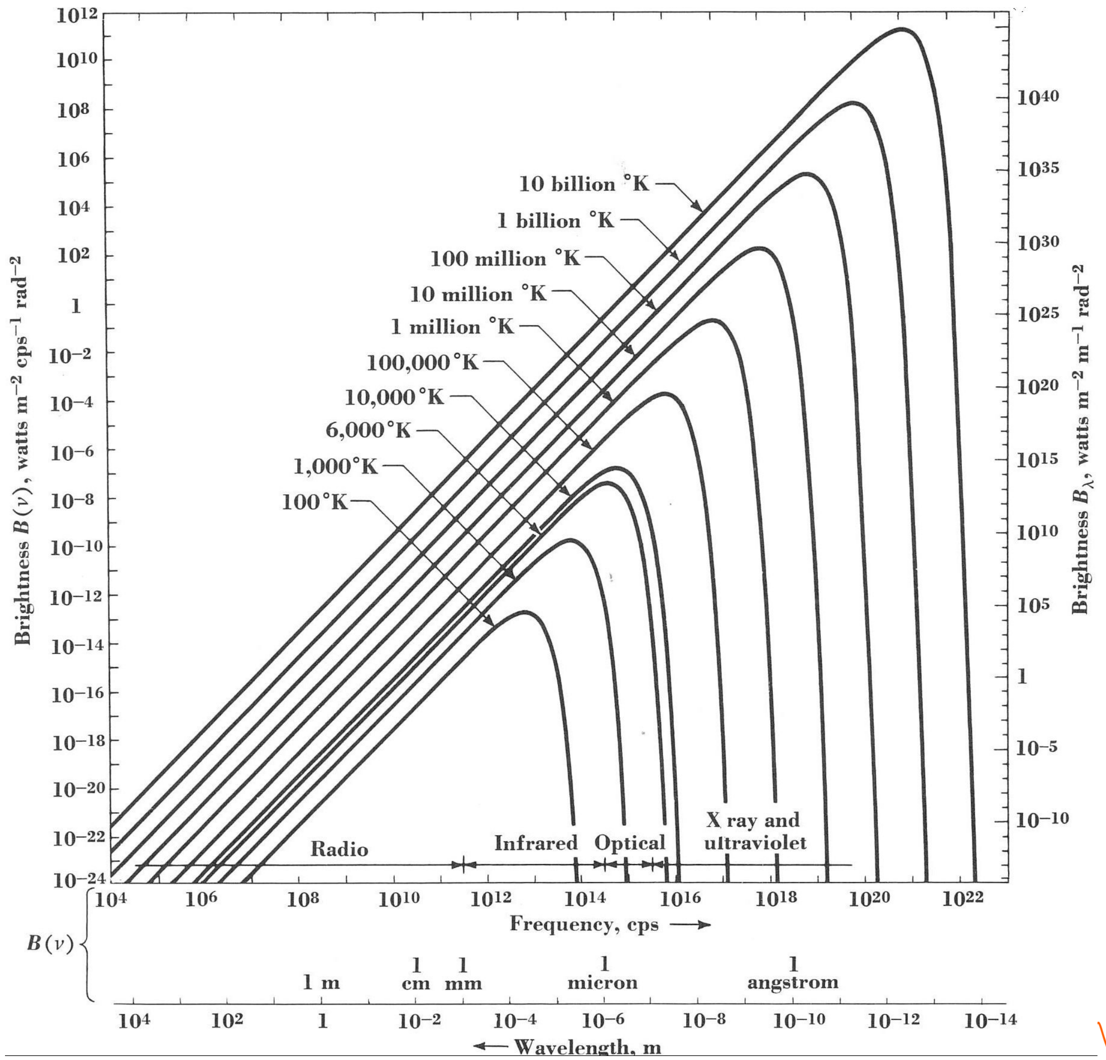
Thermal radiation

Radio astronomy we' re (nearly) always in the "Rayleigh-Jeans" regime:

$$I(\lambda) = 2kT/\lambda^2$$

units: Watt m^{-2} Hz^{-1} sr^{-1}

short-hand: refer instead to "brightness temperature" T



Antenna effective area

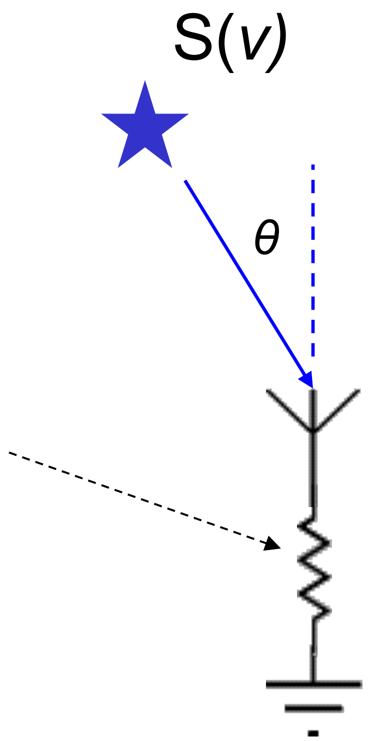
S(ν) : flux density (W m^{-2} Hz^{-1}) – "point" source

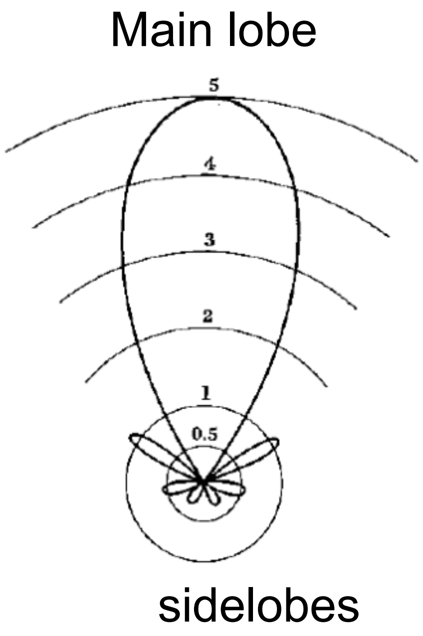
- Antenna Effective Area: how much flux is collected?

- *Matched power density, polarisation i*

$$P_i(\theta, \nu) = S_i(\nu)\mathrm{Aeff}\,(\theta, \nu)$$

$$S_i(\nu) = \frac{1}{2} S(\nu) \ \text{for unpolarized source}$$





A_{eff} (θ) : the beamshape

Antenna sensitivity

Aliases for A_{eff} (effective area):

- Aperture efficiency $\eta = A_{eff}/A_{physical}$
- Forward gain (dBi) $G = 10*\log(A_{eff}/A_{iso})$
- Gain as T/S ("Kelvin per Jansky") $:= 1 /(2k/A_{eff} \times 10^{26})$
  - Murriyang = 0.7 K/Jy, MeerKAT = 2.8K/Jy, FAST = 16 K/Jy

Two handy antenna facts

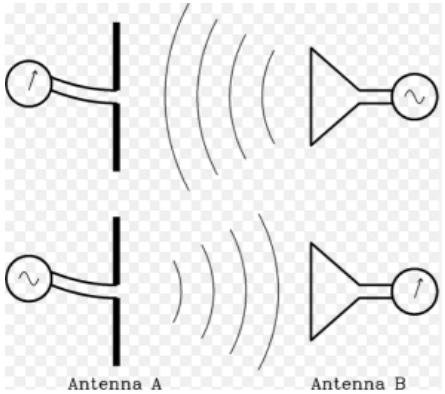
- **All-sky integral of A_{eff} depends only on wavelength:**
  - High gain = small beam area
  - "No high-gain isotropics"

$$\oint A_{eff}(\hat{\mathbf{n}}).\, d\Omega = \lambda^2$$

$$A_{iso} = \lambda^2 / 4\pi$$

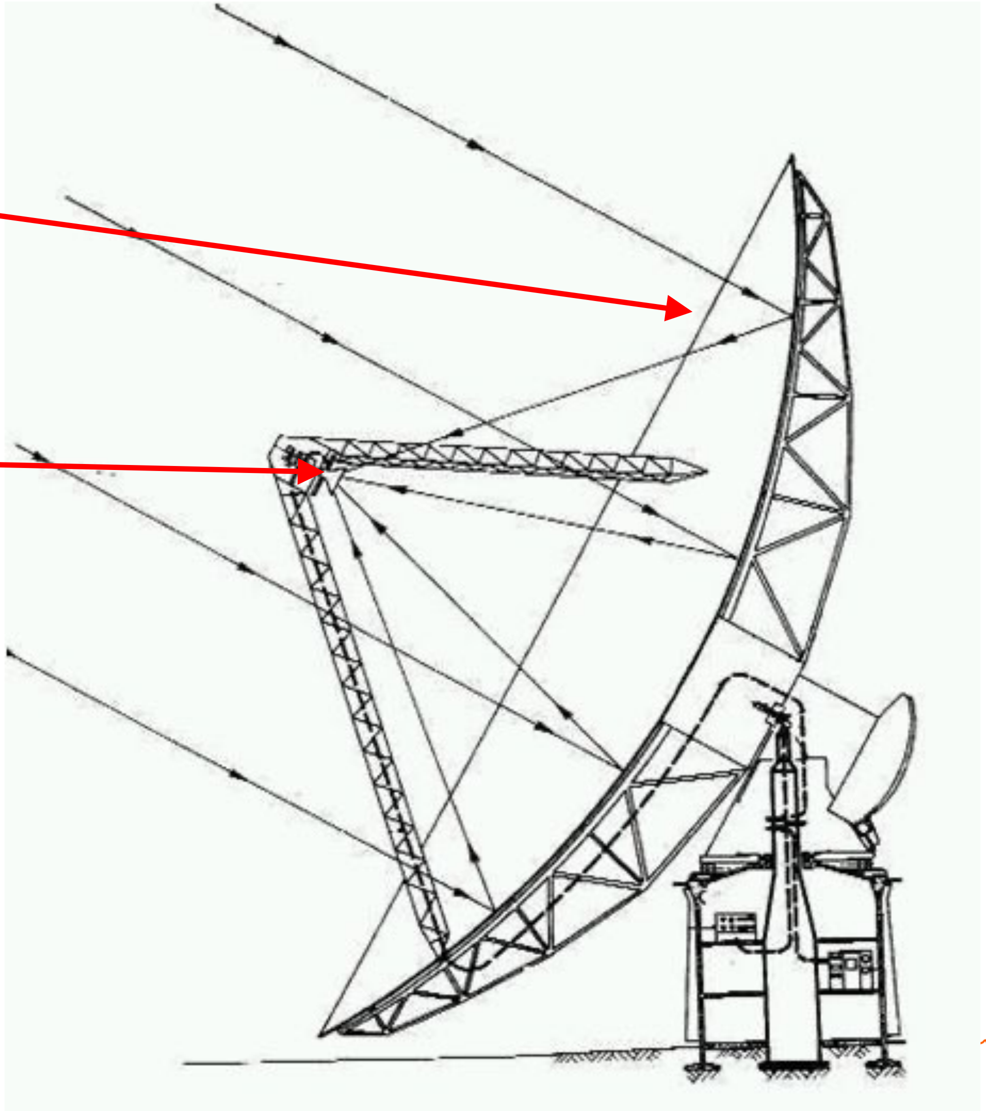
(You can re-distribute sensitivity on the sky but can't create it!)

