Radio Telescopes and Pulsar Observations

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Max Planck Institute for Radio Astronomy

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EPTA

Max-Planck-Institut für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

INTERNATIONAL PULSAR TIMING ARRAY IPTA

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Introduction

Basic view of telescope signal path

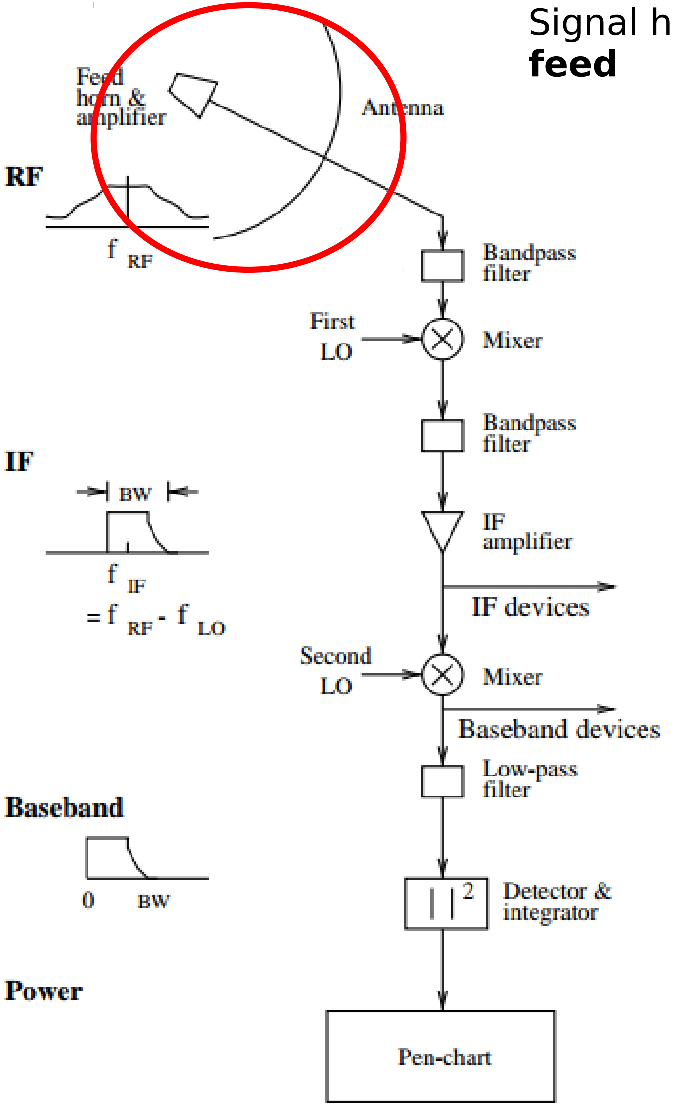
Choice of frequencies

Environmental effects

Observing strategies




Signal hits telescope, is focused by the **antenna** (dish) towards a wave-guide **feed**



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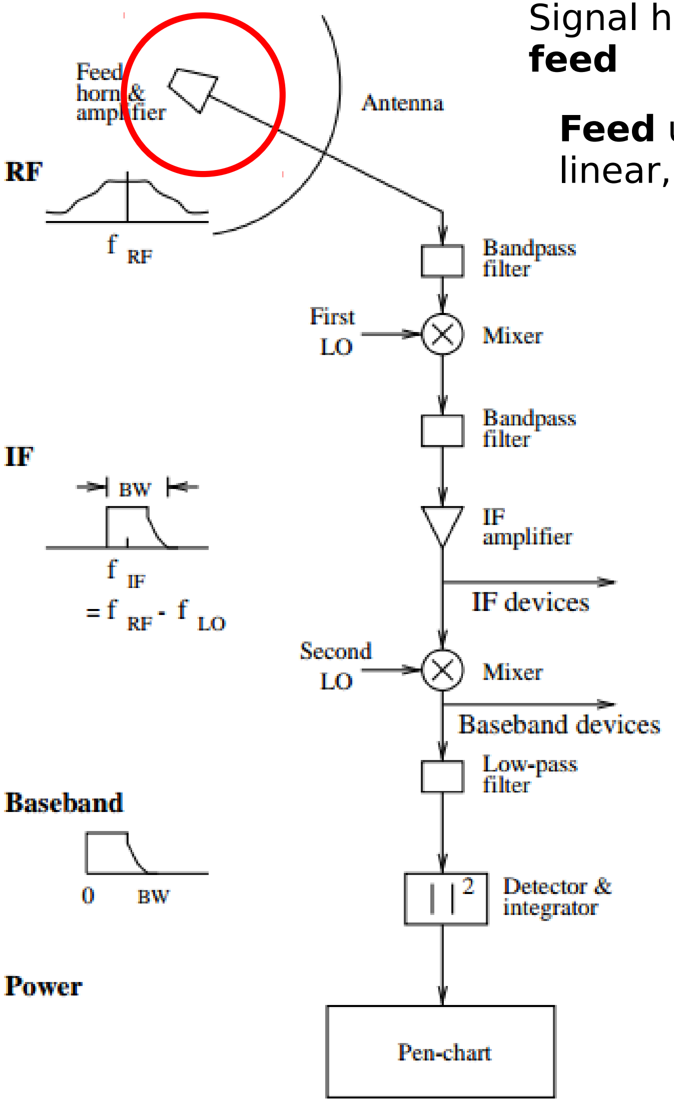
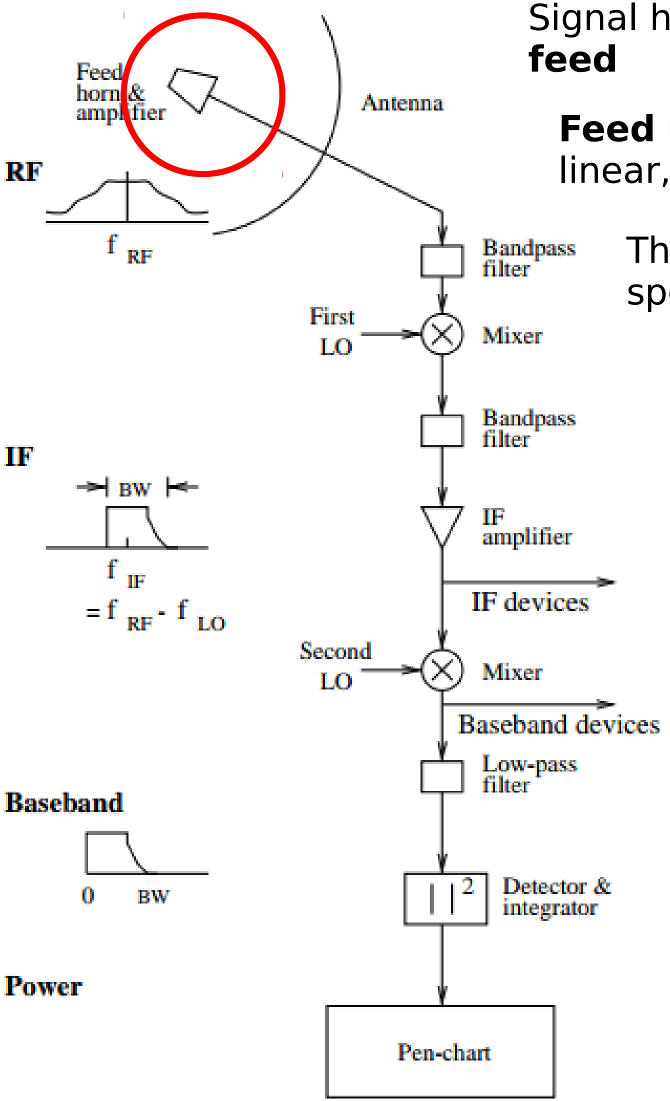
Feed usually has two receptors that sample orthogonal polarisations e.g. dual linear, dual circular (**polarisation channels**)





