Receivers and Correlators

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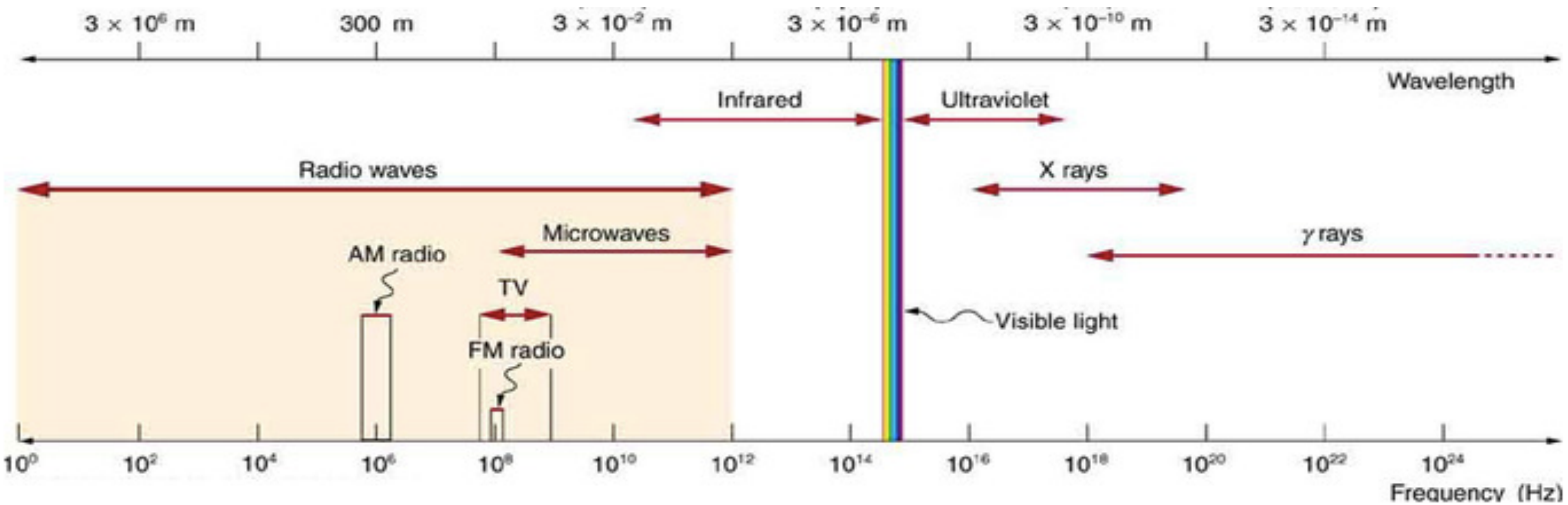
Radio Astronomy

EM spectrum



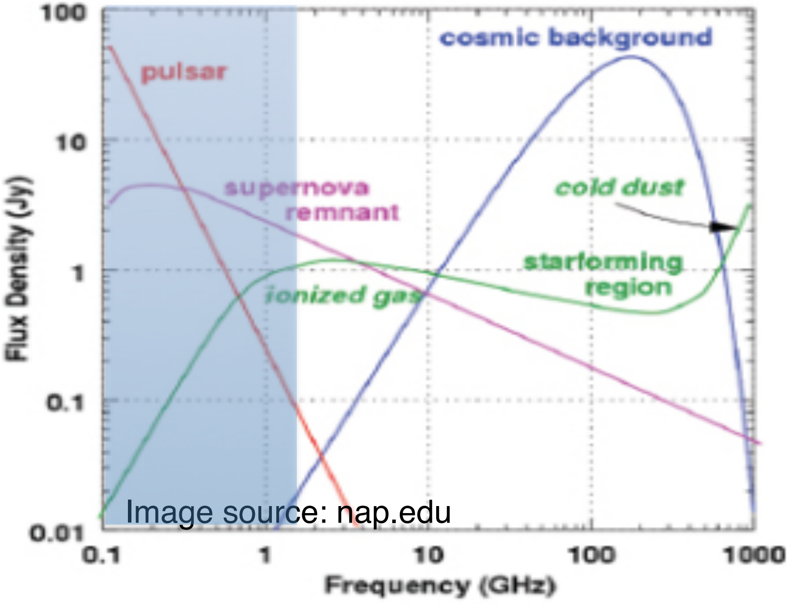


Image source: nap.edu

Objects in radio spectrum

A Basic Radio Telescope

- Collects radio waves from the celestial sky (from a narrow range of angles), over an effective aperture area

- Focuses the radiation to a feed antenna that converts the signal to an electrical voltage – in 2 orthogonal polarisations

- Converts the voltage signal to power ∞ strength of source signal + receiver noise

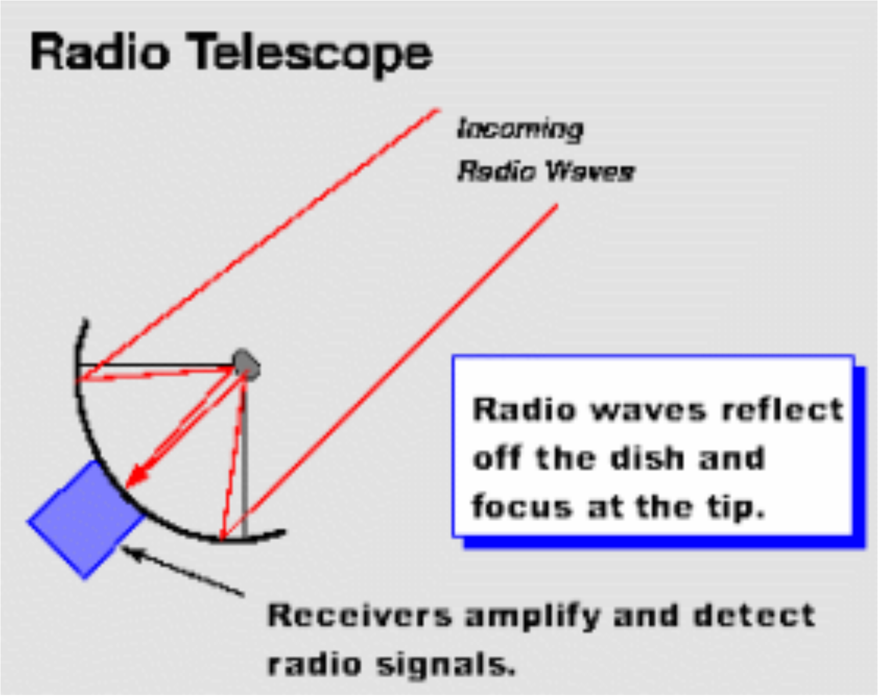
- For high sensitivity (to see faint sources out to the distant part of the universe)

  Large collecting area ⇨ Large dishes

  High quality, low noise electronics in the receivers

  Large bandwidth of observations

  Long integration time to achieve the desired signal-to-noise level

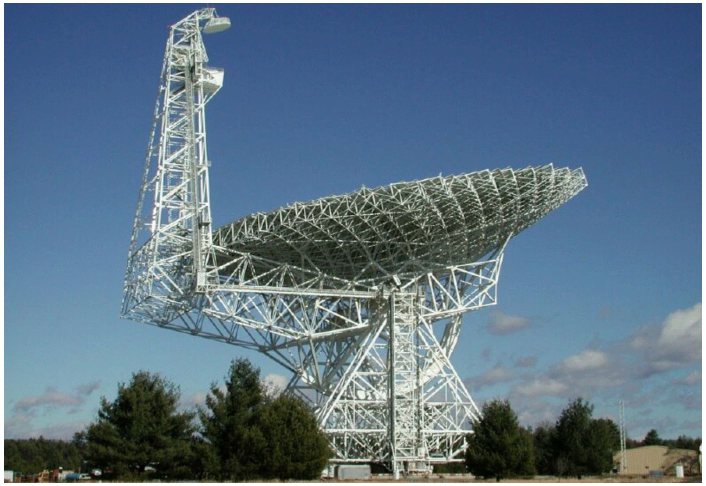


- Celestial radio signals are VERY weak ; unit of flux used is : 1 Jy = 10^{-26} W / m^2 / Hz

- Input radio power into a typical telescope is ~ -100 dBm !

Single Dish versus Array Telescopes

- Resolution and sensitivity depend on the physical size (aperture) of the radio telescope
- Due to practical limits, fully steerable single dishes of more than ~ 100 m diameter are very difficult to build
  $\Rightarrow$ resolution (λ / D) ~ 0.5 degree at 1 metre (very poor)
- To synthesize telescopes of larger size, many individual dishes spread out over a large area on the Earth are used
- Signals from such array telescopes are combined and processed in a particular fashion to generate a map of the source structure
- $\Rightarrow$ resolution (λ / D_s) , D_s = largest separation



The new 100-m Greenbank Telescope

The Very Large Array Telescope

Introducing a modern radio telescope
The GMRT

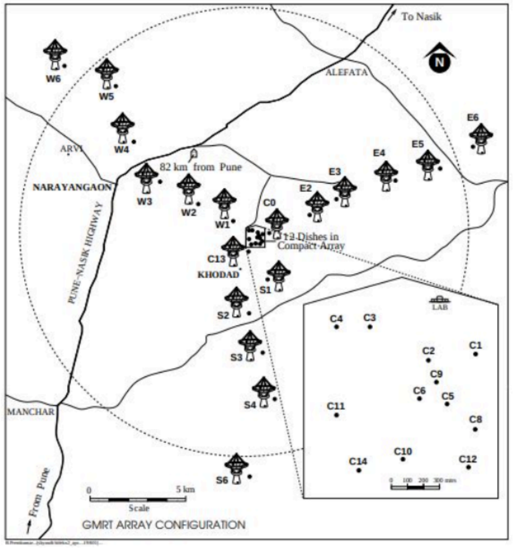
- The Giant Metre-wave Radio Telescope (GMRT) is a new, world class instrument for studying astrophysical phenomena at low radio frequencies (150 to 1450 MHz)

- Designed and built primarily by NCRA, a national centre of TIFR.