- **Reciprocity theorem:**
  - transmitted beam shape = received beam shape
  - Easier to model beam pattern



The Feed or Receiver

Reflector or
“concentrator”



Feed/receiver or
“sensor”

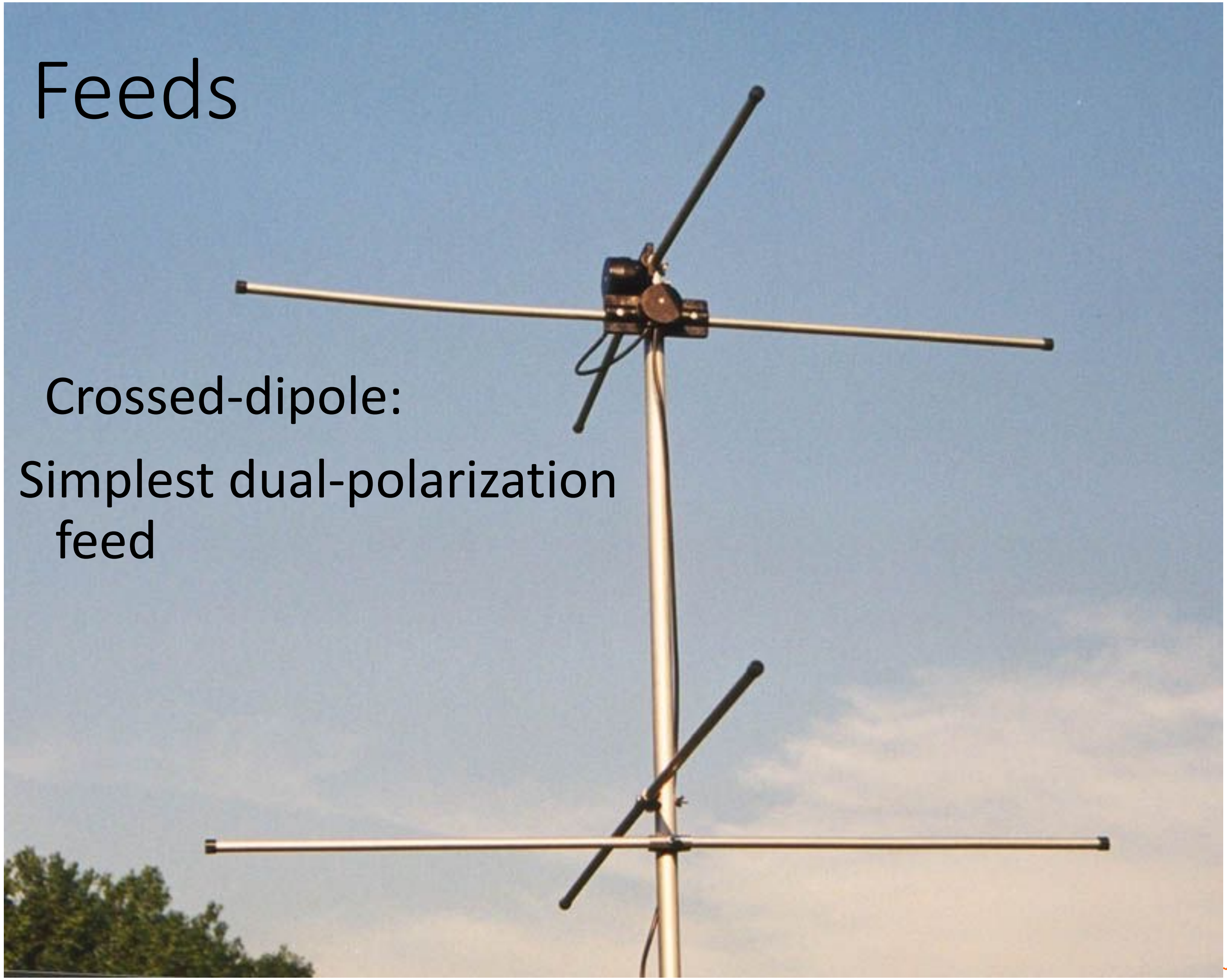
The feed collects the energy,
“illuminating” the reflector

The feed itself is a (small) antenna
- Its beam pattern paints the dish

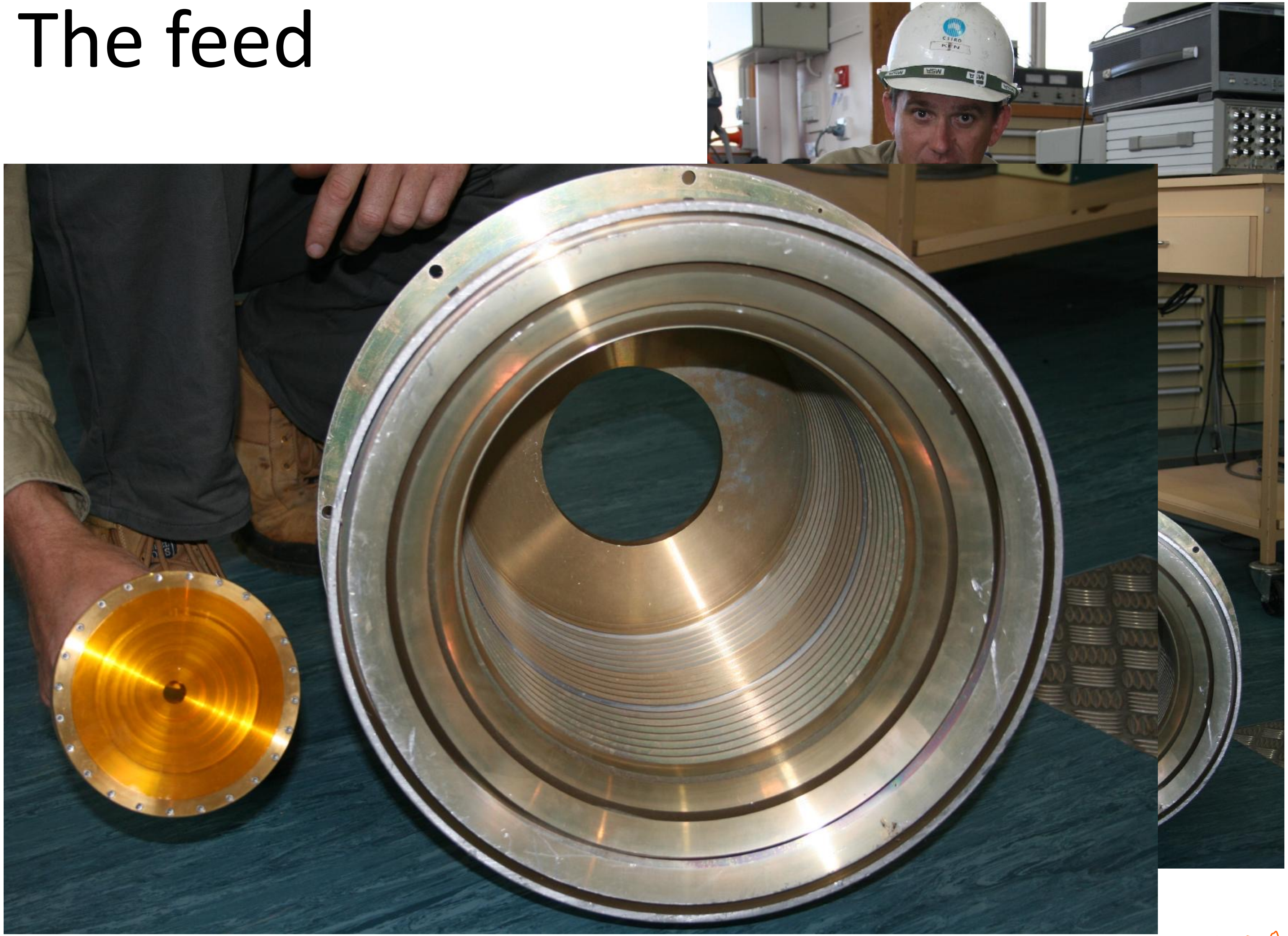
Feeds

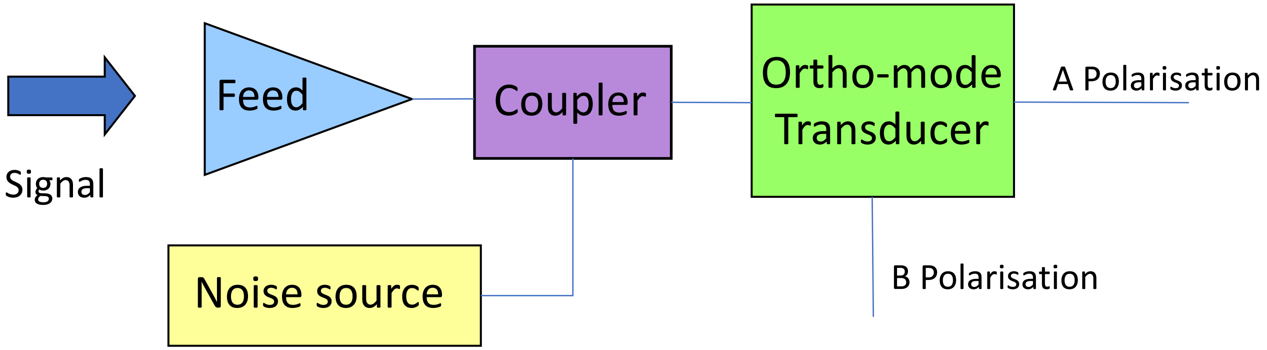
Crossed-dipole:

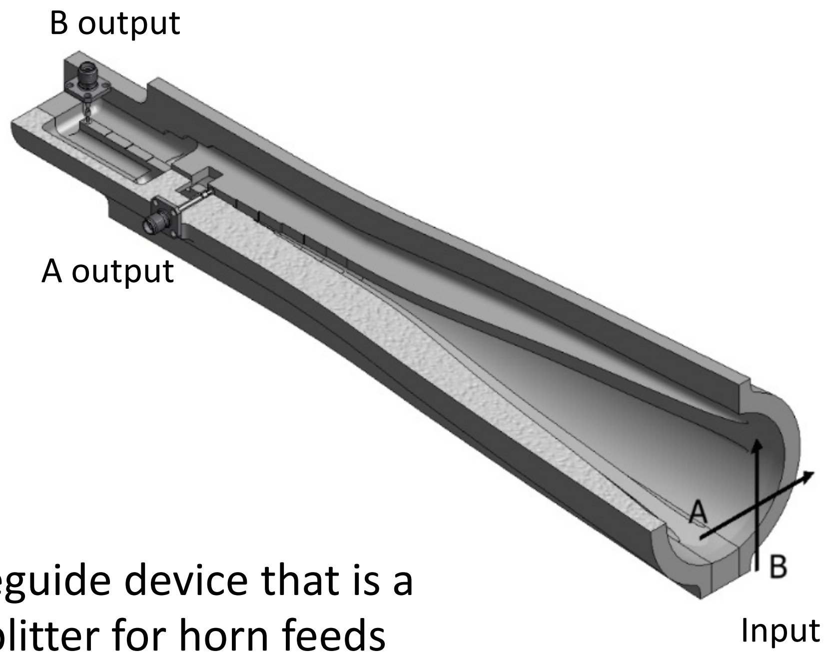
Simplest dual-polarization feed

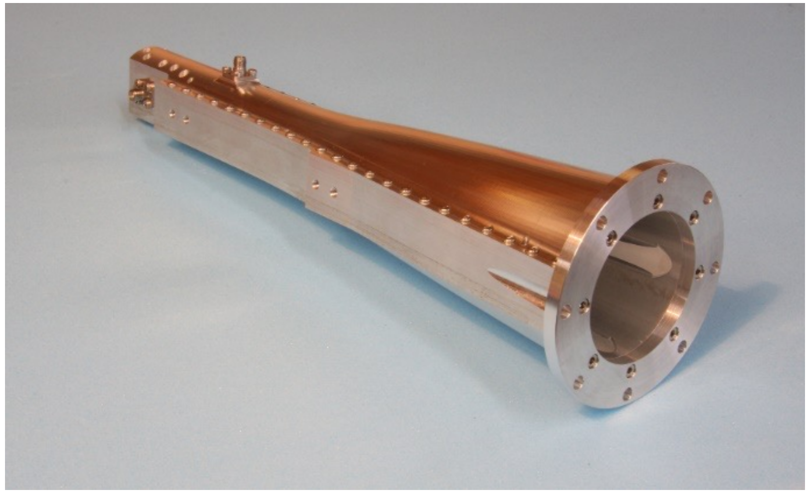


The feed

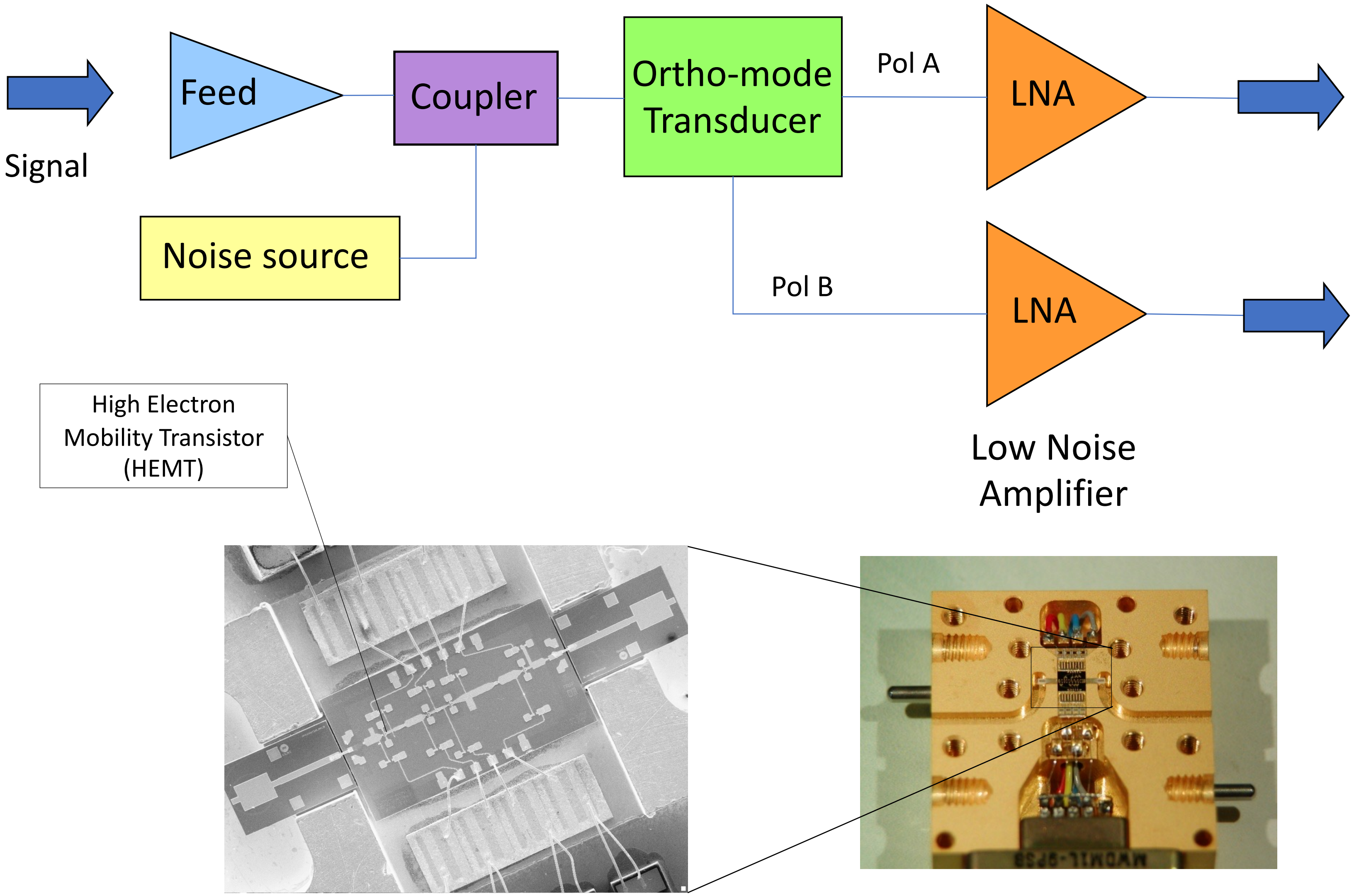








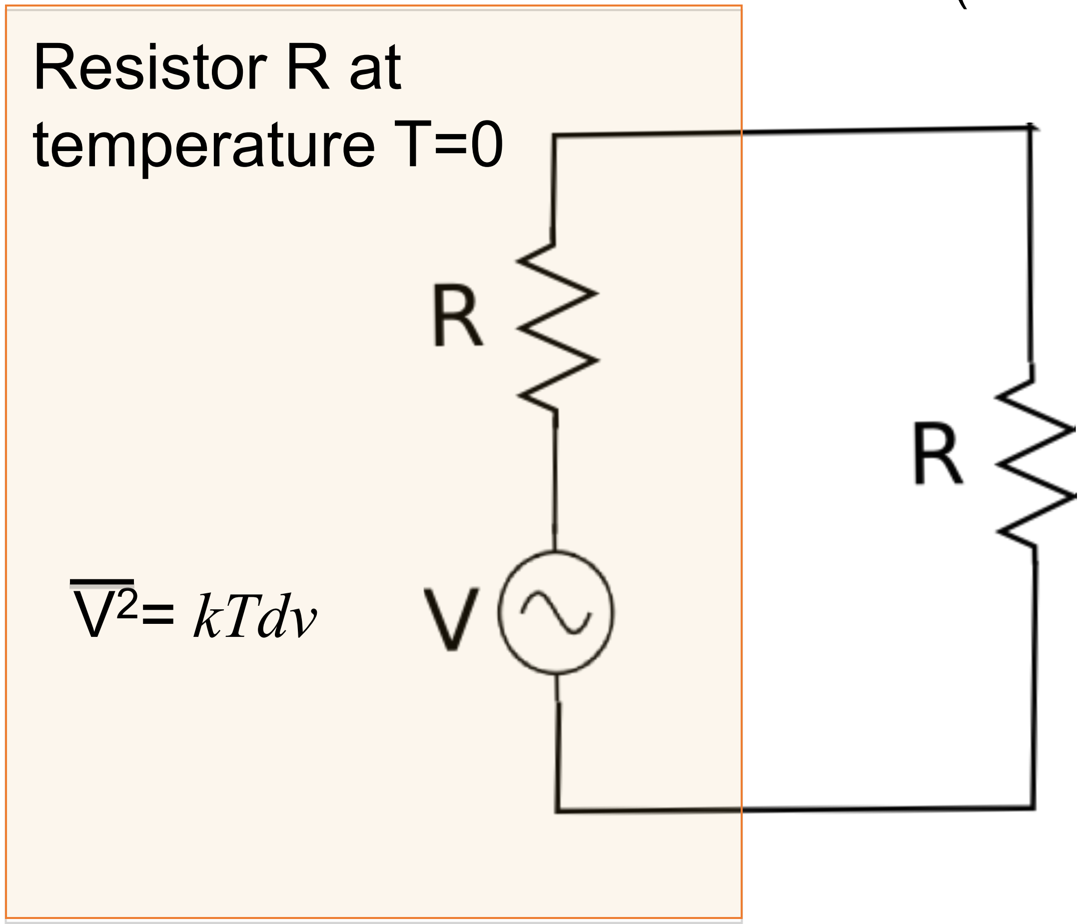
OMT is a waveguide device that is a polarization splitter for horn feeds


Signal
Feed
Coupler
Noise source
Ortho-mode Transducer
Pol A
Pol B
LNA
LNA
Low Noise Amplifier
High Electron Mobility Transistor (HEMT)

Nyquist noise theorem

(Johnson-Nyquist Theorem)

(This is why temperature the universal noise unit)



Resistor R at temperature T

white noise power:

$$P = kT\,\mathrm{d}v \quad \text{(W)}$$

or spectral density:

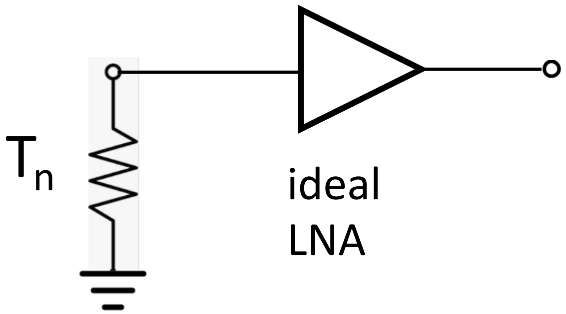
$$S = kT \quad (\text{W Hz}^{-1})$$

Equivalent temperatures:

For radiation intensity: $I(\nu) = 2kT_B/\lambda^2$ (W m^{-2} Hz^{-1} sr^{-1})

T_B : "brightness temperature"

For noise in a circuit: $S(\nu) = kT_n$ (W/Hz)



T_n: "noise temperature"

Figure of merit for LNA: $T_n = T_{LNA}$

The noise equation! T_{sys}

T_{sys} = total receiver power density expressed as temperature

$$T_{sys} = T_A + T_{spillover} + T_{sky} + T_{rx} + T_{2.7K}$$

Elevation

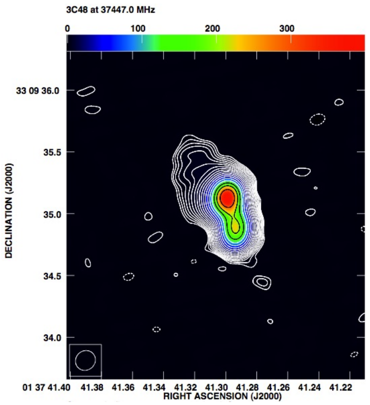
Atmospheric "seeing"

Time, weather

Engineering!