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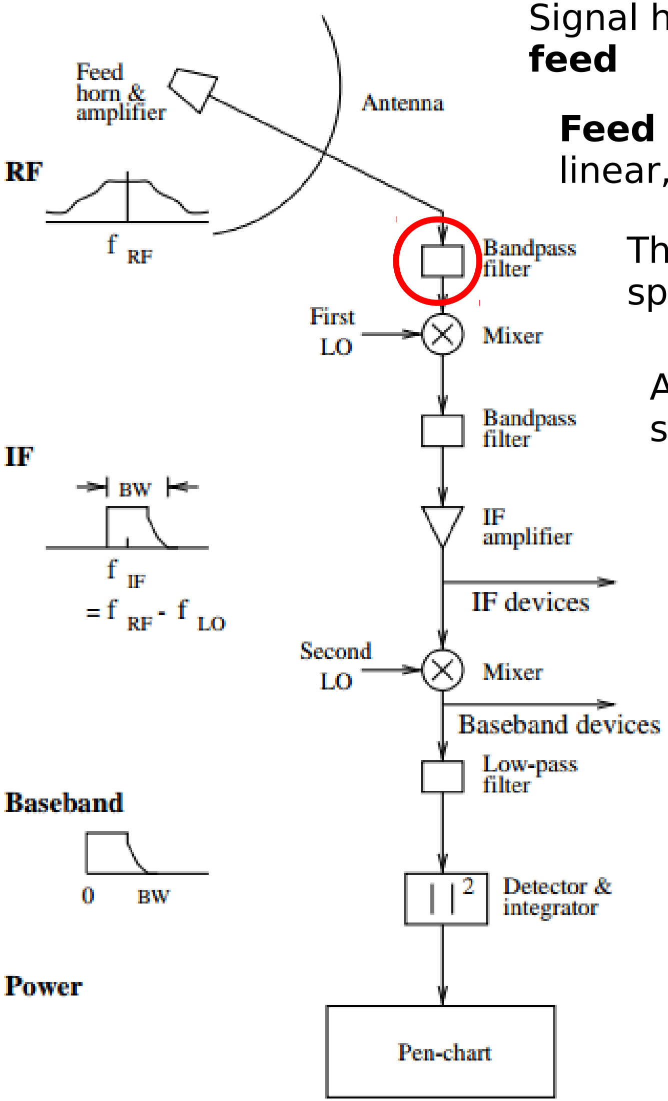

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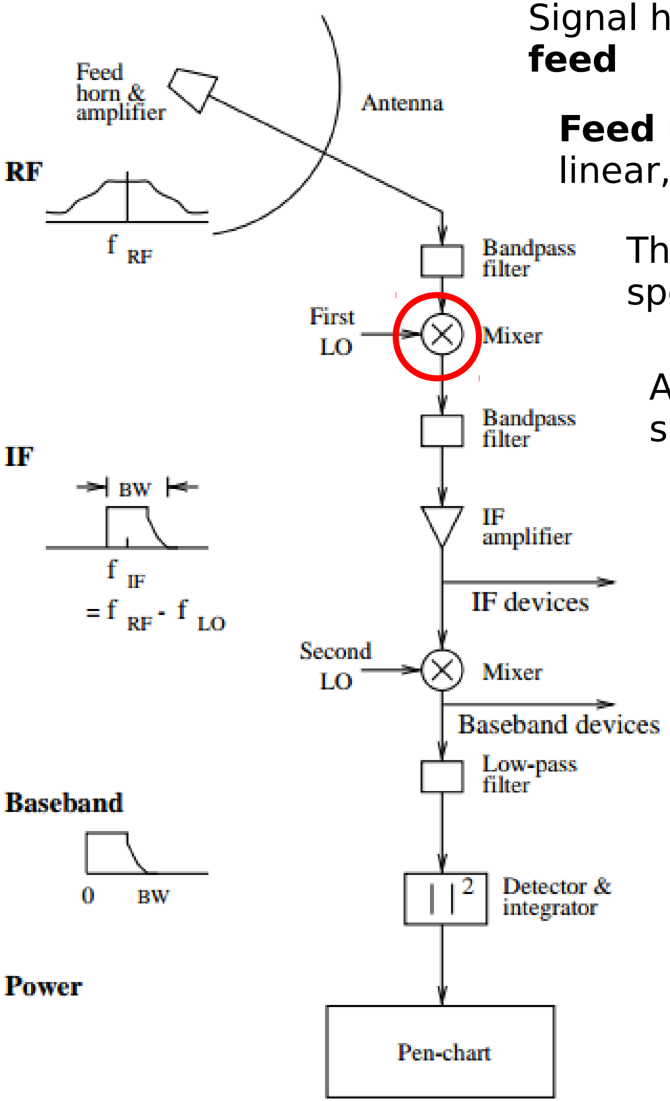

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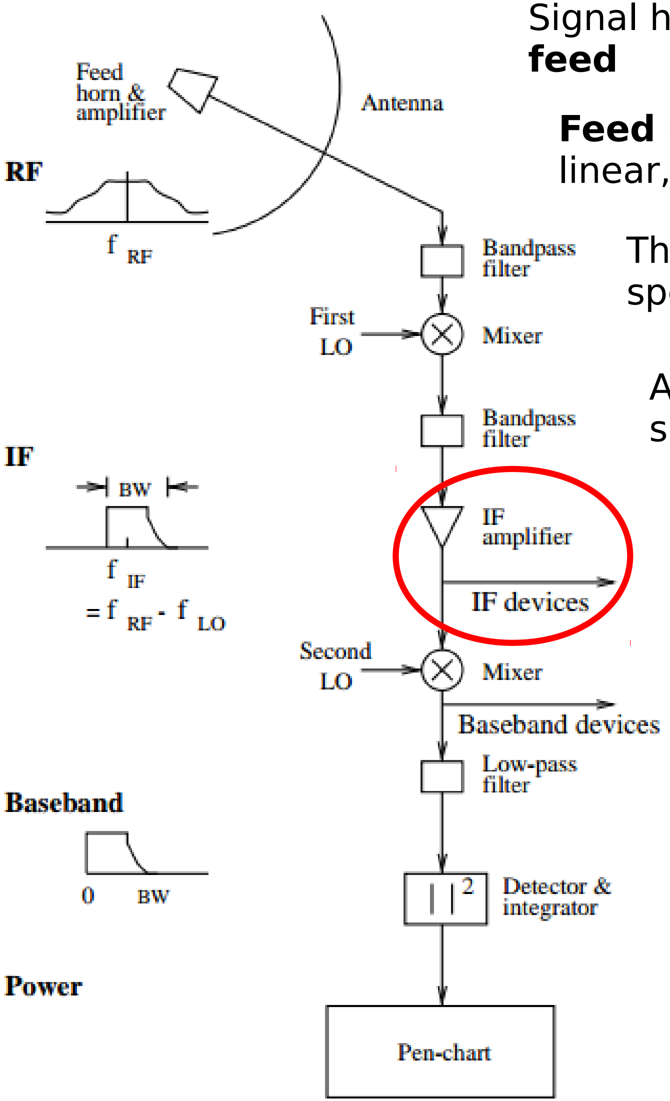
Upper sideband: $\boldsymbol{f_{LO} < f_{RF}}$ **Lower sideband:** $\boldsymbol{f_{LO} > f_{RF}}$