- Array telescope consisting of 30 antennae of 45 metres diameter, operating at metre wavelengths -- the largest in the world at these frequencies!

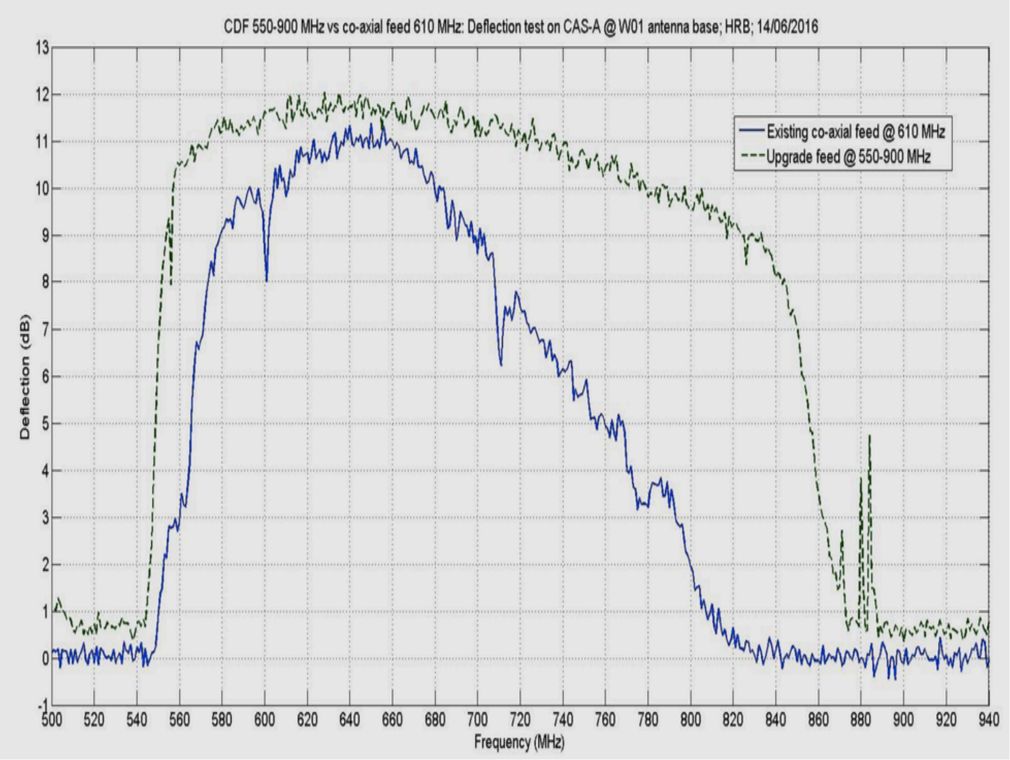
GMRT with upgrades

Array located at 80 km north to Pune consisting of 30 antennas over 25 km maximum baseline



A radio interferometer with fully steerable dishes of 45 metres diameter, operating over 120-250, 250-500, 550-850 and 1060-1460 MHz bands having good G/T_{sys}

An increase of instantaneous bandwidth from 32 to 200/400 MHz makes GMRT an excellent instrument for imaging and time-domain studies



Sub-systems of the GMRT

Mechanical sub-system

Servo sub-system

Antennas (feed and RF)

Analog Receiver sub-system

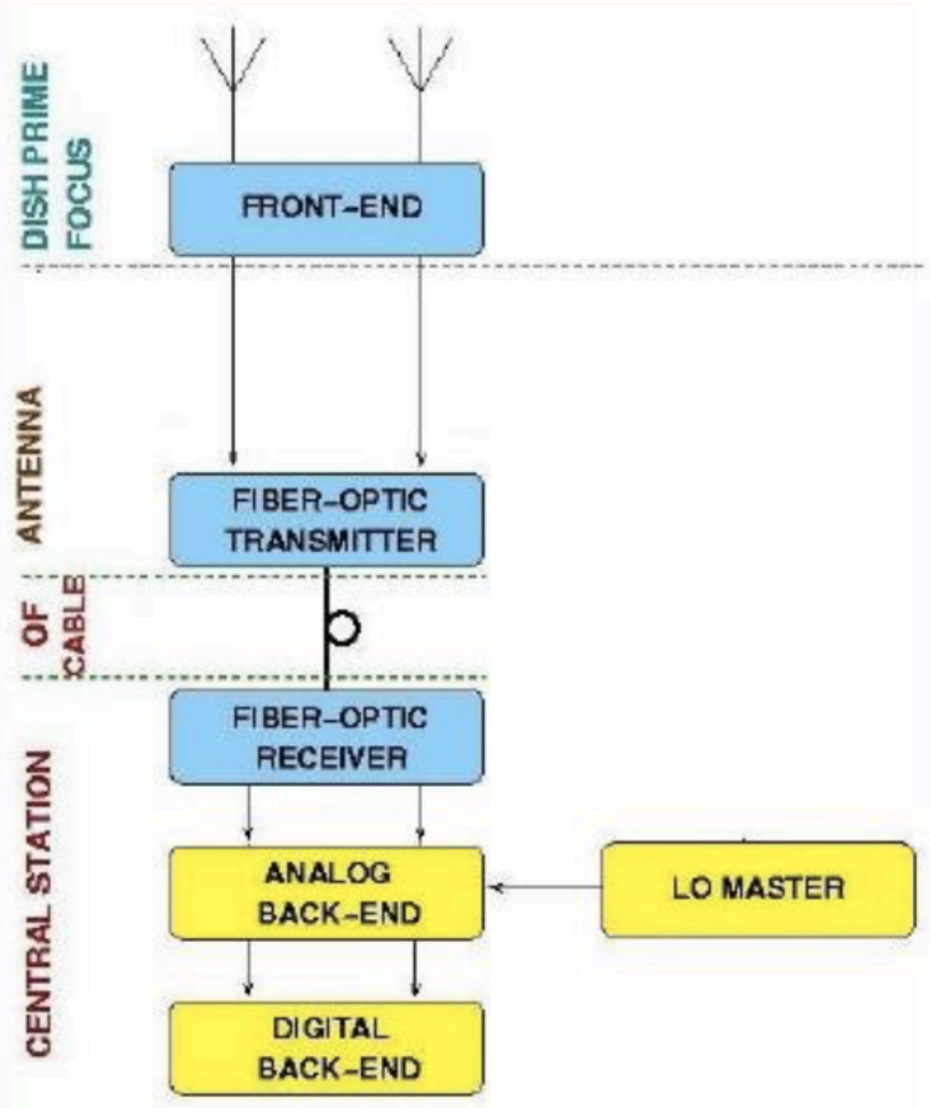
Optical fibre sub-system

Digital Receiver sub-system -- correlator

Telemetry sub-system

“On-line” Control and Monitor sub-syst

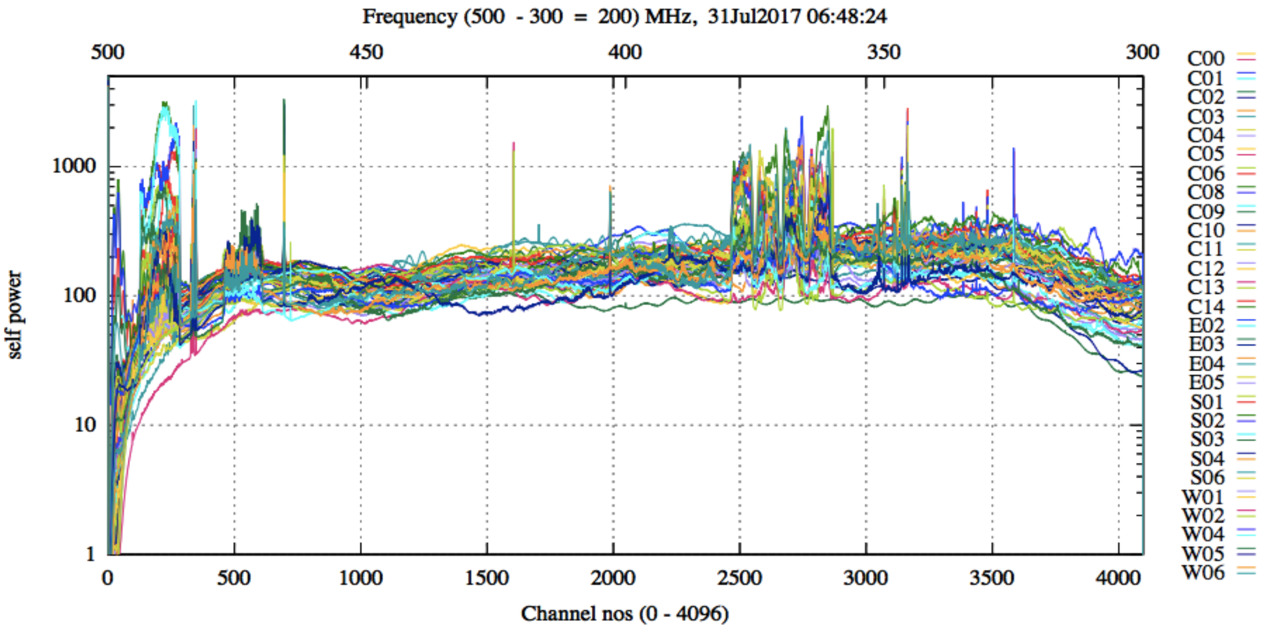
Off-line data processing chain(s)