Typically, $T_A < T_{sys}$ in radio astronomy !

(i.e. low SNR)



10Jy radio source → ~1K additional noise

Your hand → ~300K additional noise

Mobile Phone at 1 km→ ~10^{11} K !!

(in primary beam)

Radiometer Equation!

Basic problem: want $T_A = T_{sys}$ (on source) – T_{sys}(off source)

Solution:

Off source noise:

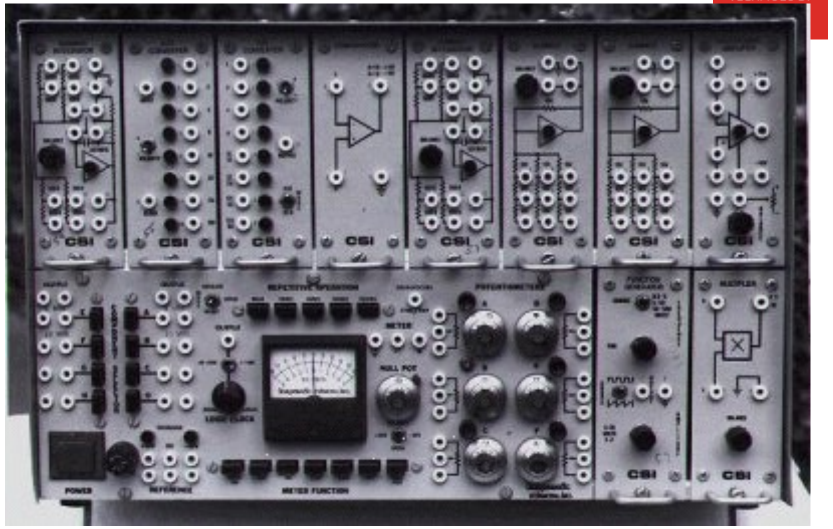
$$\sigma = \frac{T_{\rm sys}}{G\sqrt{2\Delta\nu\Delta T}}$$

ΔT = integration time (seconds)

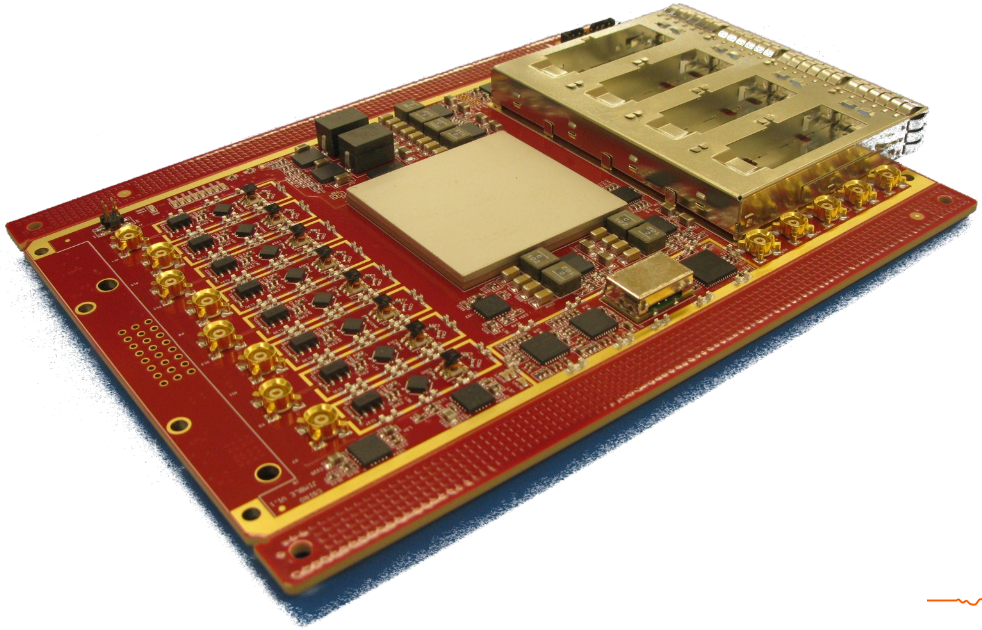
$\Delta\nu$ = detector bandwidth (Hz)

Radiometer equation is fundamental to radio astronomy

The Backend:
Digital Signal Processing - DSP



- Why digital:
  - Stability over time/temperature
  - Superior performance (e.g. filter shape)
  - Cost – can mass produce



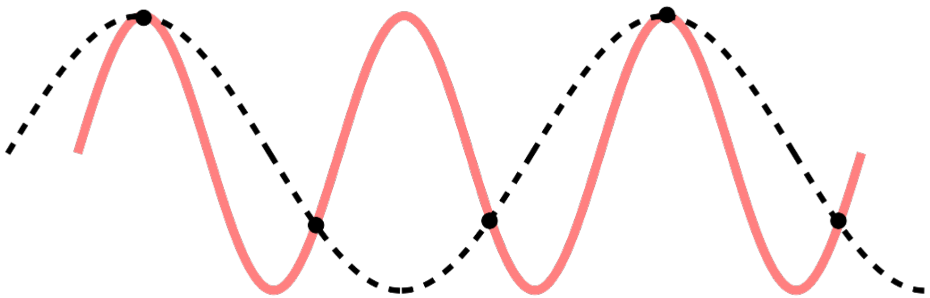
- Issues:
  - Loss of dynamic range and SNR
  - Artefacts – e.g. aliasing & birdies
  - Cross talk and reliability
  - High power requirements

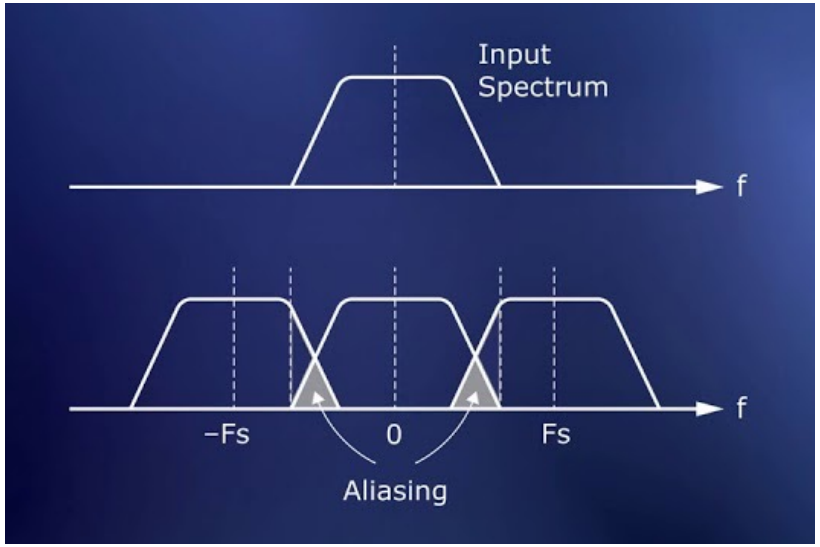
SWINBURNE UNIVERSITY OF TECHNOLOGY

OzGrav

Nyquist/Shannon Sampling

- A band-limited signal can be perfectly reproduced if it is sampled at a frequency at least twice rate of maximum bandwidth
  - Critical sampling rate Nyquist (=2*B)
  - 100 MHz bandwidth signal needs to be sampled at 200 MHz
- *Aliasing* occurs if sampling at a lower rate
  - *Frequencies can be lost, folded and mixed*
- With wide band systems need fast digitization!