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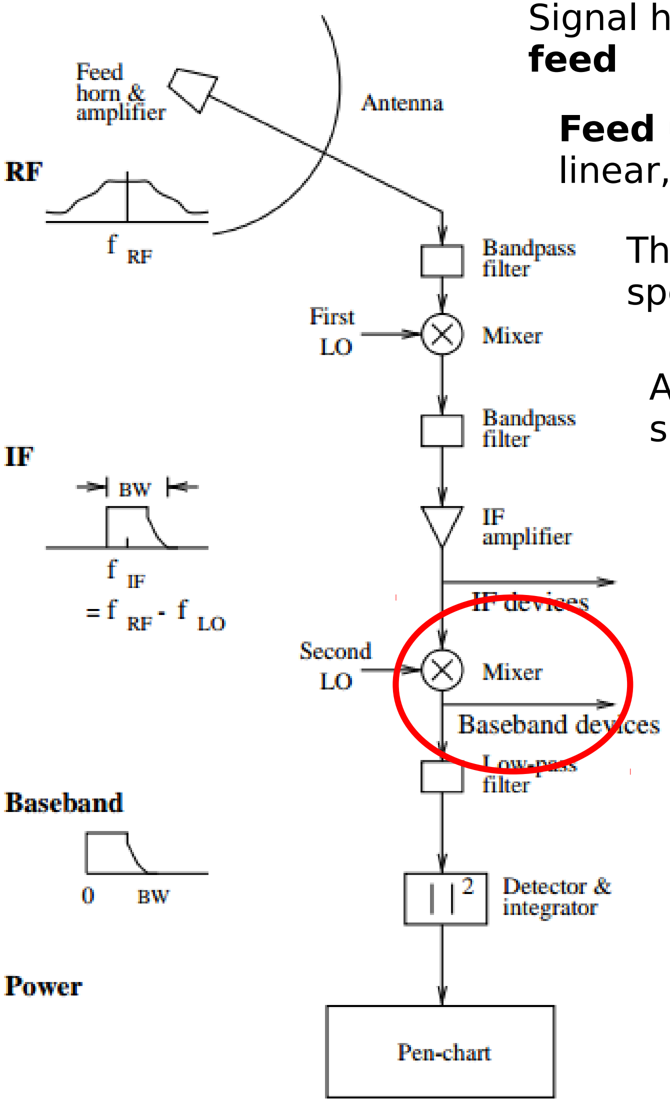

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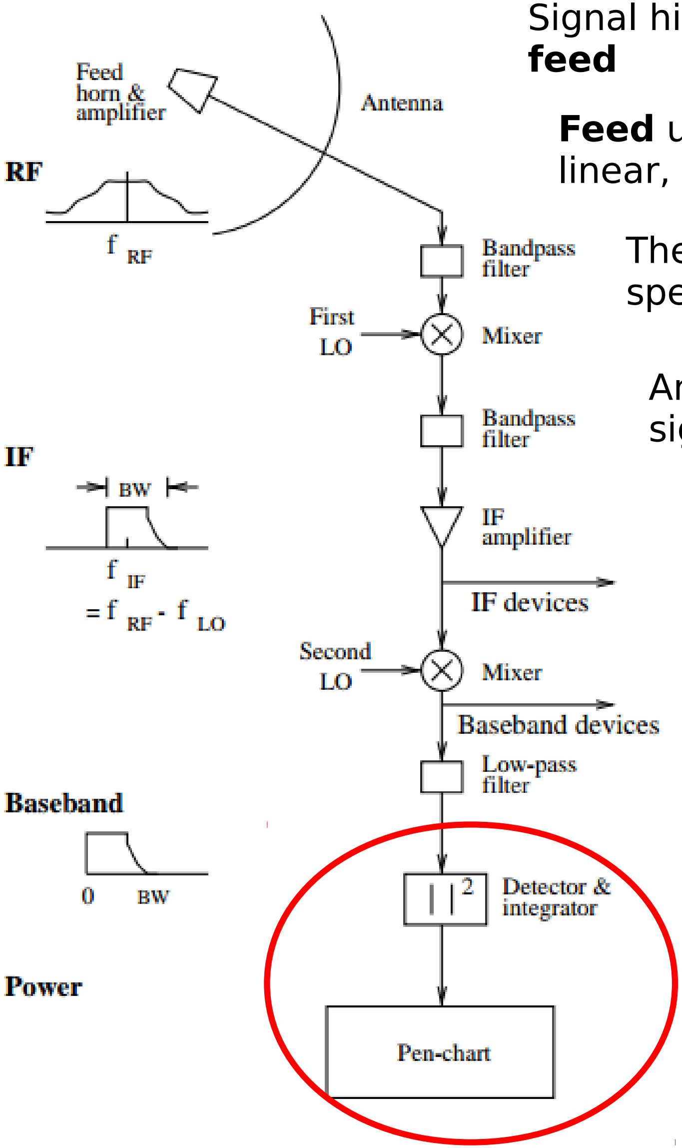