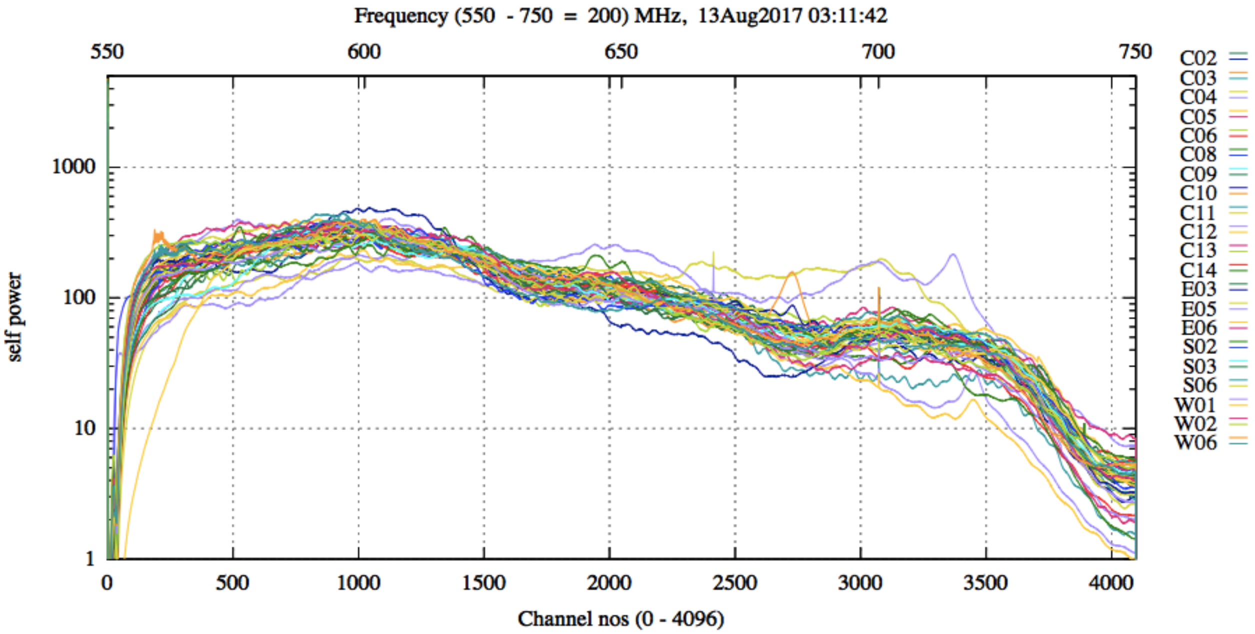


Feed/Dipole

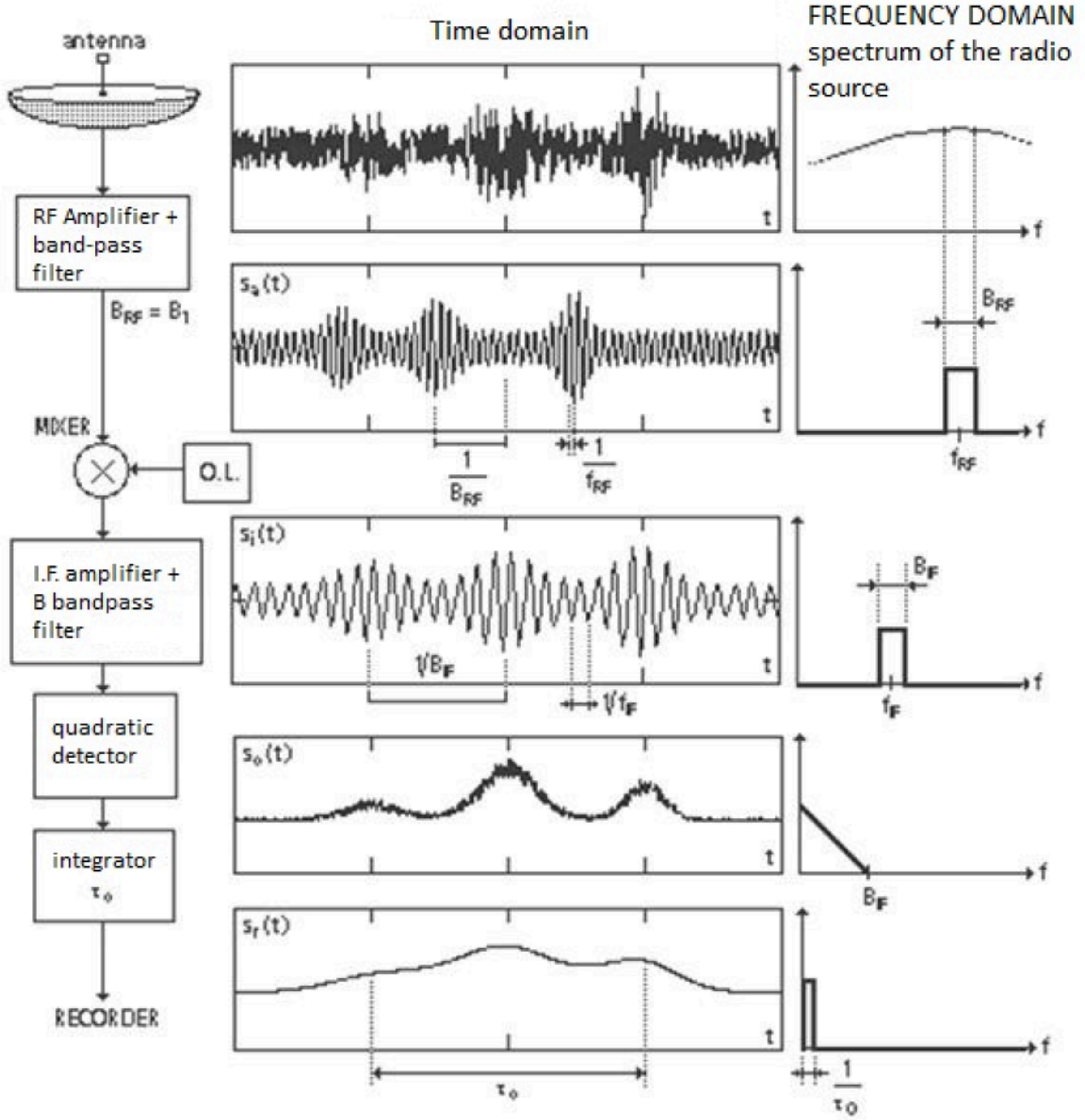
Antenna primary feeds are placed on a rotating turret near the focus of the 45-m dishes.

Band of signals





Radio Receivers



Sensitivity or radiometre Equation:

$$\Delta T = \frac{T_{sys}}{\sqrt{B_F \tau_0}}$$

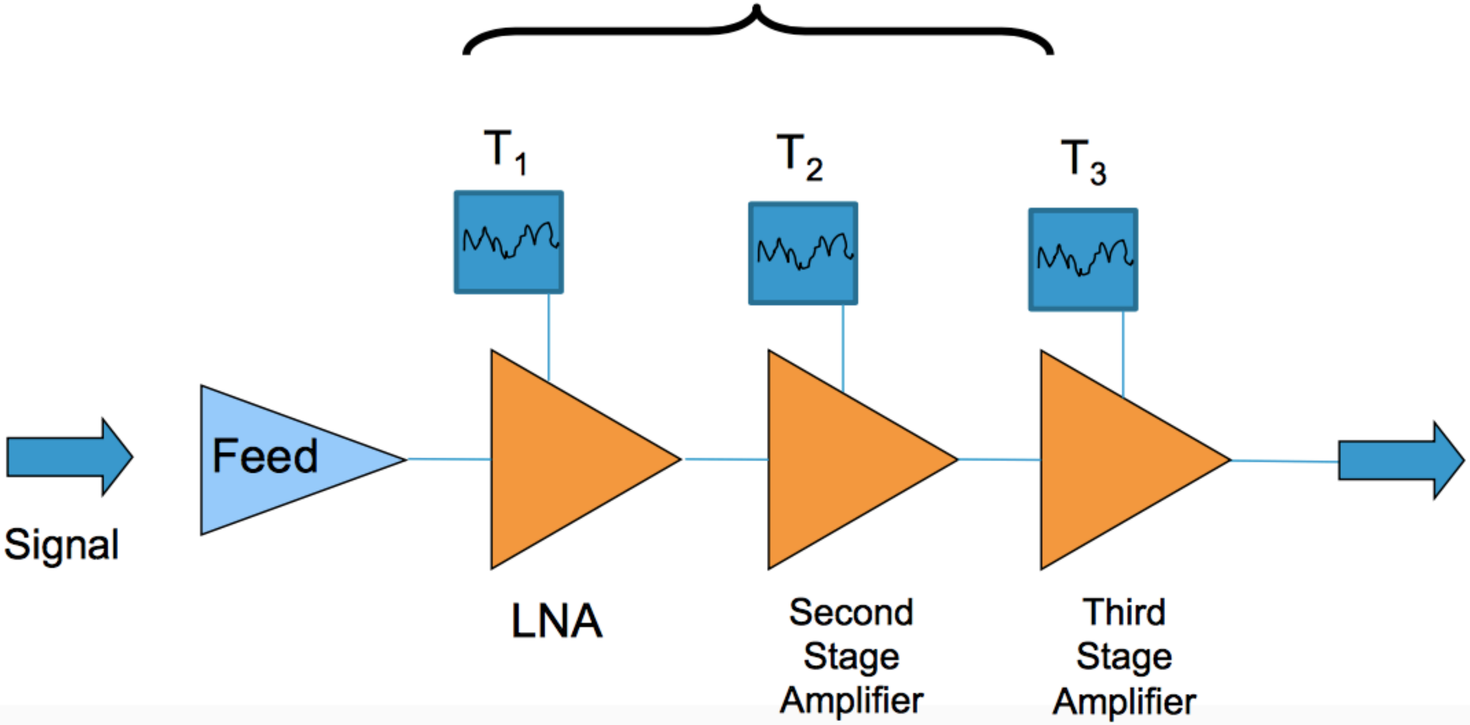
$P_{radio\_source} = S\ A_{eff} = k\ T$ (watts/Hz)

Gain (G) of radio system = T / S (Kelvins/Jy)

$G_{Arecibo} = 11$ K/Jy
$G_{GMRT} = 9$ K/Jy or 1.8 K/Jy
$G_{GBT} = 2$ K/Jy
$G_{Effelsburg} = 1.5$ K/Jy
$G_{Parkes} = 0.74$ K/Jy