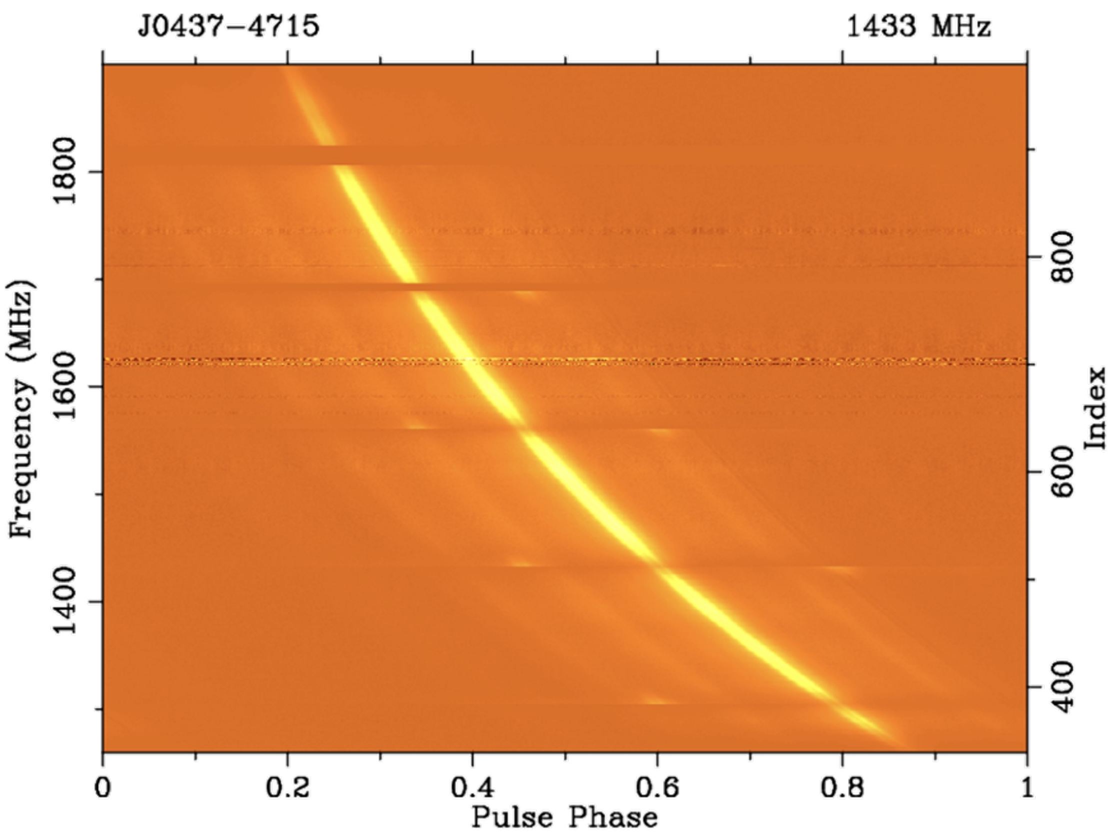




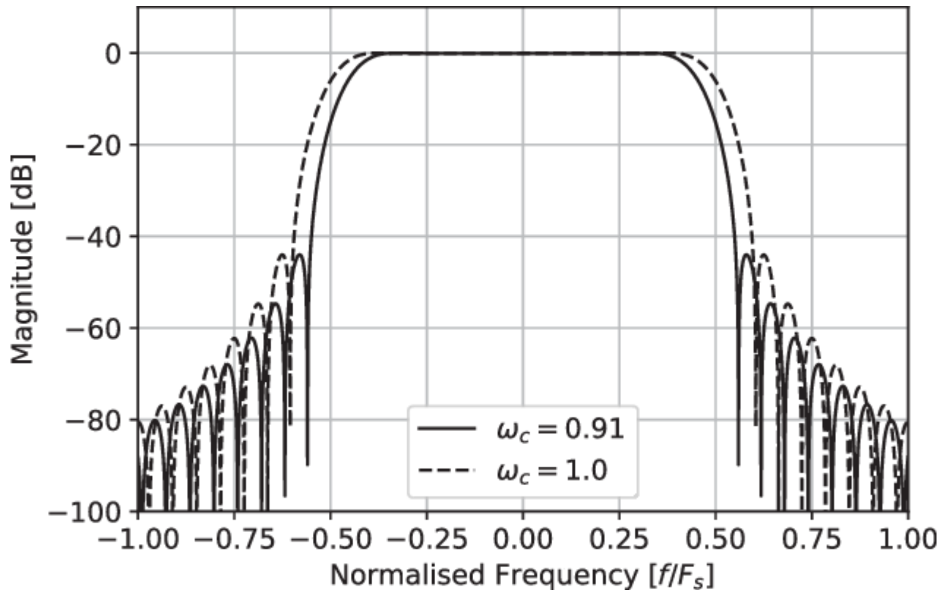
Nyquist, H. (1928). "Certain topics in telegraph transmission theory."
Shannon, C. E. (1949). "Communication in the presence of noise."

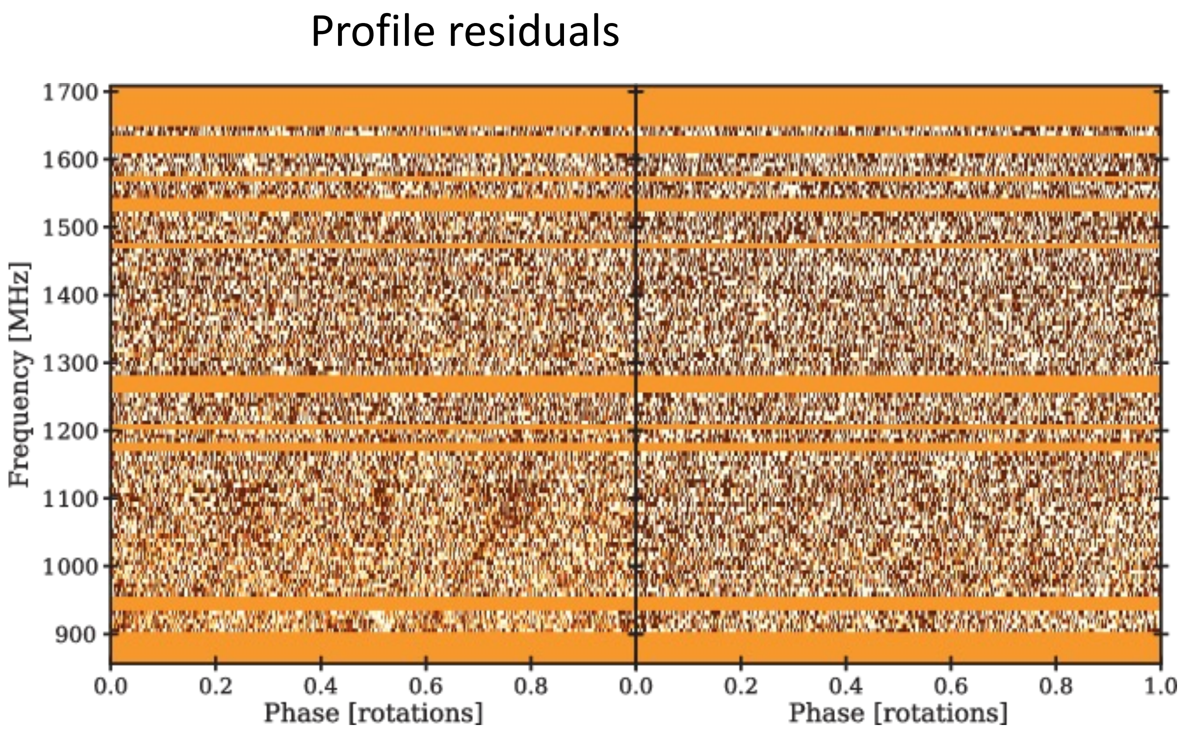
Channelisation

- Divide data into channels
- Need to disperse pulsar signal
- Enable mitigation of rdio-frequency interference
  - (zap bad channels)
- Account for profile evolution
- Uncertainty principle:
  - Can’t resolve features smaller than τ =1/(Δν) in observation



Channelisation



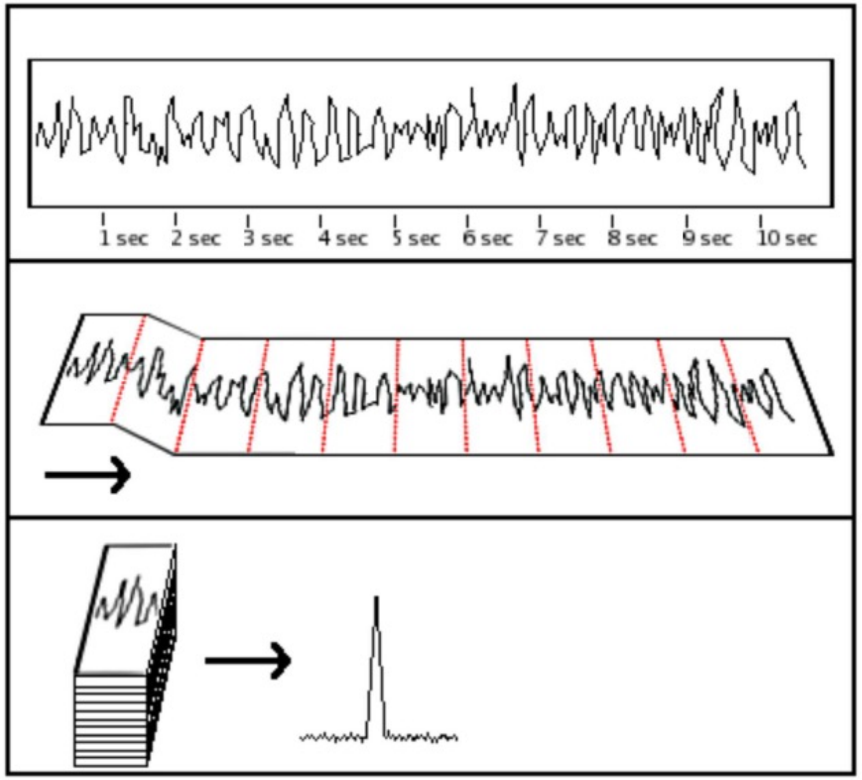


Channel filters are not sharp walls!

- Issue: aliasing of signals between channels
- Choice of filter shape can help remove correlator artefacts

Pulsar folding

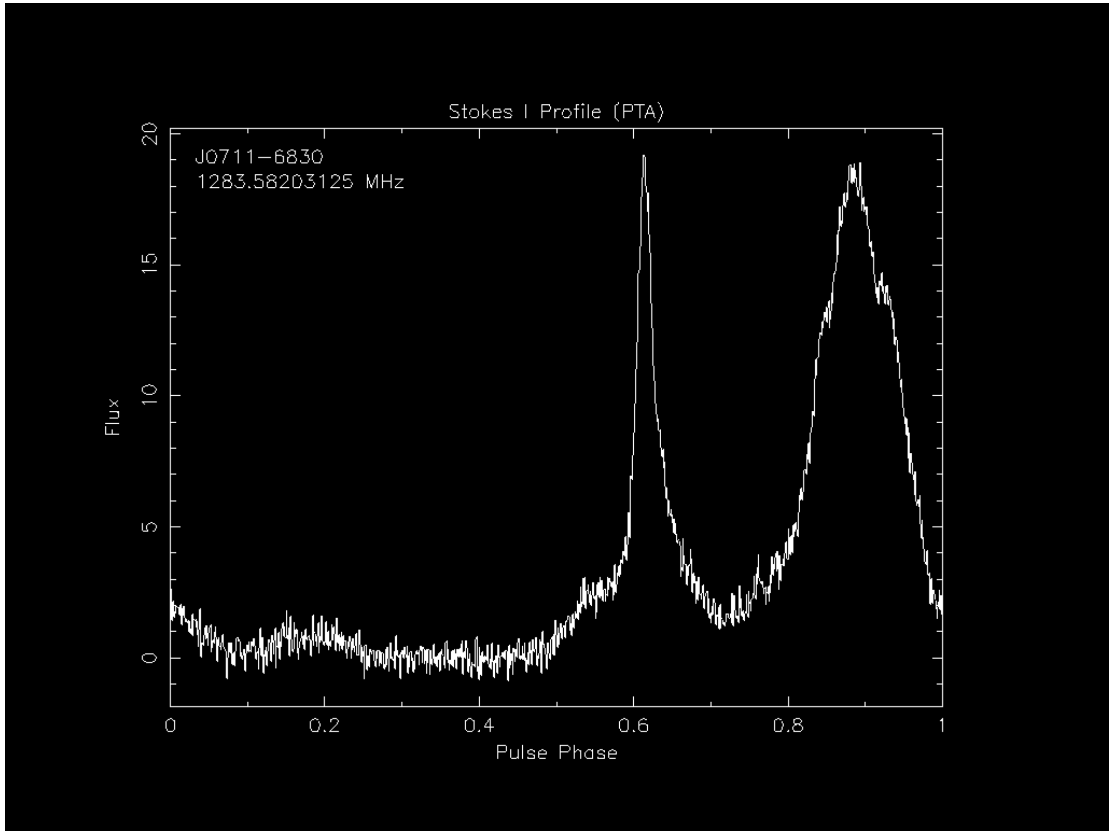
- Precision pulsar timing undertaken normally with “fold mode” observations
- Pulsars are faint
  - For most pulsars observed with most telescopes individual pulses are indistinguishable from noise
  - Average together many pulses to get achieve higher S/N
- In PTA timing, we are studying known pulsars
  - We have a good idea model for the rotation of pulsar
  - Unmodelled signals (hopefully) do not distort pulse shapes