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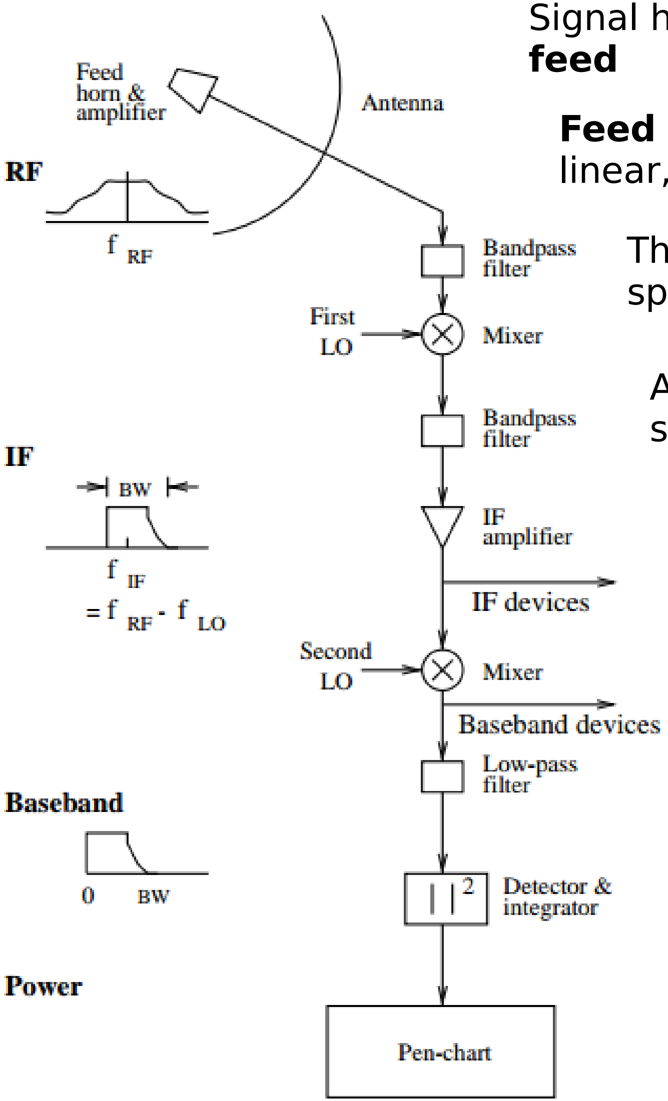
For real-time monitoring, signal is **low-pass filtered**, and **detected (squared)** to give the signal power, and sent to e.g. a **pen-chart recorder**



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Typical pulsar data pipeline

Record raw voltages (baseband) for each sub-band, usually 10sec subint (100s of gigabytes)

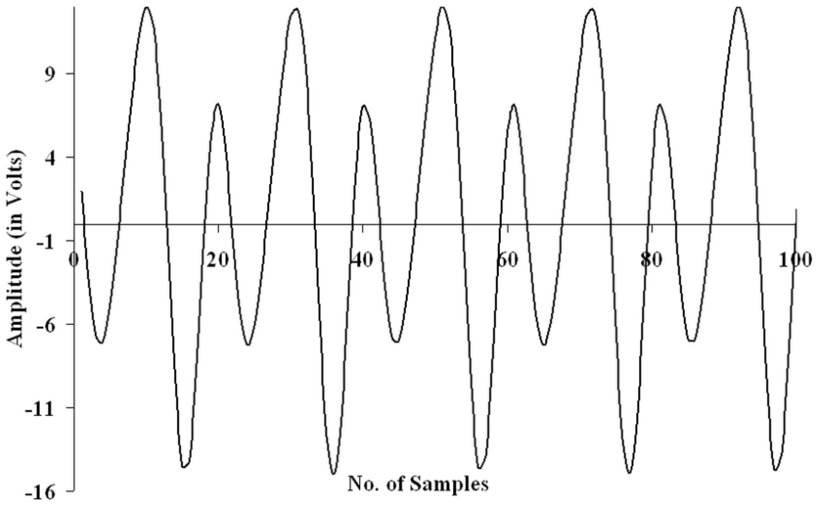
Dedisperse and fold with dspsr – reduce to archives (megabytes)

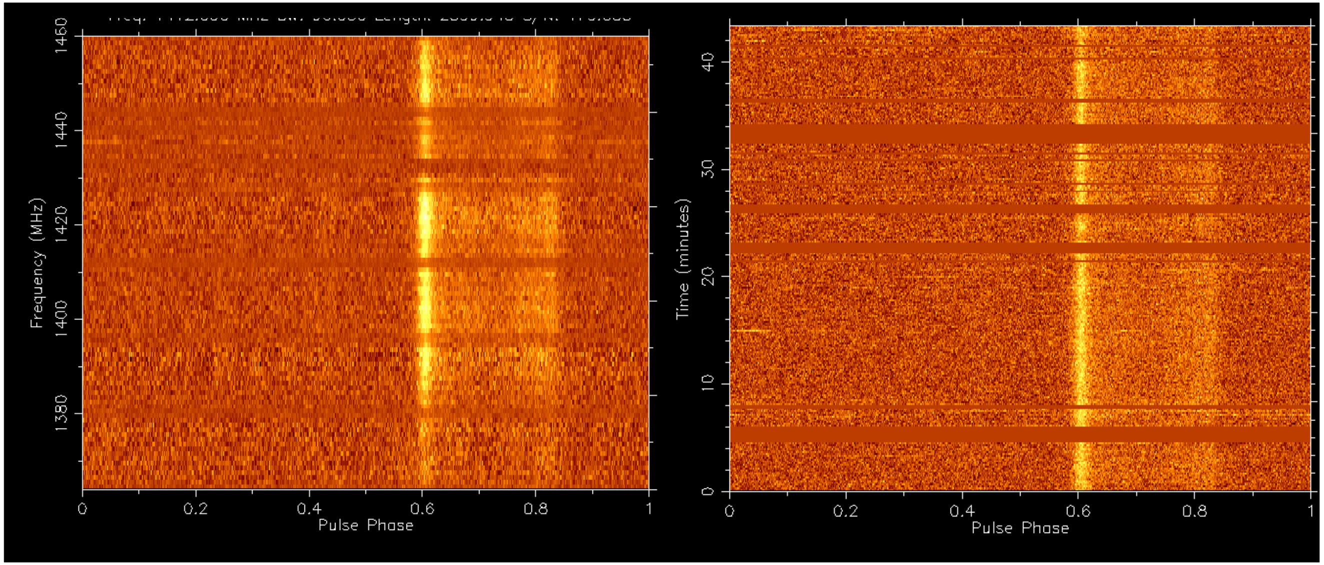
Combine archives from all sub-bands and sub-integrations into a single archive for the entire observation

Apply RFI masks

Copy somewhere for storage

Save to tape





Radiometer equation

Pulsars are weak radio sources, and often can't be distinguished from the background noise

To be able to see them, we need big telescopes, large bandwidths, and long integration times

Quantify this with the radiometer equation

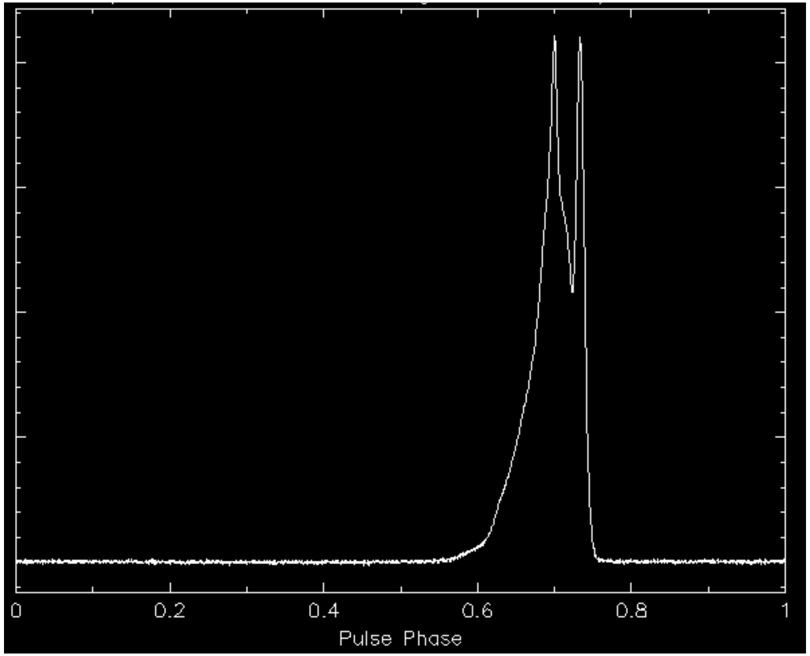
$$S_{\rm mean} = \frac{({\rm S/N})\,\beta\,T_{\rm sys}}{G\sqrt{n_{\rm p}t_{\rm obs}\Delta f}}\sqrt{\frac{W}{P-W}}$$