Receiver noise temperature

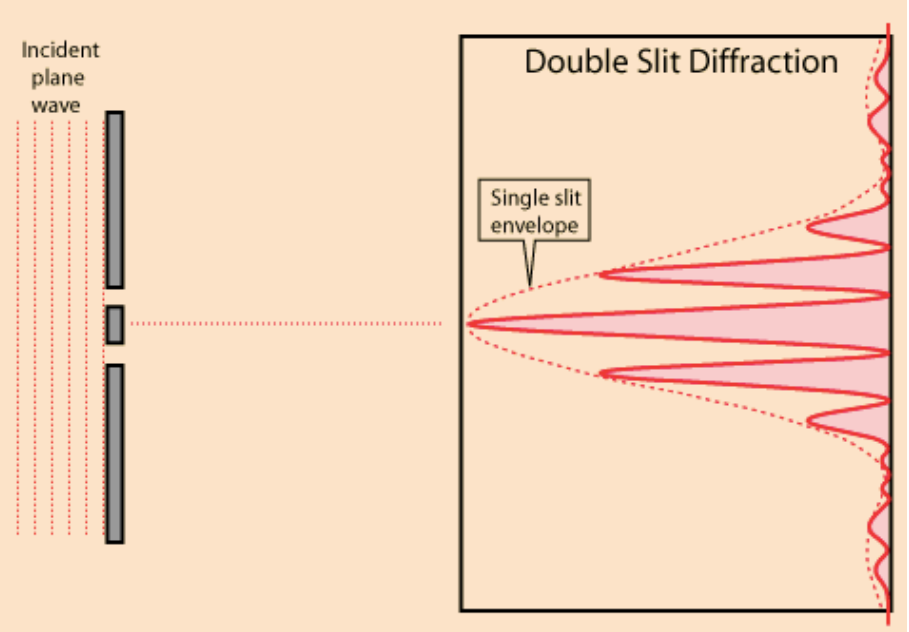
$$T_{system} = T_1 + \frac{T_2}{Gain_{LNA}} + \frac{T_3}{Gain_{LNA} \times G_2} + \frac{T_4}{Gain_{LNA} \times G_2 \times G_3} \quad \ldots\ldots$$



Noise in the data $\sigma_S = \frac{T_{\mathrm{sys}}}{G\sqrt{2\,\Delta\nu\, t_{\mathrm{samp}}}}$

Radio Interferometers

Interference fringe patterns



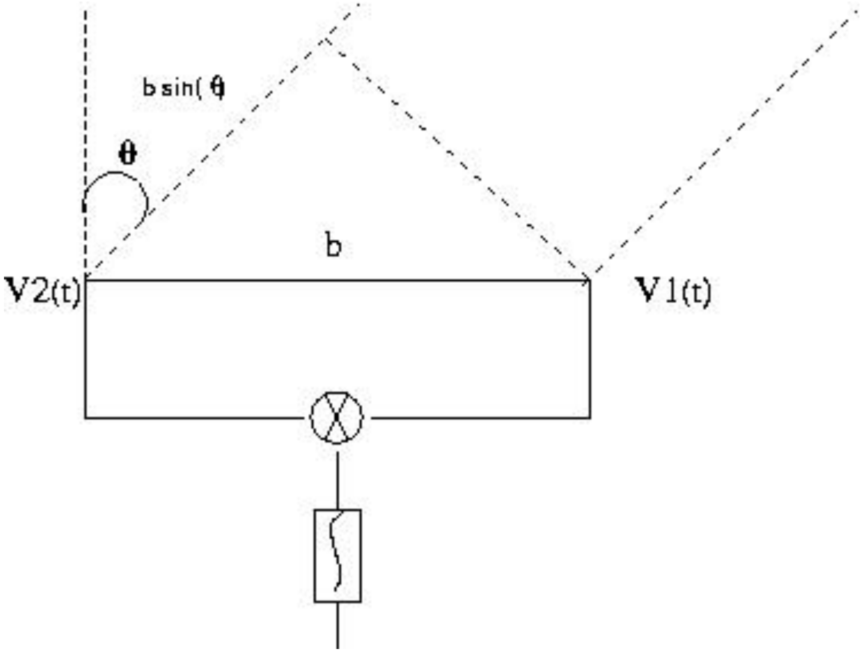
Diffraction limit of a telescope = 1.22 λ/D

Interferometer measures the spatial coherence function of the incident electric field

Signals arrive at Correlator from different Antennas have different *propagation* and *instrumental* delay.

$\tau = b/C \, \mathrm{Sin}(\theta)$

$d\tau/dt = b/C \, \mathrm{Cos}(\theta) \, d\theta/dt$

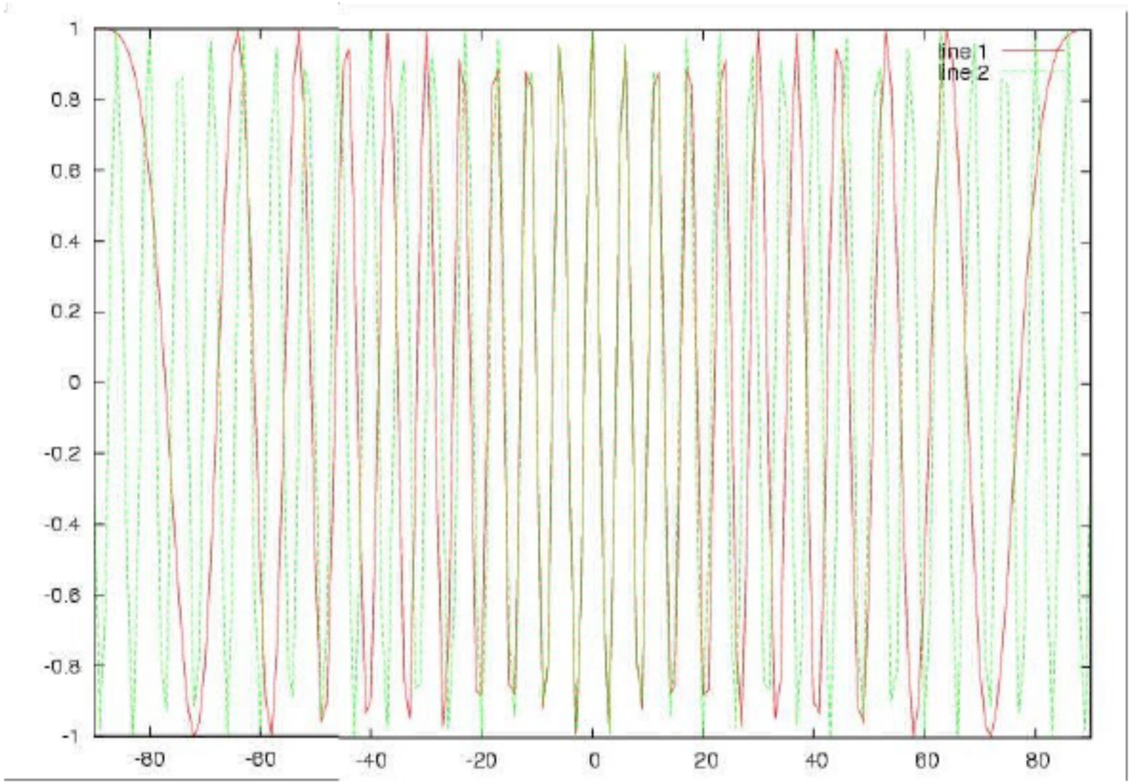


Monochromatic radiation

$$V_1(t)=\cos(2\pi\nu t)$$

$$V_2(t)=\cos(2\pi\nu(t-\tau_g))$$

Output of the interferometer : $\cos(2\pi\nu\tau_g)$



<u>Try with different b and ν combinations</u>

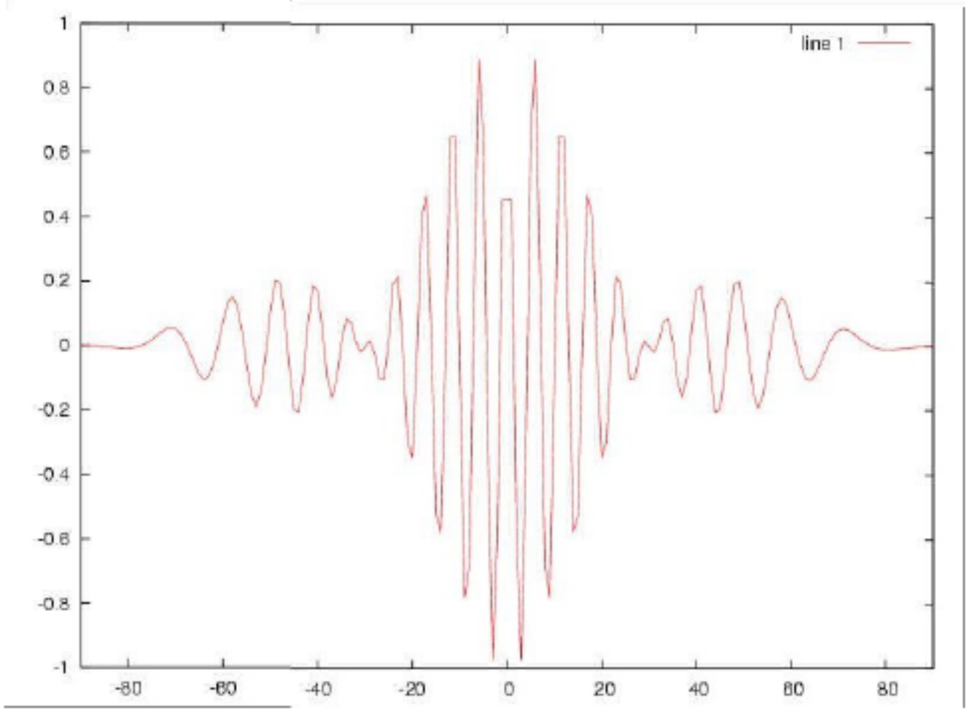
Fringe rate is maximum at zenith and minimum when source is rising or setting

Quasi-monochromatic radiation

Radiation spectrum contains all frequencies in a band $\Delta\nu$ around ν

Averaging over the all ν reduce the amplitude of the fringe

Output of the interferometer : $\cos(2\pi\nu\tau_g)\dfrac{\sin(\pi\Delta\nu\tau_g)}{\pi\Delta\nu\tau_g}$