Credit: R. Lynch

Pulsar timing data

- Average data to reduce volume
  - 8-30 seconds
- Data cubes
  - Polarisation
  - Frequency channels
  - Subintegrations
  - Pulse phase
- Visual data in “waterfall plots”
- Average along various axes
  - “scrunching”



MeerKAT observations of J0711-6830

Pulsar timing data

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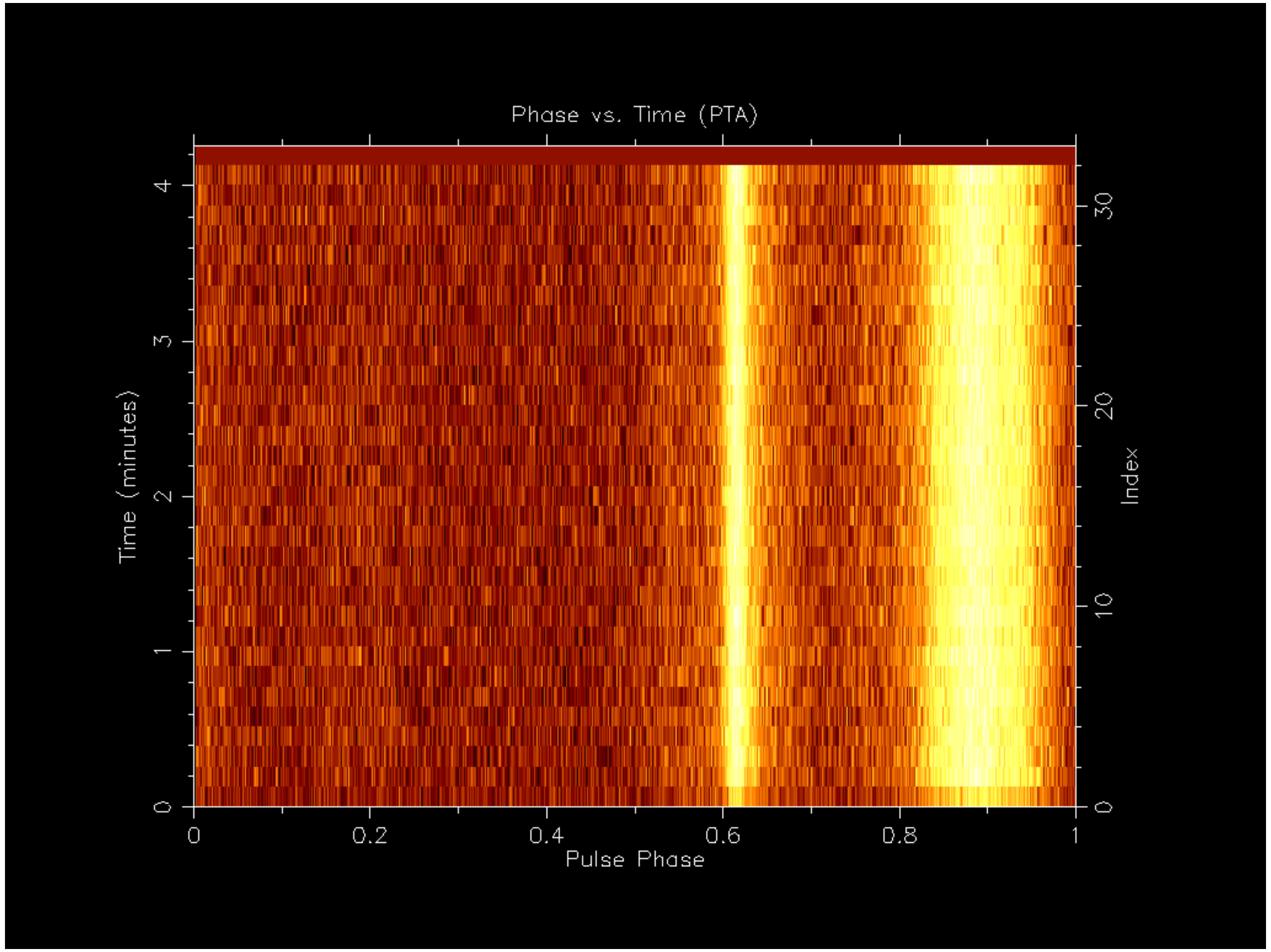

MeerKAT observations of J0711-6830

Timing precision!

- Sensitivity depends on gain of telescope and system temperature
  - T_{sys}: system temperature (20 K)
  - n_p: number of polarisations (2)
  - G: gain (0.9 – 10 K/Jy^{-1})
  - t: integration time
  - Δν: Bandwidth (10^2-10^3 MHz)

$$S_{\mathrm{sys}} = \frac{T_{\mathrm{sys}}}{G\sqrt{n_p t \Delta\nu}}$$

$$\sigma_{\mathrm{TOA}} \approx \frac{S_{\mathrm{sys}}}{\sqrt{t\Delta\nu}} \frac{P\delta^{3/2}}{S_{\mathrm{mean}}}$$

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LNA, spillover, sky, etc.

$$S_{\rm sys} = \frac{T_{\rm sys}}{G\sqrt{n_p t \Delta\nu}}$$

Feed, digitizer, backend

Dish size and aperture efficiency

$$\sigma_{\rm TOA} \approx \frac{S_{\rm sys}}{\sqrt{t\Delta\nu}} \frac{P\delta^{3/2}}{S_{\rm mean}}$$

Timing precision!

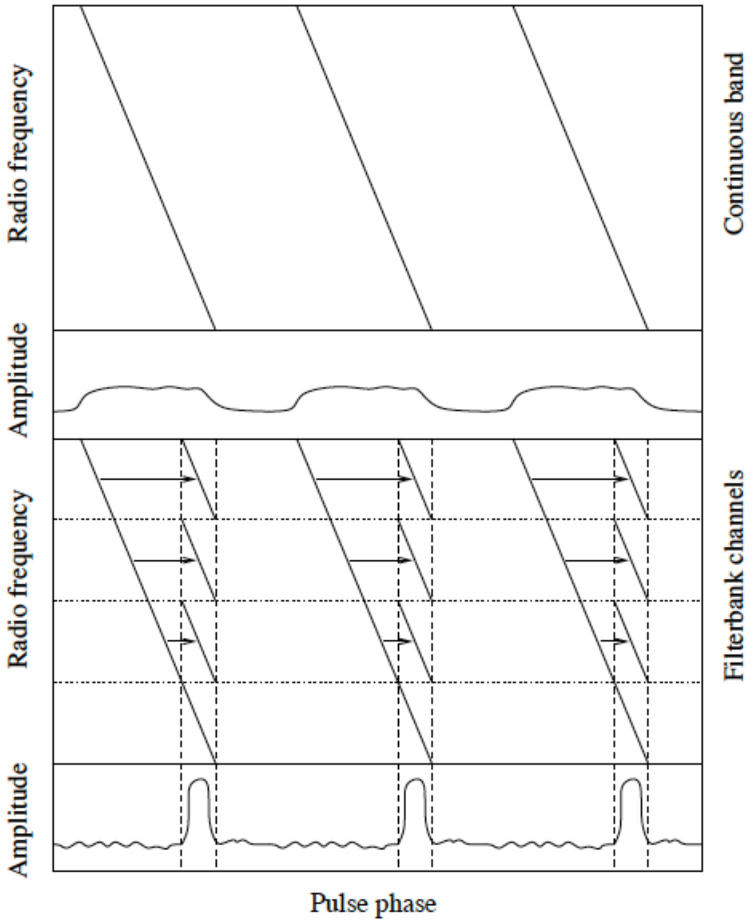
- Timing precision depends on the pulse width
  - S_{mean}: period averaged flux density
  - P: pulsar spin period
  - δ: pulsar duty cycle
    - (pulse width/pulse period)

$$S_{\rm sys} = \frac{T_{\rm sys}}{G\sqrt{n_p t \Delta\nu}}$$

$$\sigma_{\rm TOA} \approx \frac{S_{\rm sys}}{\sqrt{t\Delta\nu}} \frac{P\delta^{3/2}}{S_{\rm mean}}$$

Coherent dedispersion

- Issue: If the dispersion delay across a single channel is larger than the time resolution (or structure in pulse profile) profile will be smeared
- Solution: If you know the dispersion measure ahead of time you can correct for its effect on the voltage signals to remove intrachannel smearing
- Most modern pulsar timing systems employ coherent dedispersion



Lorimer & Kramer (2004)