G is the telescope gain (K Jy^{-1}), β is a correction factor (accounts for errors in digitisation of signal)

To achieve high TOA precision, we cool the receiver, record both hands of polarisation, use a wide bandwidth, and use long observations

The choice of pulsar also helps – the lowest TOA errors come from pulsars that are bright, and have small duty cycles

$$\sigma_{\rm TOA} \simeq \frac{S_{\rm sys}}{\sqrt{t_{\rm obs}\Delta f}}\frac{P\delta^{3/2}}{S_{\rm mean}}$$



$T_{\rm sys}$ = system temperature (20 K)
$n_{\rm p}$ = number of polarisations (2)
$t_{\rm obs}$ = integration time (1 hour)
Δf = bandwidth (500 MHz)
$S_{\rm mean}$ = mean pulsar flux density (0.1 Jy)
P = pulse period (5 ms)
δ = duty cycle (pulse width/pulse period)

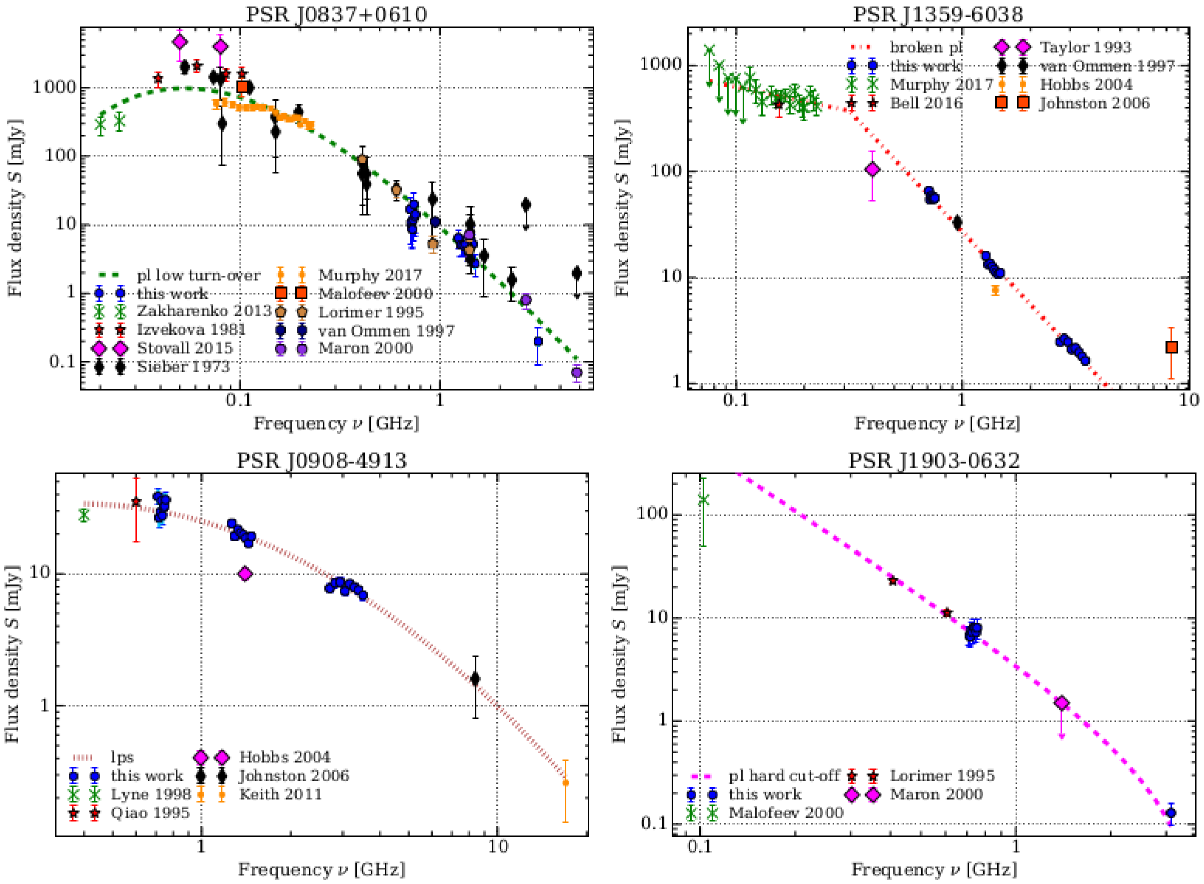
Choice of frequency – flux density

Pulsars are steep-spectrum emitters: they generally modelled as decreasing in flux density at higher frequencies

Power law dependence (sometimes more complicated)

This is why we generally use long wavelengths (radio telescopes)

Some exceptions – X-ray, Gamma ray, etc. to study certain pulsars



Jankowski et al. (2017)

Choice of frequency – ISM effects

The interstellar medium broadens pulse shapes in two ways that are frequency dependent:

1. Dispersion (f^{-2})

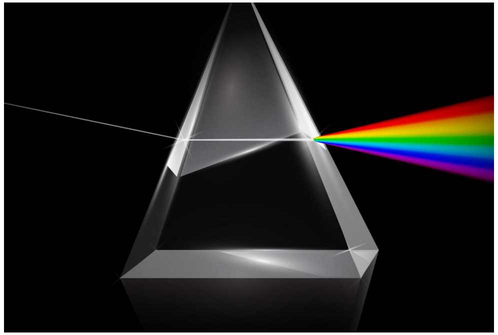
2. Scattering ($f^{-4.4}$)