<u>Increase $\Delta\nu$ to see how fringe amplitude decreases</u>

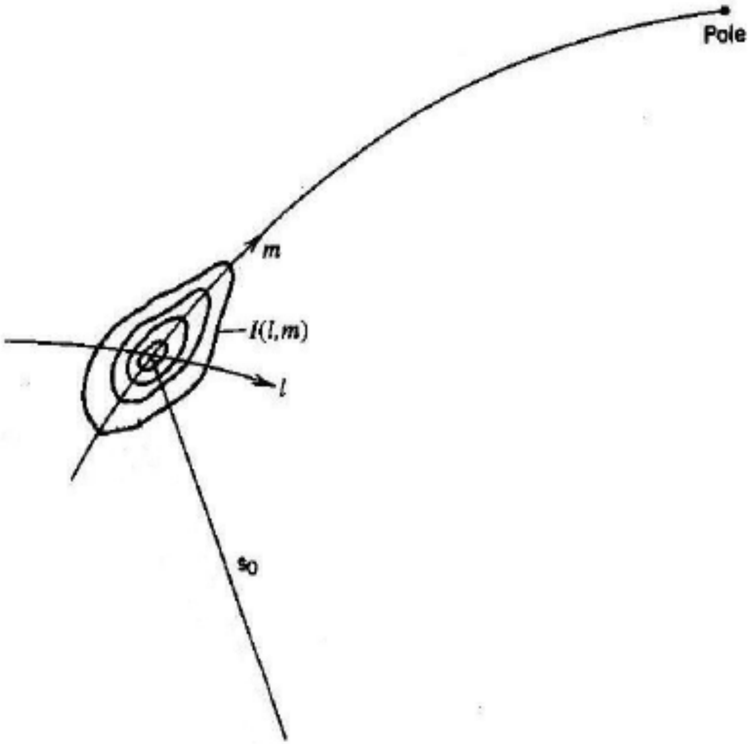
Increase $\Delta\nu$ without loosing fringe amplitude !!

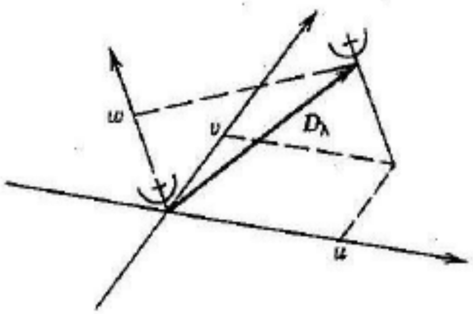
Mapping from Antenna spacing co-ordinates (X, Y, Z) to Projected baseline co-ordinates (u, v, w)

$$u_{\lambda}=X_{\lambda}\sin(H)+Y_{\lambda}\cos(H)$$

$$v_{\lambda}=-X_{\lambda}\sin(\delta)\cos(H)+Y_{\lambda}\sin(\delta)\sin(H)+Z_{\lambda}\cos(\delta)$$

$$w_{\lambda}=X_{\lambda}\cos(\delta)\cos(H)-Y_{\lambda}\cos(\delta)\sin(H)+Z_{\lambda}\sin(\delta)$$





All fringe and delay corrections apply for a specific point on the sky S_0 : Phase tracking center

w-term for a baseline is giving path length difference between two antennas

Required parameters :

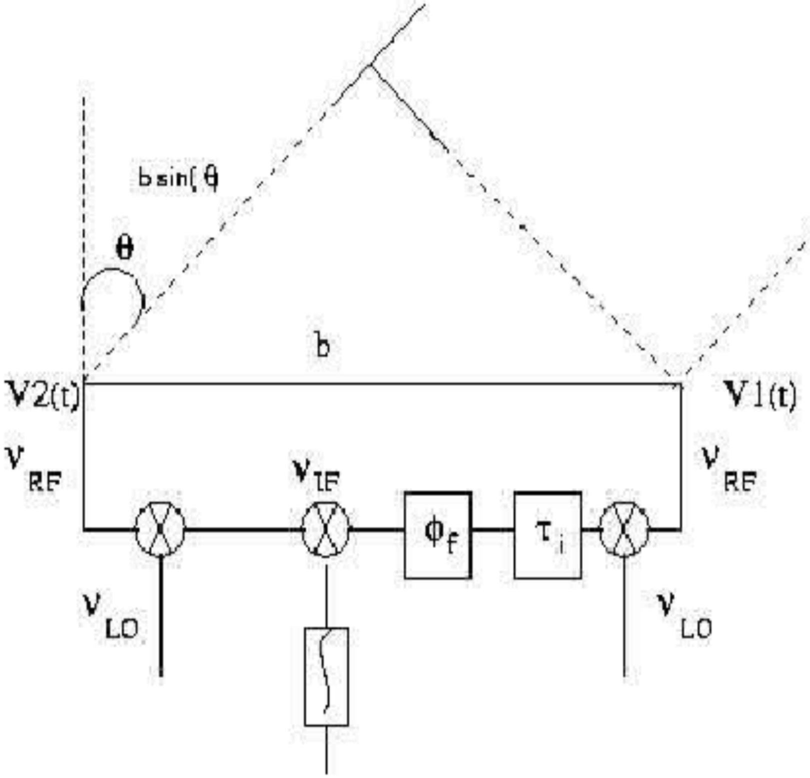
Delay $\tau_g = \frac{w}{c}$

Fringe phase $\phi = w_\lambda$

Fringe frequency $\frac{dw_\lambda}{dt} = \frac{dw_\lambda}{dH}\frac{dH}{dt} = (\nu_{observation})\frac{d\tau_g}{dt}$

$$= -\omega_e[X_\lambda \cos(\delta)\sin(H) + Y_\lambda \cos(\delta)\cos(H)]$$

What is fringe stopping and delay tracking



Delay suffered at RF frequency

Correction applies at IF frequency

$$< \cos(\phi_\nu + 2\pi\nu_{IF} t - 2\pi\nu_{RF}\tau_g)\cos(2\pi\nu_{IF}(t-\tau_i)+\phi_f) >$$

$$= \quad \cos(\phi_\nu + 2\pi\nu_{LO}\tau_g - \phi_f)$$

Applying this time varying phase ϕ_f is called : fringe stopping

Applying this additional delay τ_i is called delay tracking

Logical flow of the fringe stopping and delay correction :

- Get antenna co-ordinates (x,y,z)
- Get source co-ordinates (RA,DEC)
- Read the time-stamp value
- Calculate the HA(t) of the source
- Estimate the projected baseline co-ordinate (u,v,w)
- delay $\tau = \frac{W(t)}{C} + \tau_{Fix}$; phase $\Phi = 2\pi\tau(\nu_{RF} + \nu_i)$
- New $\tau = \tau + \frac{d\tau}{dt}\Delta(t)$
- Linear interpolation goes on till re-calculation of $(\tau, \dot{\tau})$

Total phase $\Phi = 2\pi(\nu_{RF} + \nu_i)\left(\frac{W(t)}{C} + \tau_{fix}\right) = 2\pi\nu_{RF}\left(\frac{W(t)}{C} + \tau_{fix}\right) + 2\pi\nu_i\left(\frac{W(t)}{C} + \tau_{fix}\right)$

$$\Phi_{frng}(t) = 2\pi\nu_{RF}\left(\frac{W(t)}{C} + \tau_{fix}\right)$$

$$\Phi_{fstc}(\nu, t) = 2\pi\nu_i\tau_{frac}$$

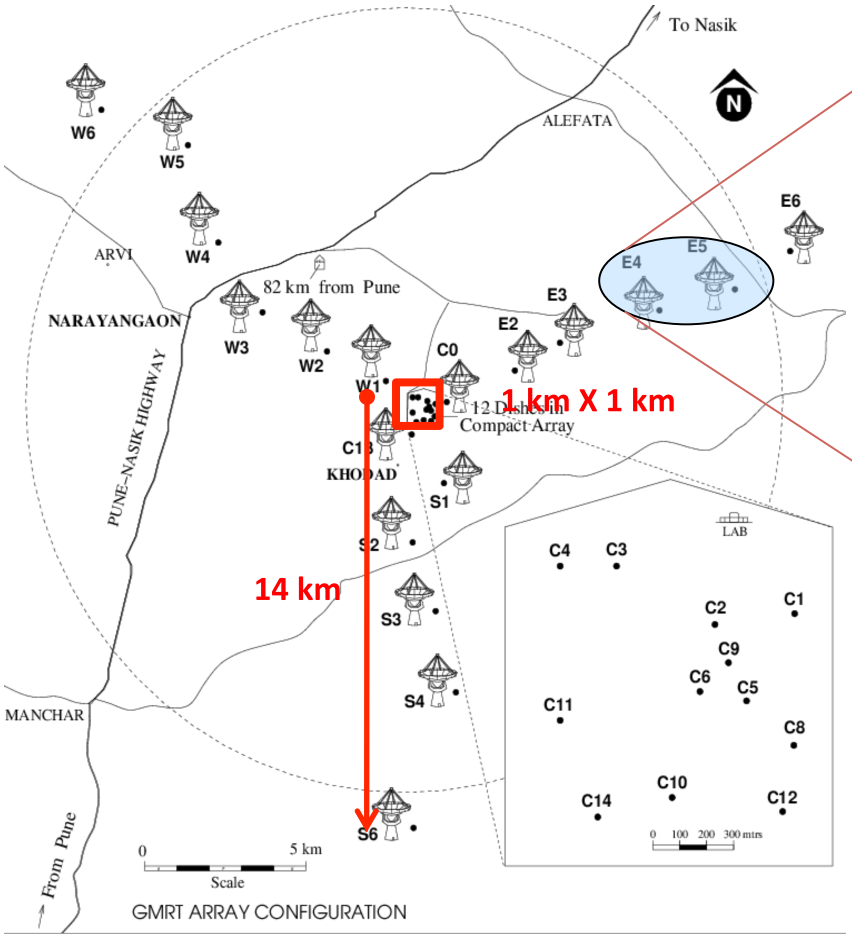
$$\boxed{(\dot{\phi}_{frng})_{\max} = 5 cycles/\sec}$$