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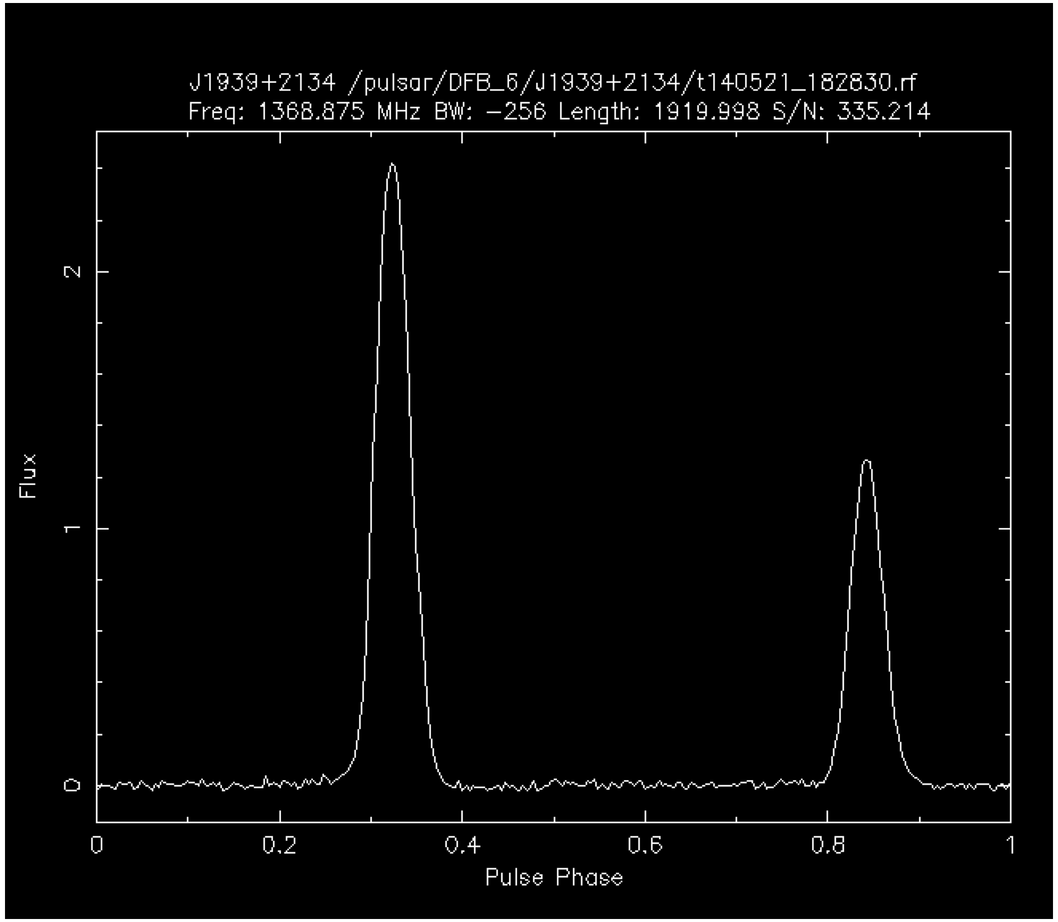
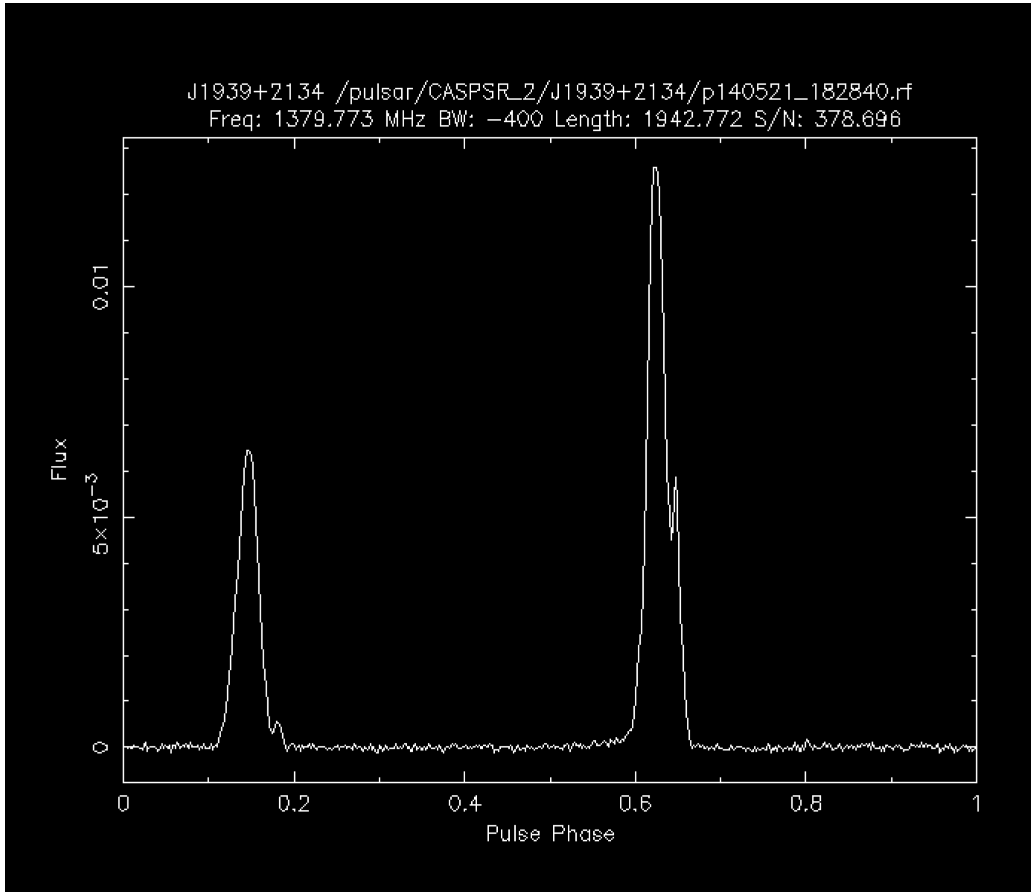


Parkes digital filterbank 4: incoherent dedispersion

Coherent dedispersion

- The ISM is a known phase-changing filter
- Correct for phase delay imparted by ISM on voltages (Electric fields) by deconvolving it, prior to forming intensity

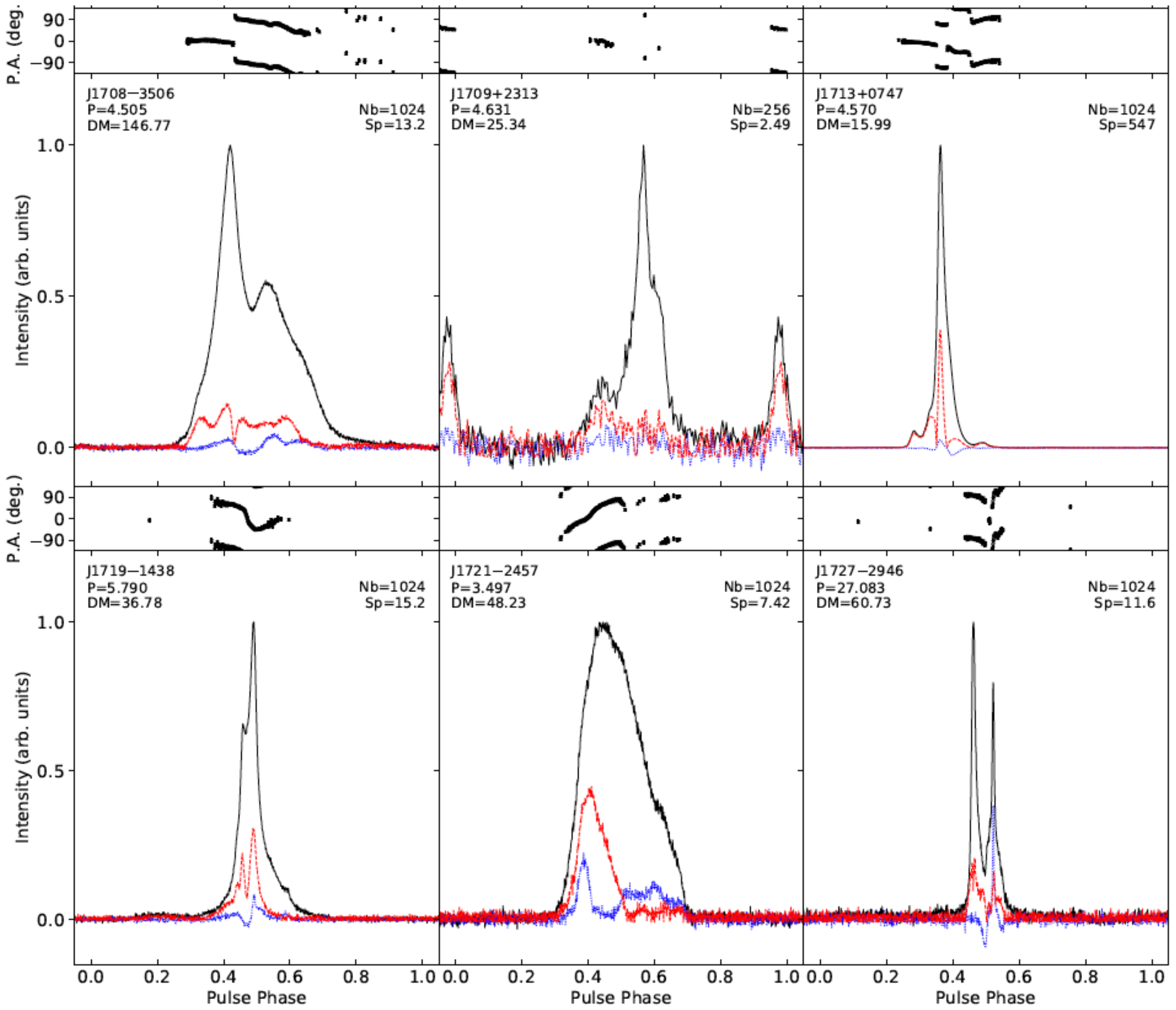


CASPSR: coherent dedispersion

Calibration

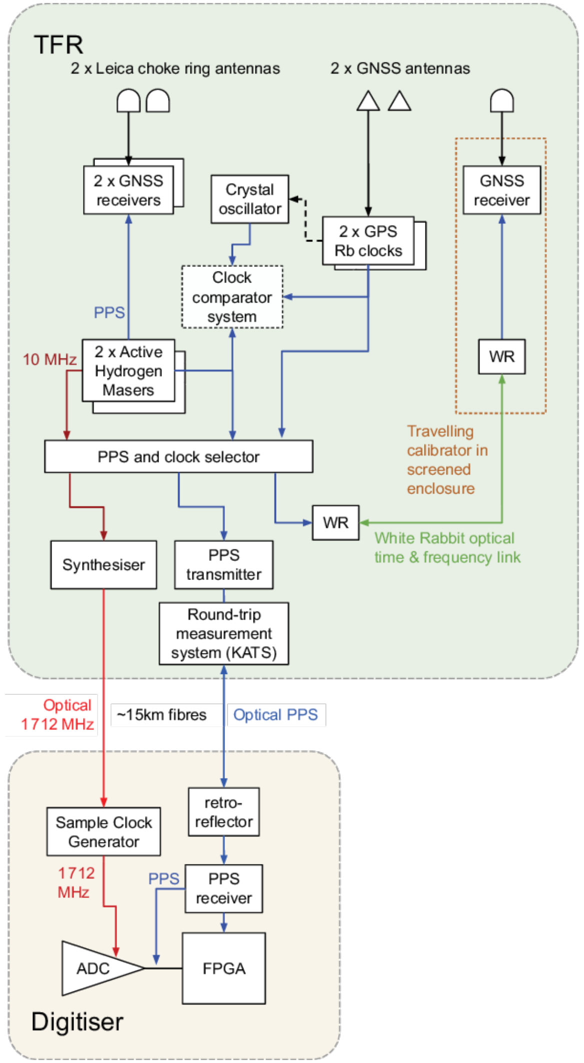
- Pulsars are highly polarized
- Need to account for differential gain and phase variations between feeds when timing pulsars
  - Even when timing in Stokes I (van Straten et al. 2006)
- Inject noise sources into feeds
  - Polarisation
- Observe sources of constant flux density
  - Flux
- Solve for feed ellipticity

Spiewak et al. (2022)