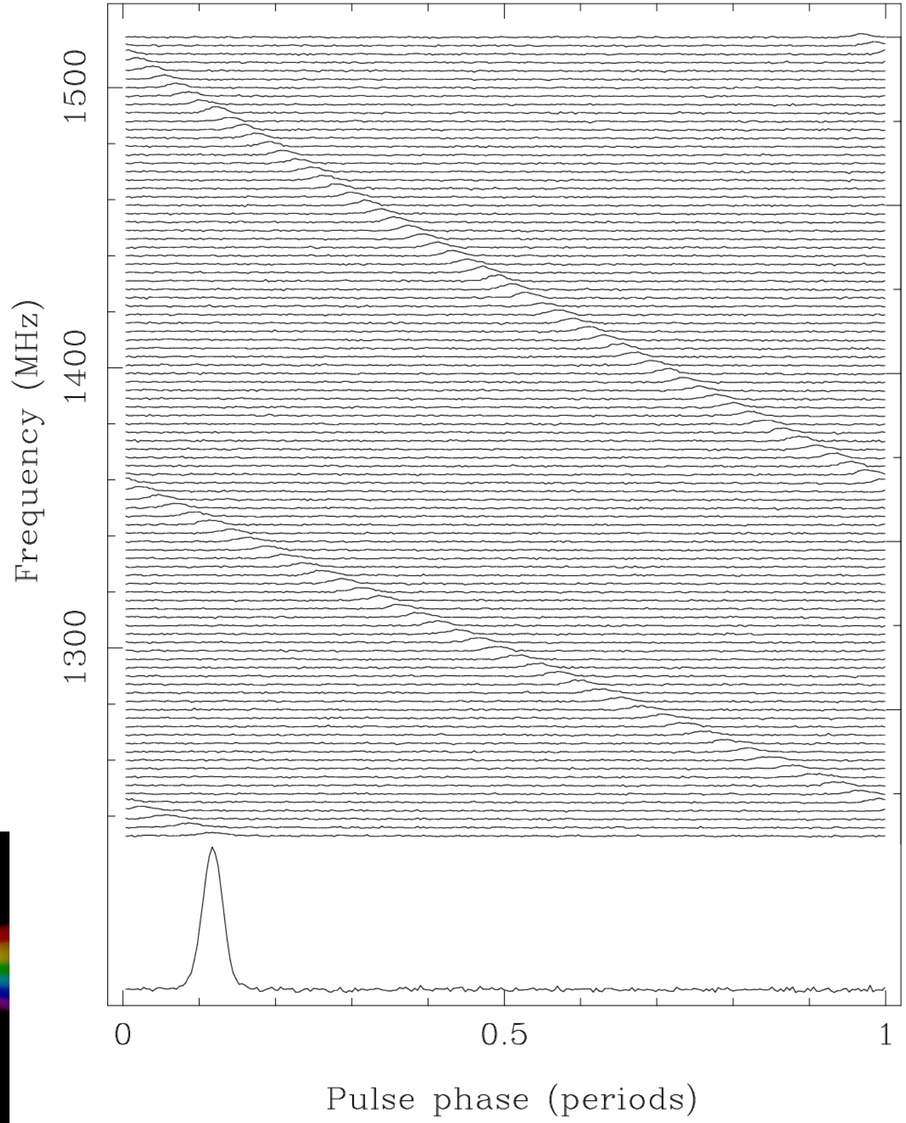
Lower frequencies are affected more strongly than higher frequencies

For precision timing, we typically use 1400 MHz (L-band)

Trade-off between flux density and magnitude of ISM effects

Can be done in conjunction with other frequencies, to measure ISM effects





Lorimer & Kramer (2005)

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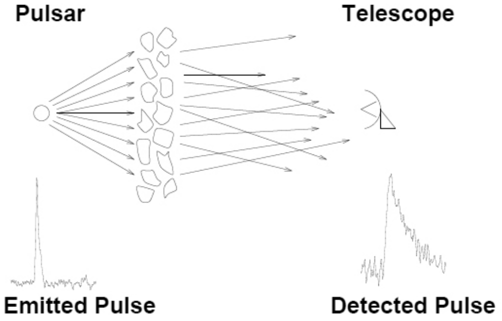
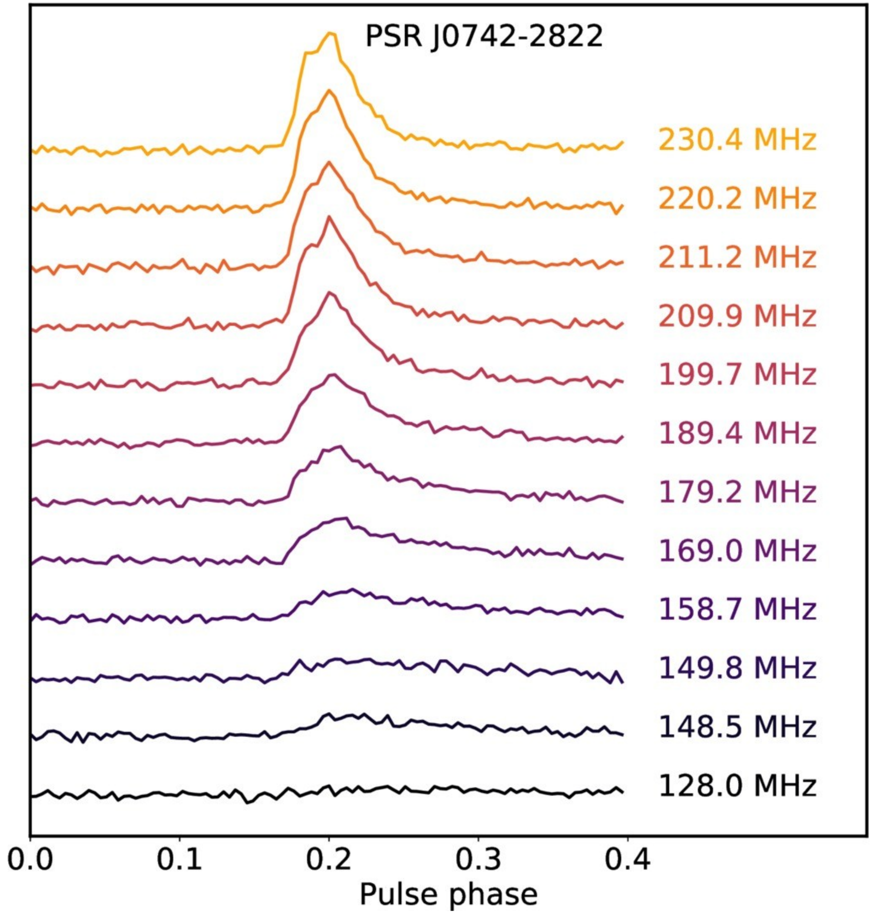




Kirsten et al. (2019)