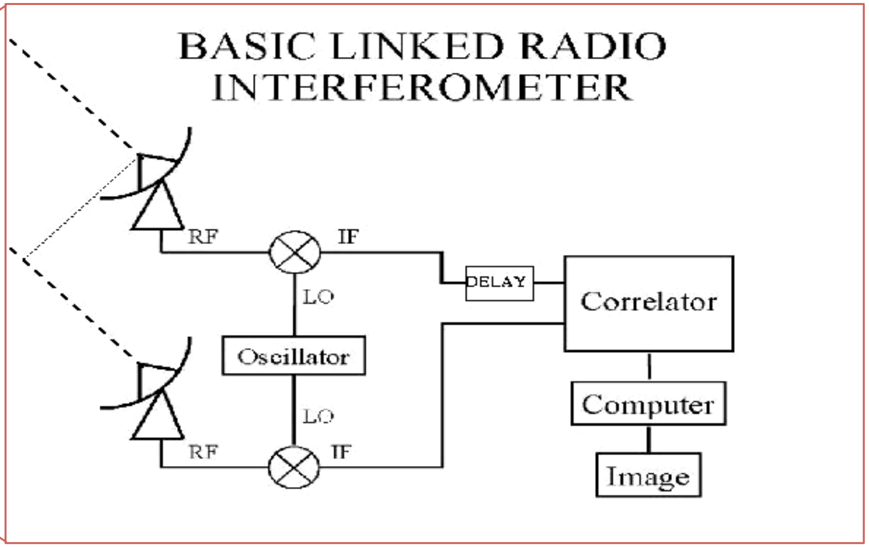
$$\boxed{(\tau)_{\max} = 150\mu s}$$

$$\boxed{(\dot{\tau})_{\max} = 3ns/\sec}$$

$$\boxed{\Delta\tau = 2ns}$$

The GMRT array distribution :
Concept of Radio Interferometry and Aperture Synthesis





- Signals from pair of antennae are cross-correlated (cross-spectrum is obtained)
- Product of Interferometer :
  Visibility Function : V(r1,r2)
  V(r1,r2) = <E(r1) E*(r2)>
- ~ N(N-1) such instantaneous measurements (Fourier components of the image)
- Reconstruction of Source Brightness Distribution : I $\xleftrightarrow[\text{FFT}]{}$ V (Aperture Synthesis)

Design consideration of a back-end for an array telescope

- Digitisations of the analog signals : more bits per sample ⇨ better dynamic range
- Ability to correct for variable time delays between pair of antennae ⇨ delay and fringe correction
- Extract the spectral information about the celestial source ⇨ realization of FFT
- Variable spectral resolutions ⇨ ranges from studying continuum sky to finer emission/absorption features of the HI cloud
- Complex correlator ⇨ in order to get N^2 instantaneous measurement of the Fourier components of the sky brightness distribution
- Variable time resolution ⇨ snapshot imaging to study the dynamic sky
- Ability to observe the Polarized sky
- A high time resolution total power receiver ⇨ to study the time domain features of the periodic signal from Pulsars
- Ability to add sophisticated algorithms to detect and filter out RFI signals at various stages in processing pipeline (wish-list)

Digitization of signals

Sampling

Band-limited signal down-converted to baseband sampled at Nyquist rate with 8 bits per sample

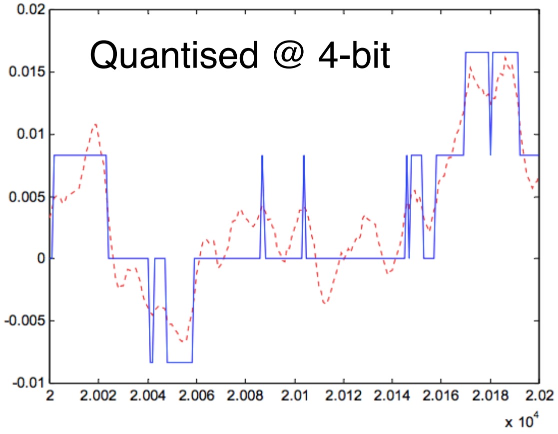
Input power level adjustment for 10*sigma range

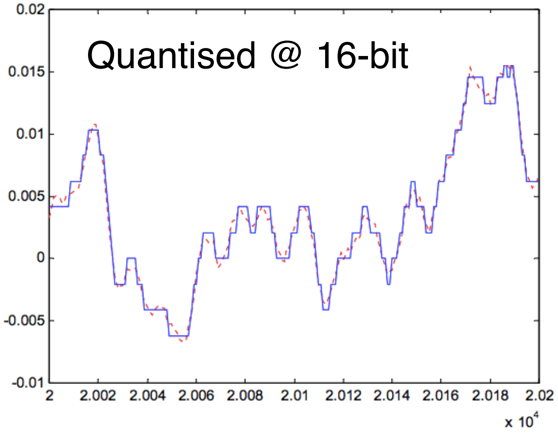
Quantization

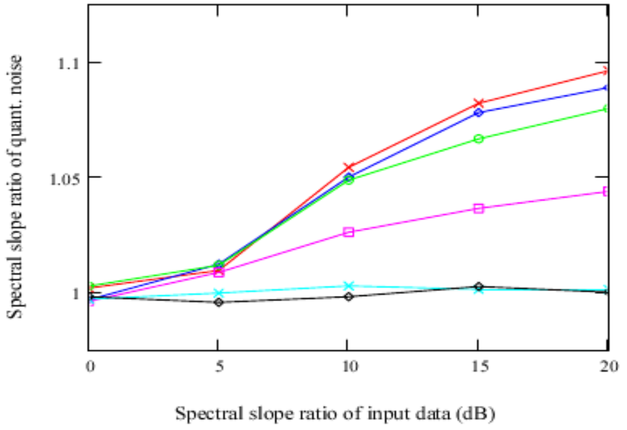
Discretization add quantization noise, more severe for fewer levels system.

Variation of gain with frequency makes the SNR of correlated signal varies across the band due to quantization noise

No. of levels	Quantize efficiency
3	80.9%
8	96.25%
16	98.84%
32	99.65%
256	99.99%