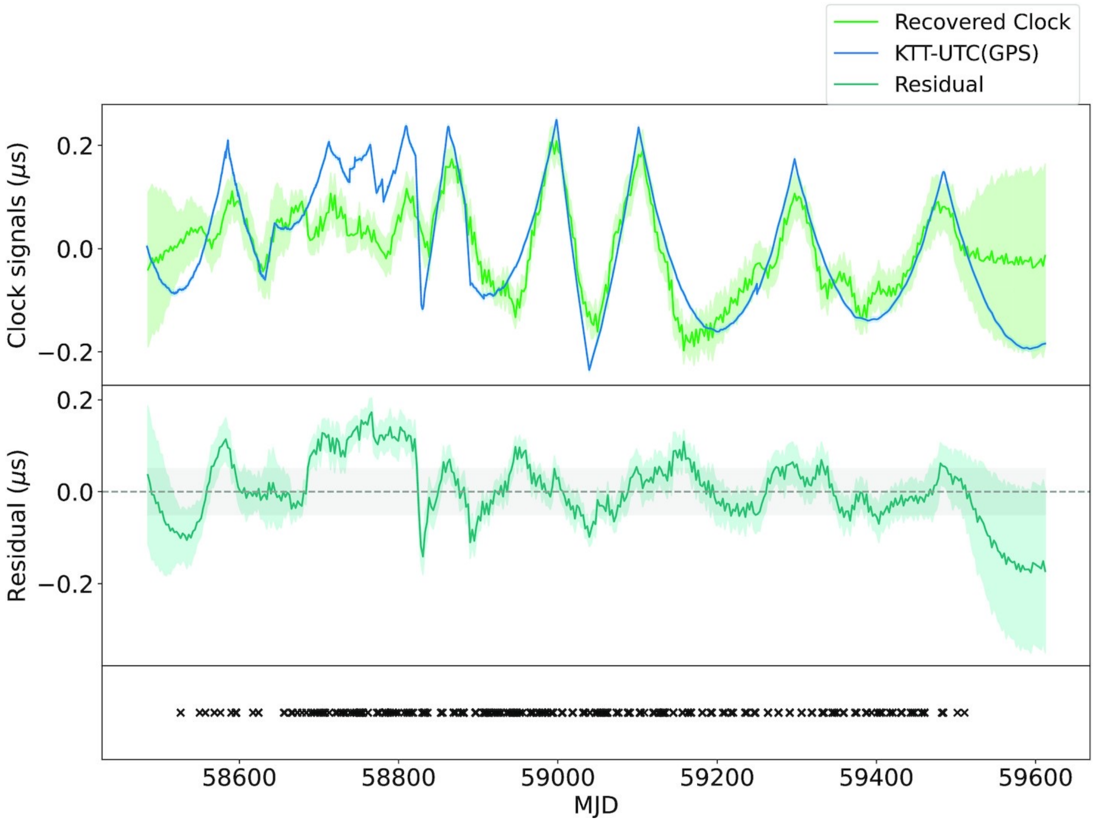
Clock correction

- Data are time tagged relative to observatory "clock"
  - Hydrogen maser (or multiple masers)
  - Maser also provides frequency standard
- Masers drift slowly with time
  - Environmental/nature of system
- Compare maser to time delivered by global navigation system



Clock correction

- Difference between GPS and TAI (international atomic time)
- Corrections made yearly to TAI
  - Small recently, larger in the 1990s.
- Issue: clock induced signal correlated between pulsars



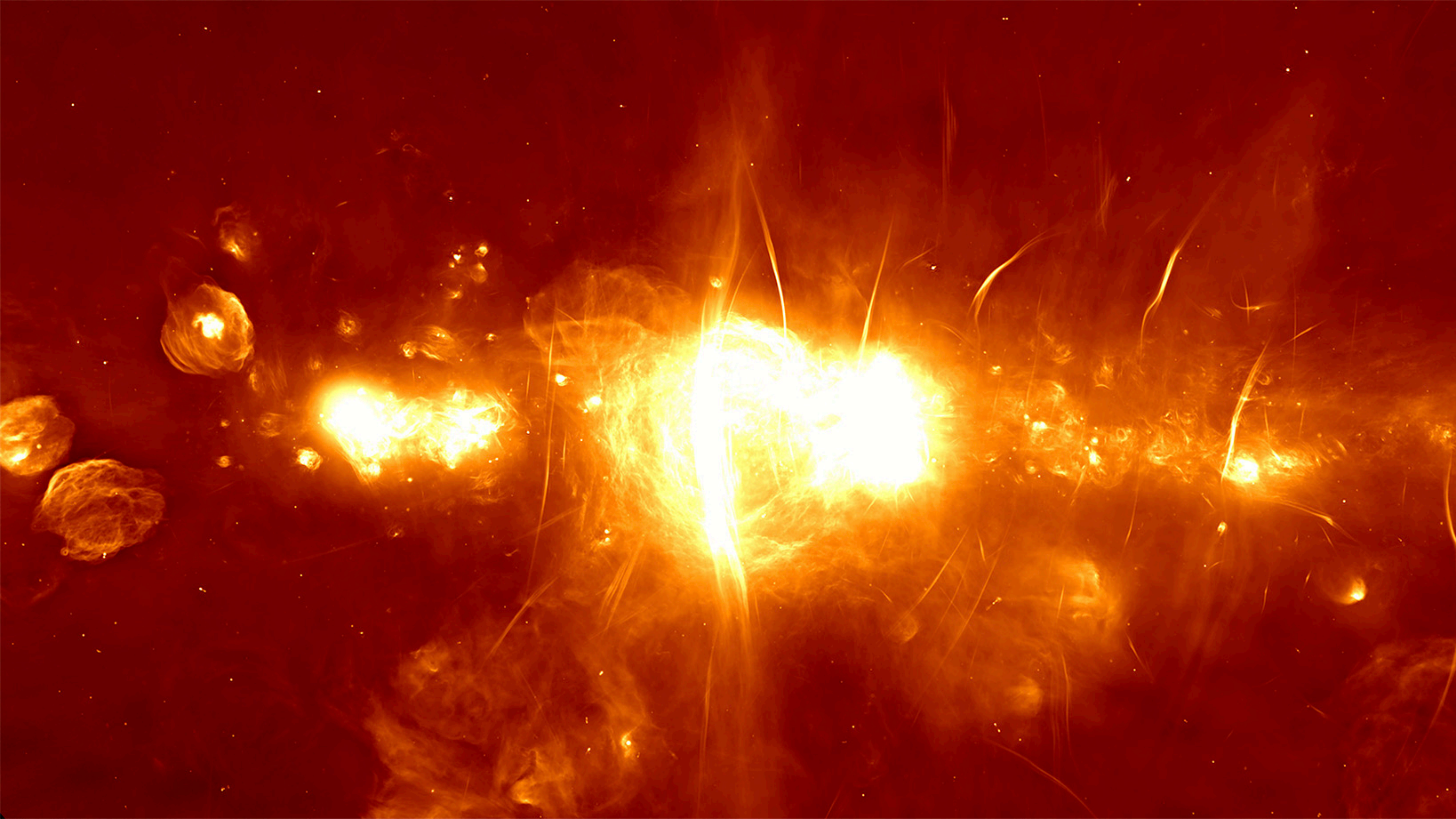
Miles et al. (2023)

Radio interferometers

- Radio telescopes formed from collection of smaller antennas
- Motivated for use in aperture synthesis
    - Radio imaging
    - Distribute antennas over hundreds of metres to thousands of km to increase angular resolution
- Most pulsar timing (and searching) has been undertaken with single dishes
    - Sensitivity (Arecibo/FAST/PKS more sensitive than comparable interferometers in their hemisphere)
    - Signal processing easier

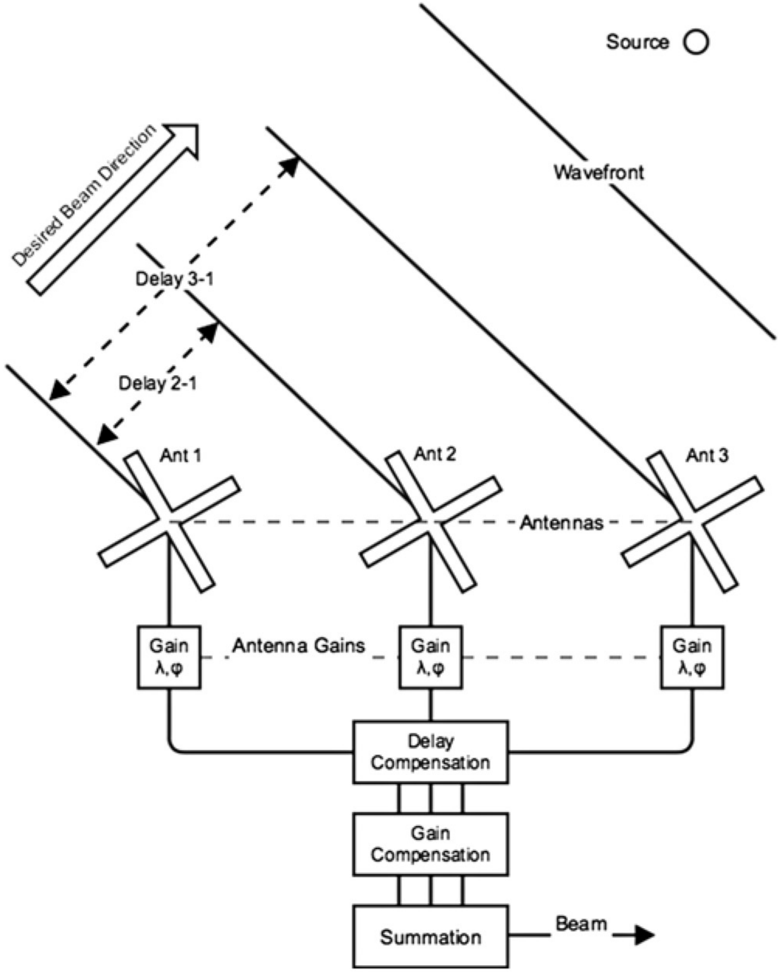
MeerKAT

SKA/DSA-1650



Pulsar timing with interferometers

- Phase array
  - Phase and delays from individual antennas are corrected
- Form tied-array beam(s)
  - Voltage time series either derived from baseband data or produced by telescope correlator/beamformer architecture
- Observe pulsars using instrumentation similar to single dishes
  - Pulsar timing backends with Murriyang and MeerKAT have common architecture and background code



How to improve your (I)PTA telescopes:

- Increase sensitivity
  - Higher gain/wider bandwidth/lower T_{sys}
- Larger telescopes
  - Increase sensitivity
- Improve receivers
  - Lower system temperature
  - Better polarisation response
- Improve backend signal processing
  - Fewer artefacts in pulse profiles
  - Coherent dedispersion
- Improve RFI mitigation
- More telescopes! (IPTA)
- Need to keep in mind astrophysical noise when assessing PTA sensitivity
  - Pulse jitter, interstellar medium, intrinsic red noise.