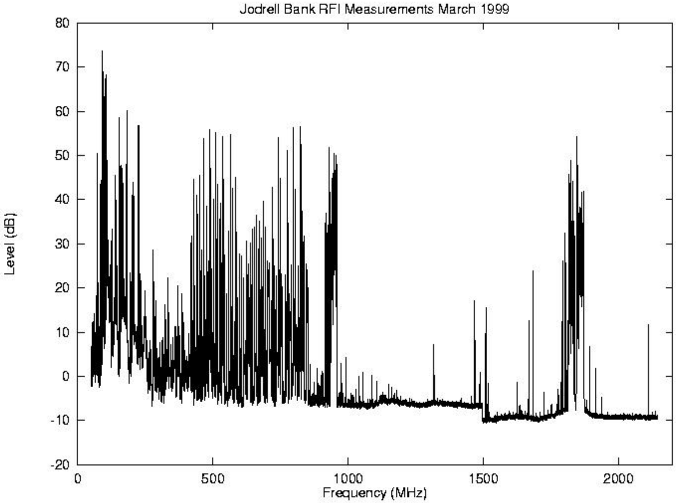
RFI Contamination

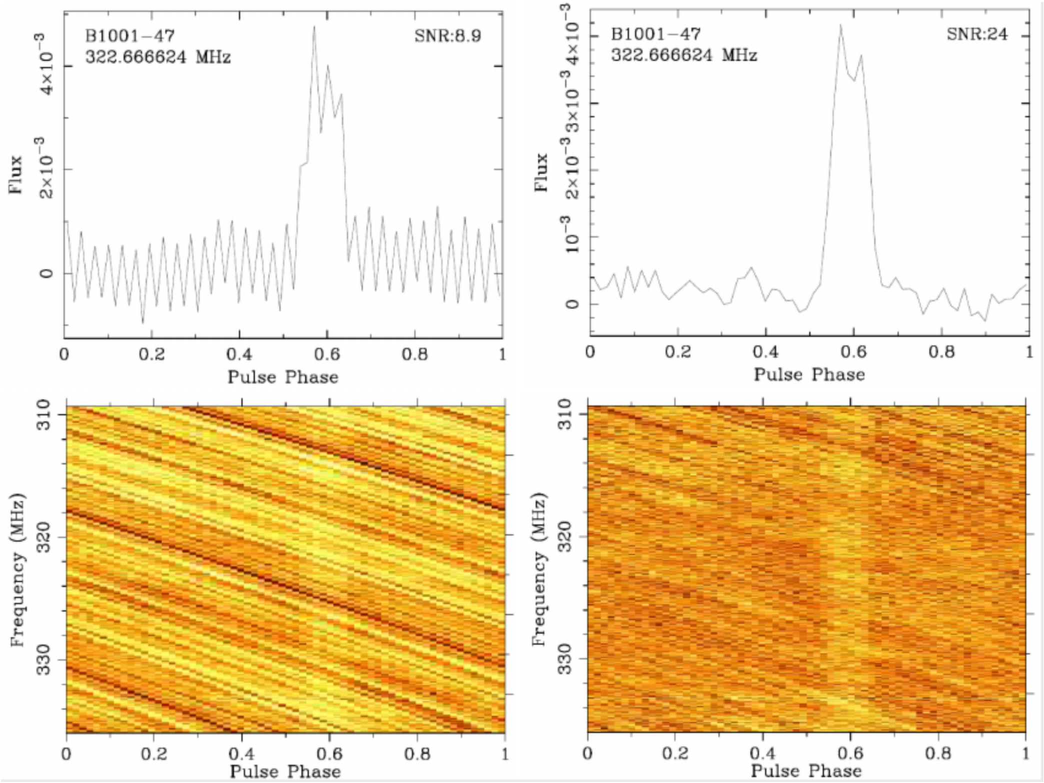
Some radio frequencies are protected for astronomy use

However, as we use a wide range of observing frequencies, this can still be affected

Some is caused by e.g. electronic devices, motors, microwaves

RFI power is reduced by filters in the signal path, but remains in recorded data and must be removed (see PSRCHIVE talk/activity)





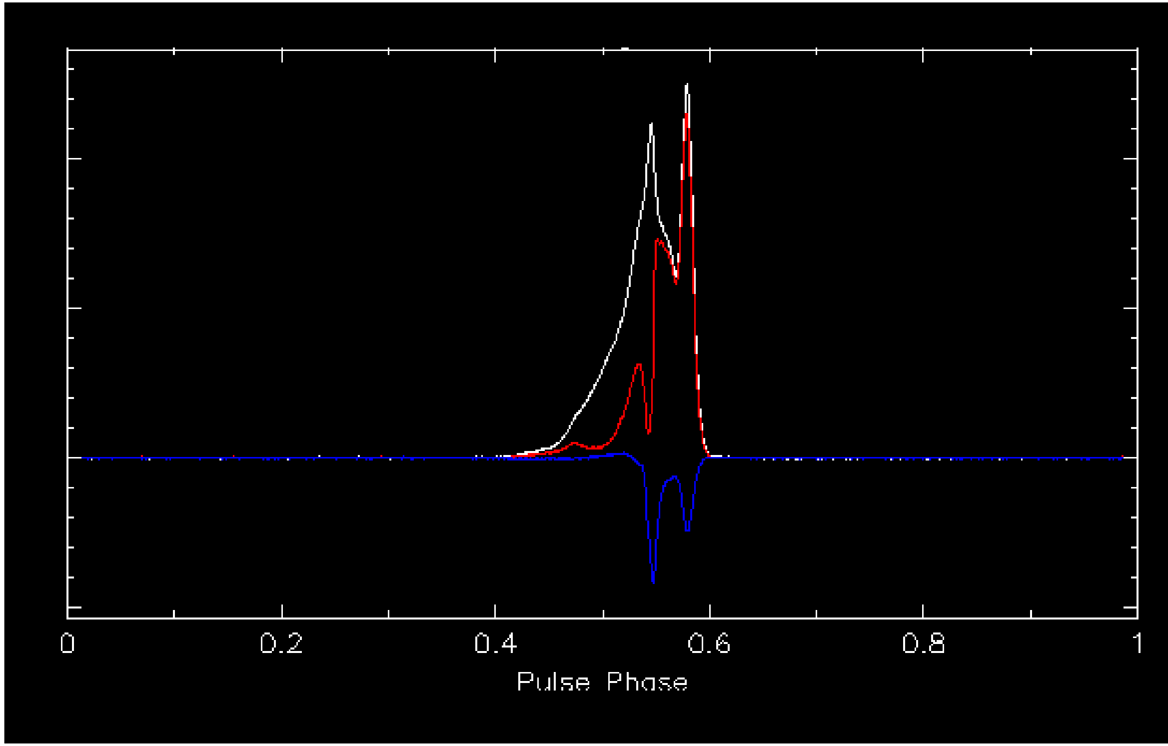
Polarisation

Pulsars are highly-polarised sources (circularly-polarised sources are rare in astronomy)

The feed angle and power of each feed on the telescope must be well-known and accounted for to correctly sample polarisations

Before an observation of a pulsar, observe a polarised noise diode in the telescope

As well as being important for studying pulsar emission, errors in polarisation calibration can cause distortions in the pulse shape, which impacts the timing precision



White = total intensity (Stokes *I*)
Red = linear polarisation *V*
Blue = circular polarisation $\sqrt{(Q^2 + U^2)}$