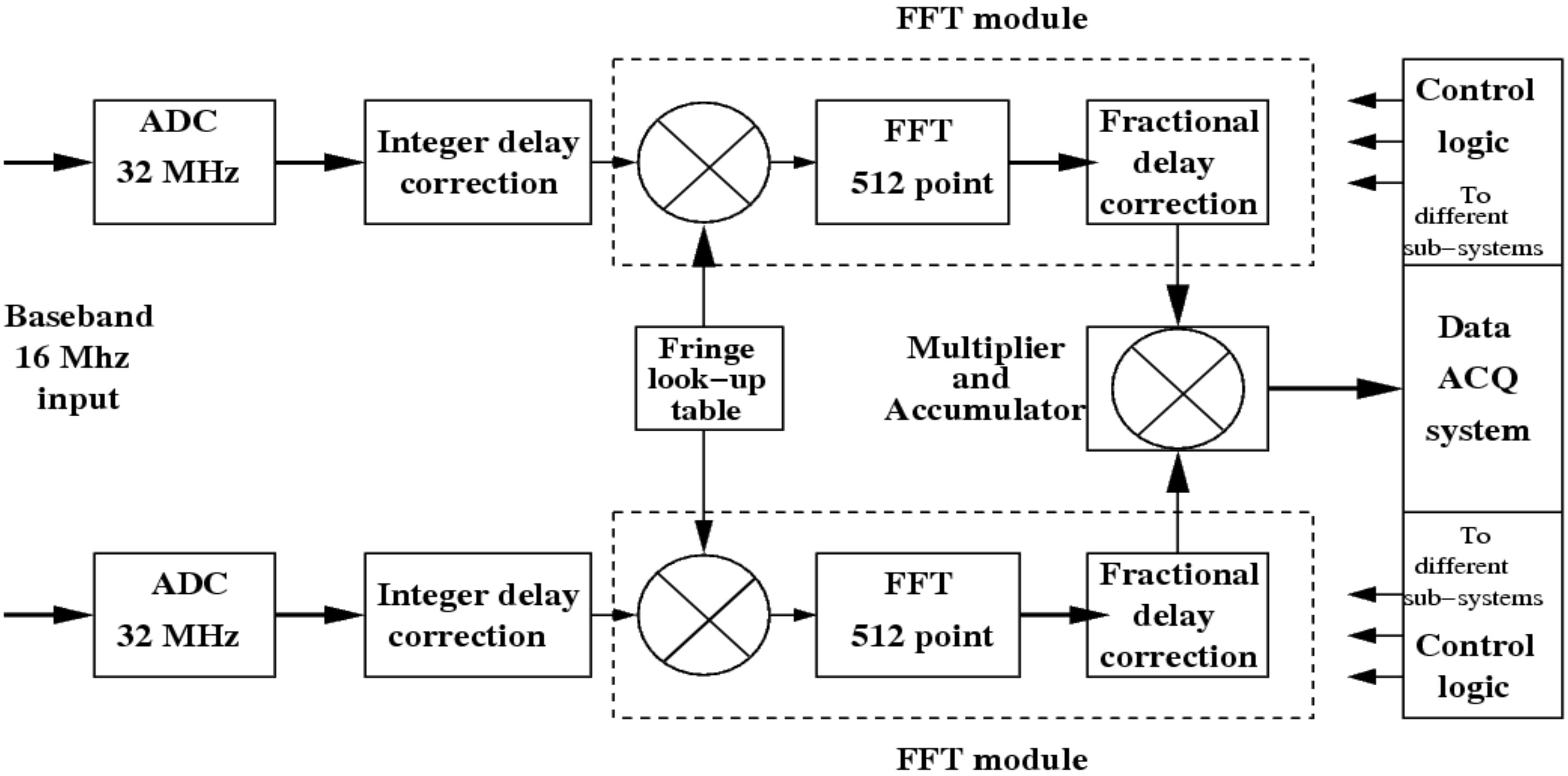




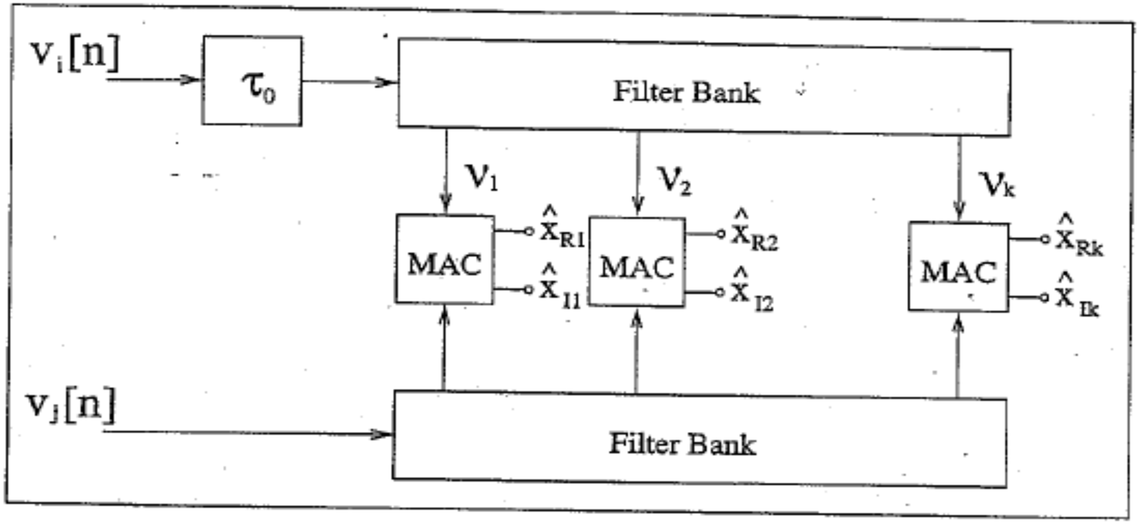


Digital Backend of a radio telescope like the GMRT

- Simultaneous operation as
  - FX correlator as an Imaging instrument
  - Beamformer as a Pulsar receiver



Spectral correlator : FX Vs XF

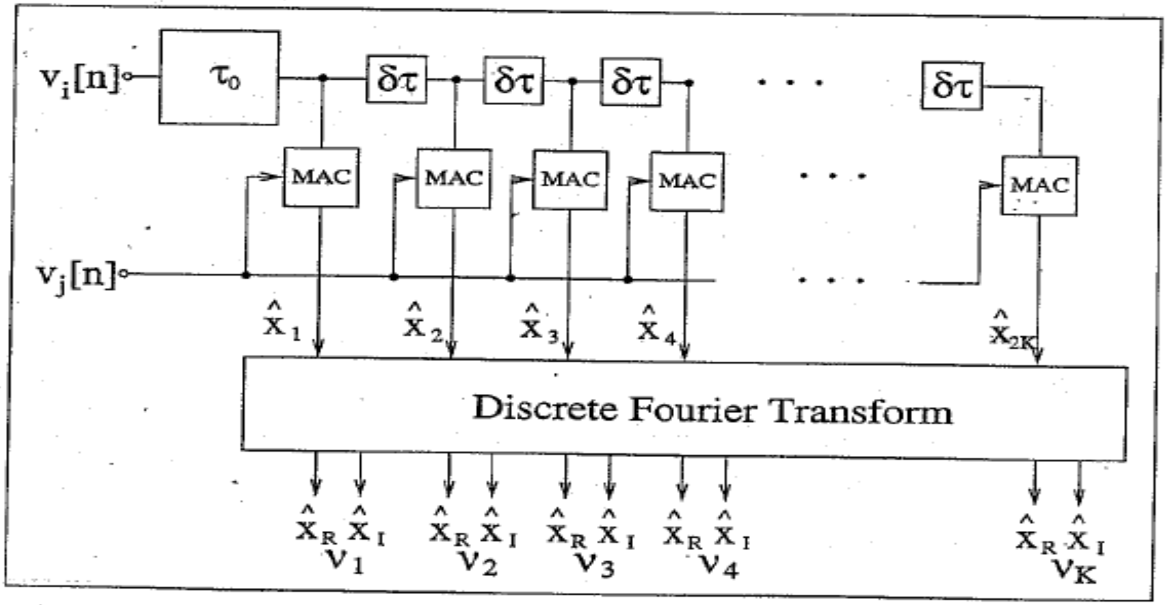


FX correlator

*~ 2*Na* BW * log(NFFT) +*

*BW * Na*(Na + 1)*

*= 2*Na*BW[log(NFFT)+(Na+1)/2] Cops*



XF correlator

*~ BW *Na*(Na+1)**

[1 + log(NFFT)]

Cops

For GMRT, Na=30, NFFT=1024

$C_{XF}/C_{FX} > 3$

Spectral correlator : FX Vs XF

Sensitivity
FX operates on block of data determined by the FFT algorithm. Cross-correlation is derived from fewer pair of samples than XF ⇨ loss of sensitivity in FX, requires overlapping adjacent blocks, net increase in computing load in FX

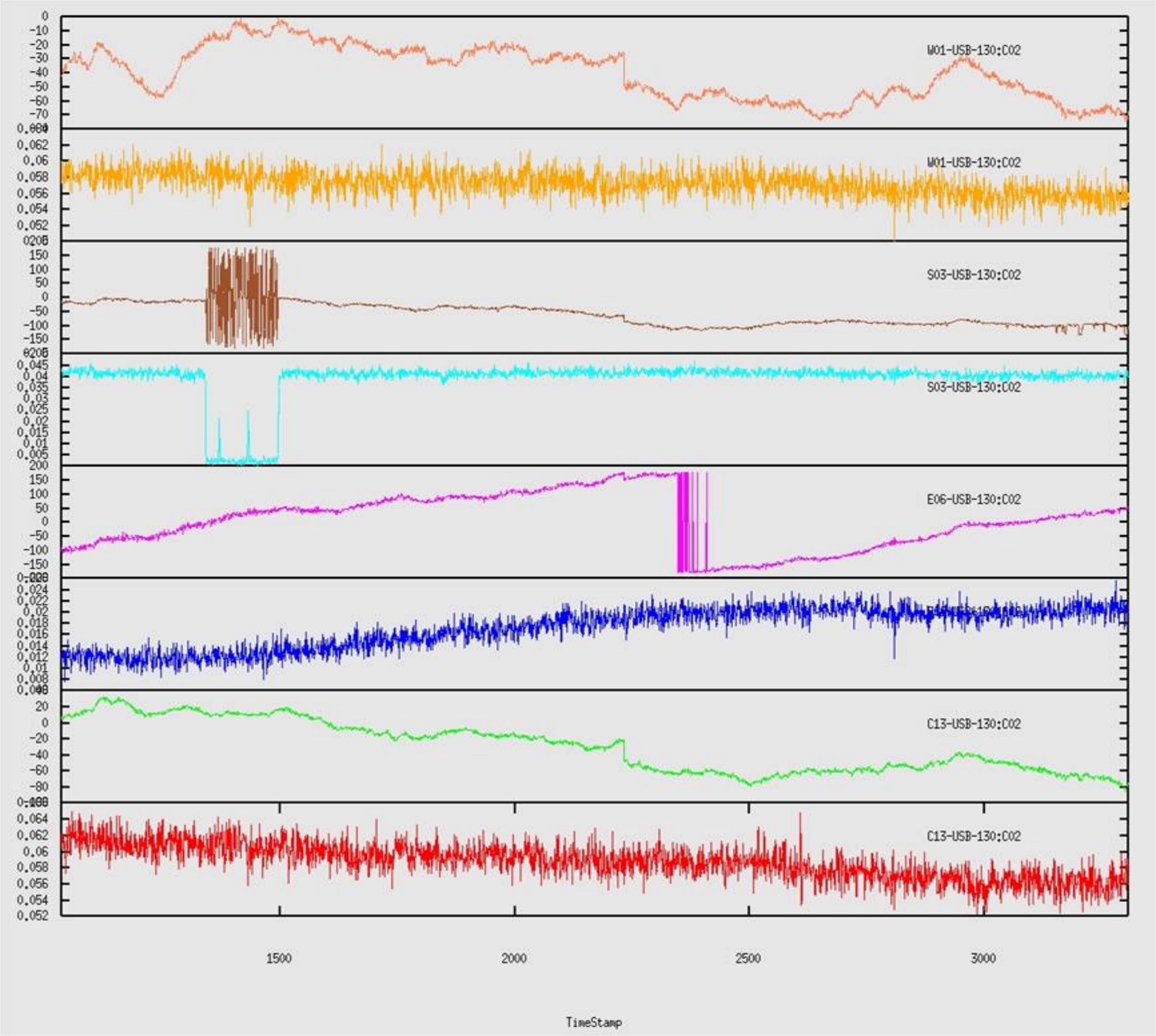
Quantization
Correction for quantization efficiency before correlation possible for XF, but difficult for FX ⇨ XF is advantageous for small no. of bit corrrelator

Closure errors
FX correlator is less vulnerable to baseline dependent systematic effects

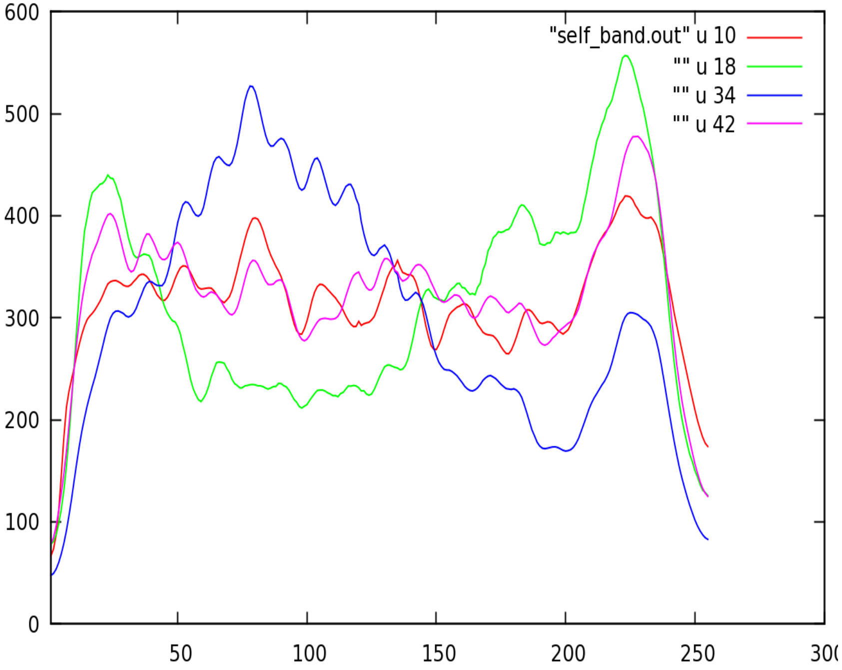
Fractional sample correction
In XF correction can be done in base-line base after transform