Observing strategy

We choose a certain strategy

Observing cadence – for PTAs we typically want observations every 1-2 weeks

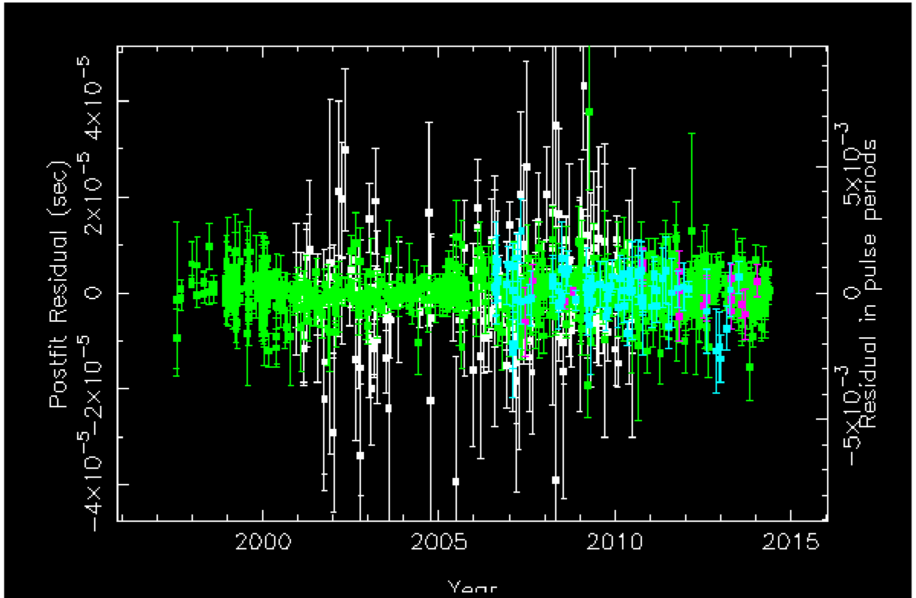
Frequencies – usually L-band for precision timing, but use different frequencies (P-band, S-band) to better understand ISM effects

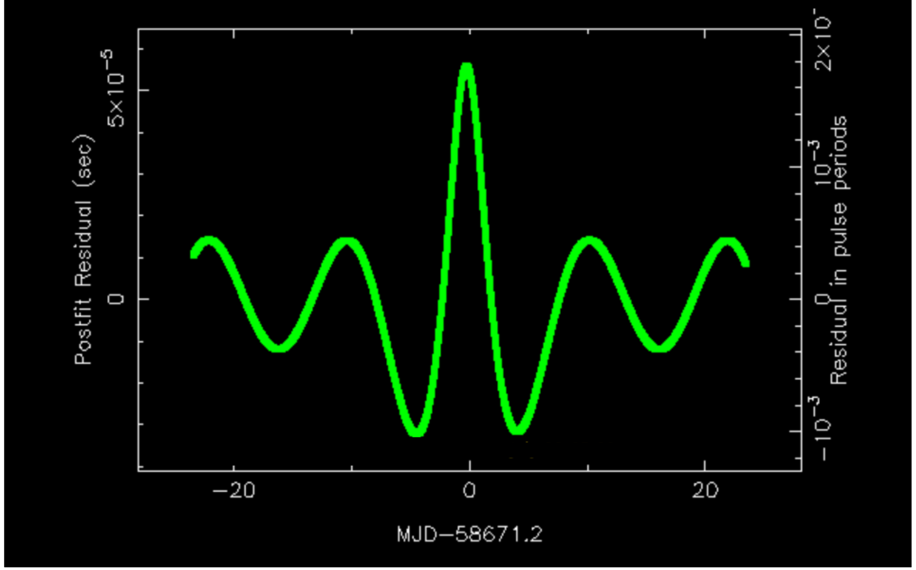
Length of observation – usually about 1hr, improves TOA precision

Binary coverage – sample a lot of the pulsar's orbit, particularly important for relativistic systems

Above: J1012+5307 TOA from the EPTA data release 1.0 (mean cadence 4.2 days)

Below: Shapiro delay signature decomposed into harmonics (see pulsar timing talks)



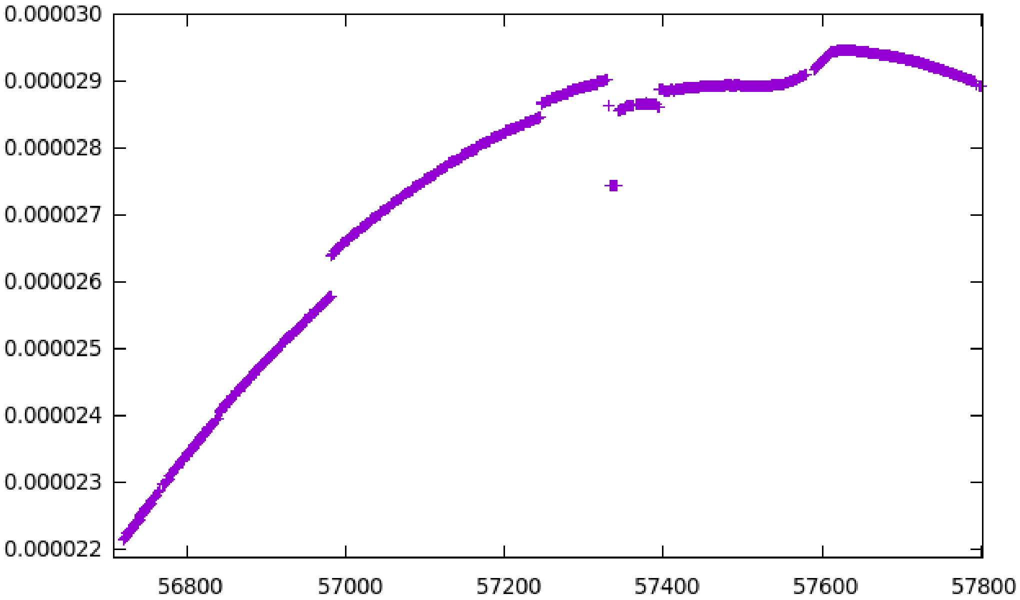


Observatory clock

For pulsar timing, we need very accurate time-stamps during the observations (see pulsar timing talk)

We use a local clock at the observatory (usually a hydrogen maser)

This can also reflect delays in the signal path due to changes in hardware



Usually see this quadratic shape in the clock corrections

Breaks are due to changes in hardware

Interferometers

More convenient to tie many telescopes together

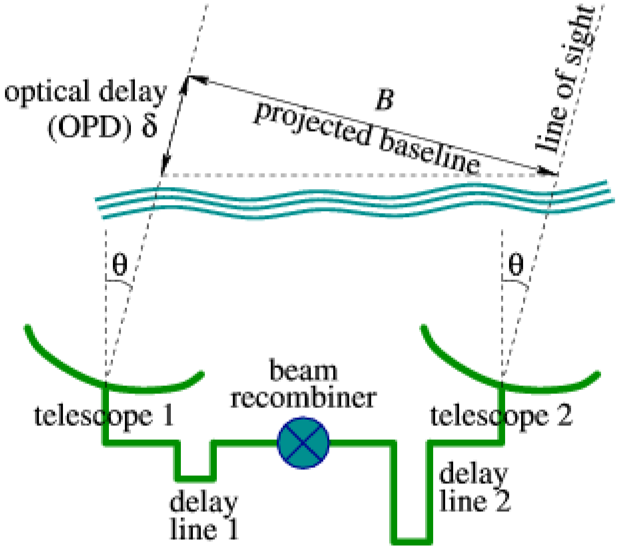
Easier to construct than a single huge dish

Angular resolution increases with distance between dishes λ/D

Telescopes are phased up by accounting for the delays between elements in receiving a signal

RFI is local to telescopes – not correlated across interferometer elements

Examples of interferometers: GMRT, LEAP, LOFAR, WSRT, VLA, MeerKAT, SKA



Conclusion

Covered some of the basic ideas behind radio telescopes

Only scratched the surface – many different approaches exist

Radio telescopes have a variety of setups, dependent on the experiment they are a part of