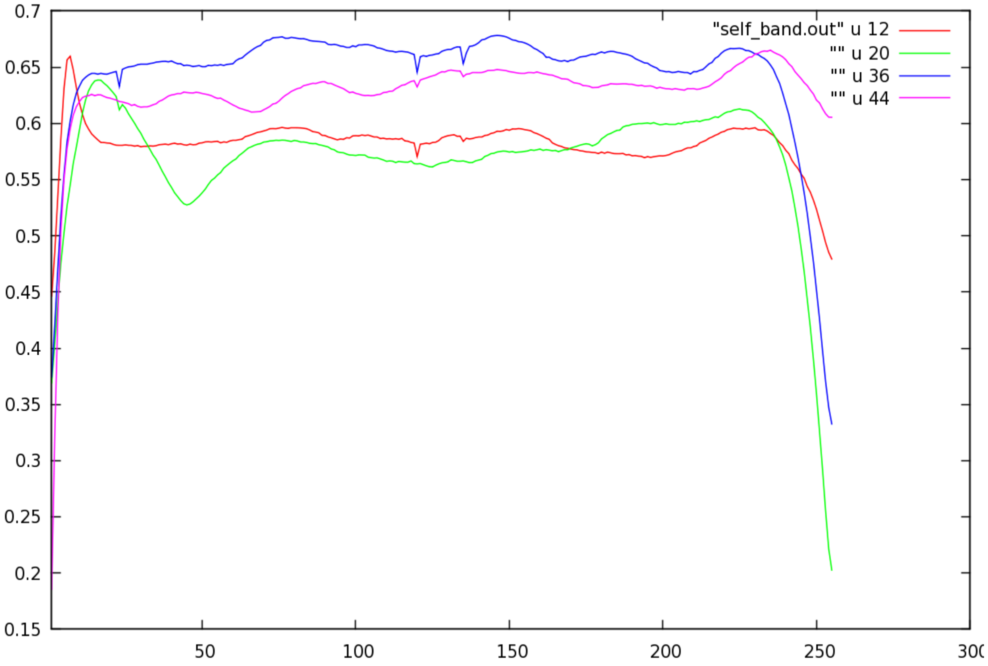
Improvement in the shape of channel bandpass
FX correlator bandpass function of each channel is Sinc^2, whereas for XF it is Sinc

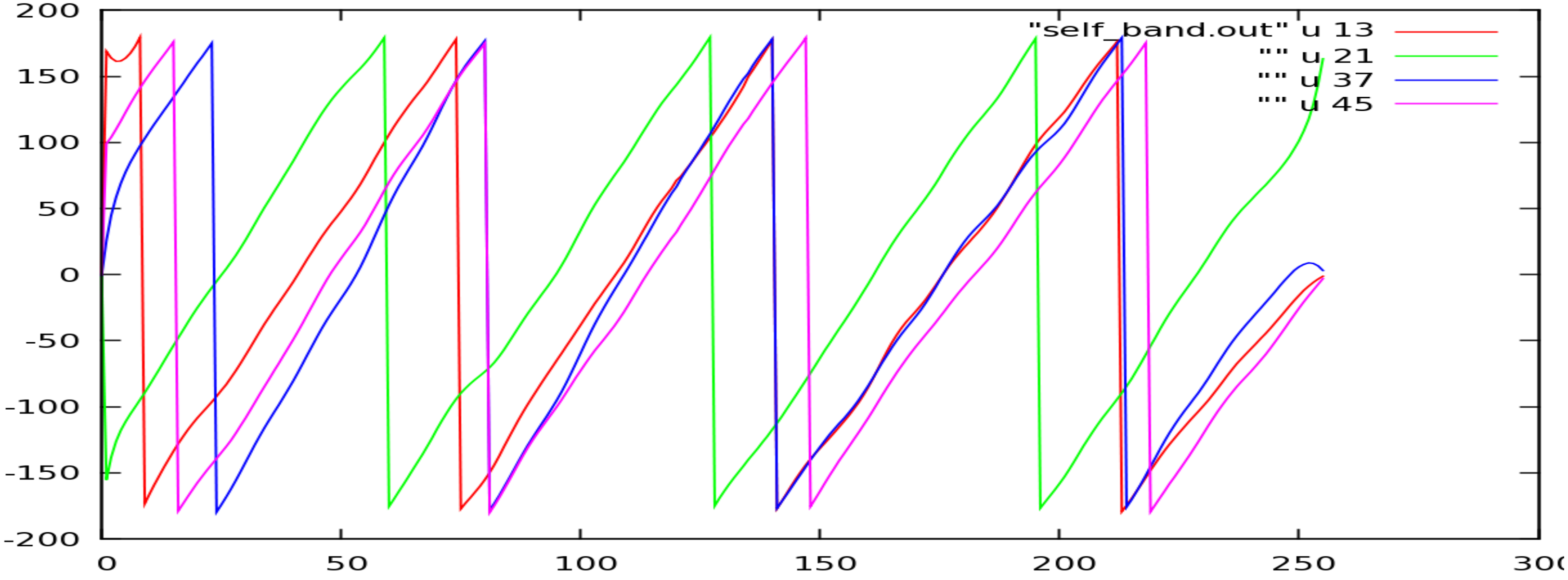
Cross correlation output



Cross spectrum in presence of correlated signals

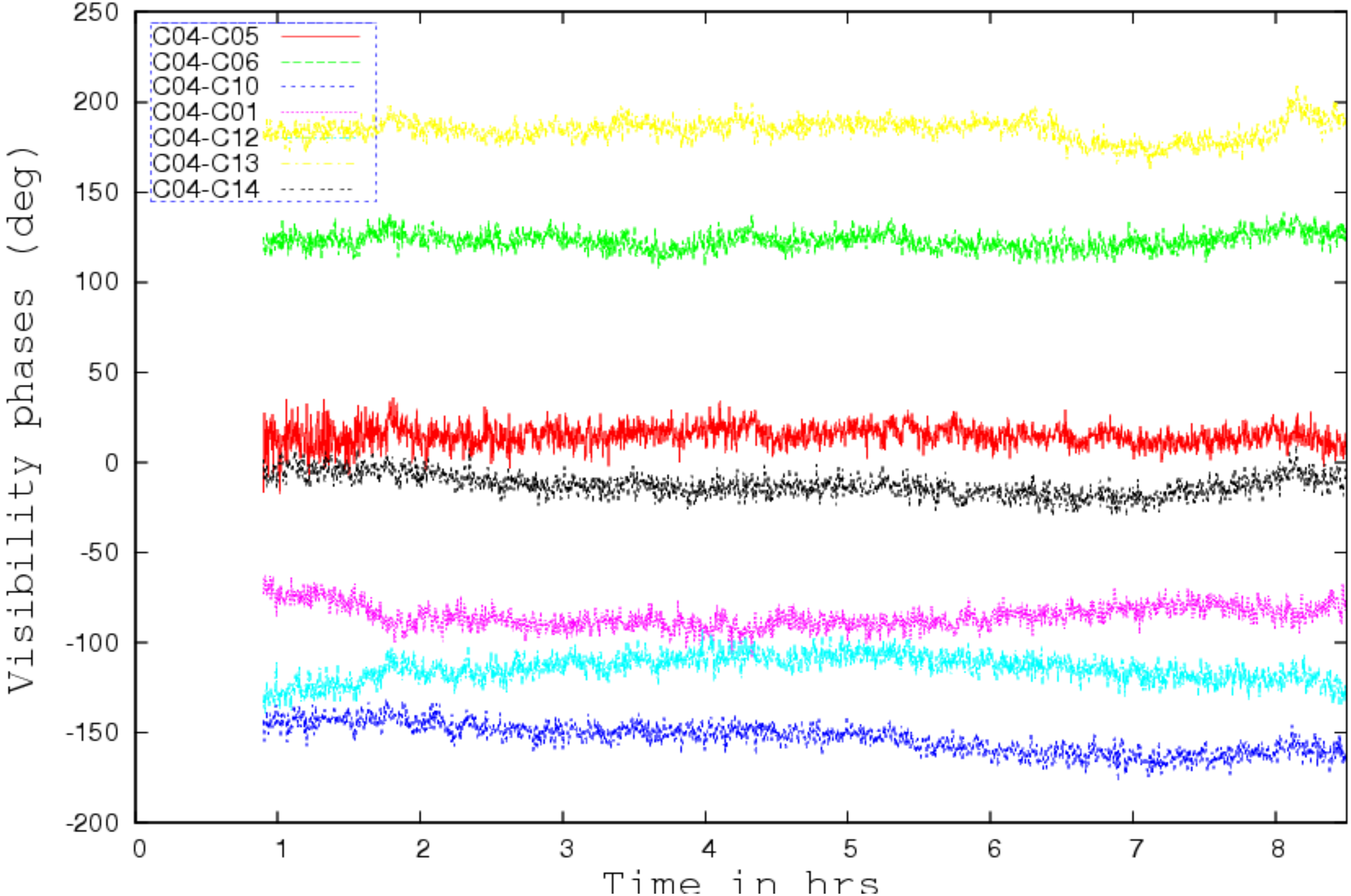






Long term phase stability

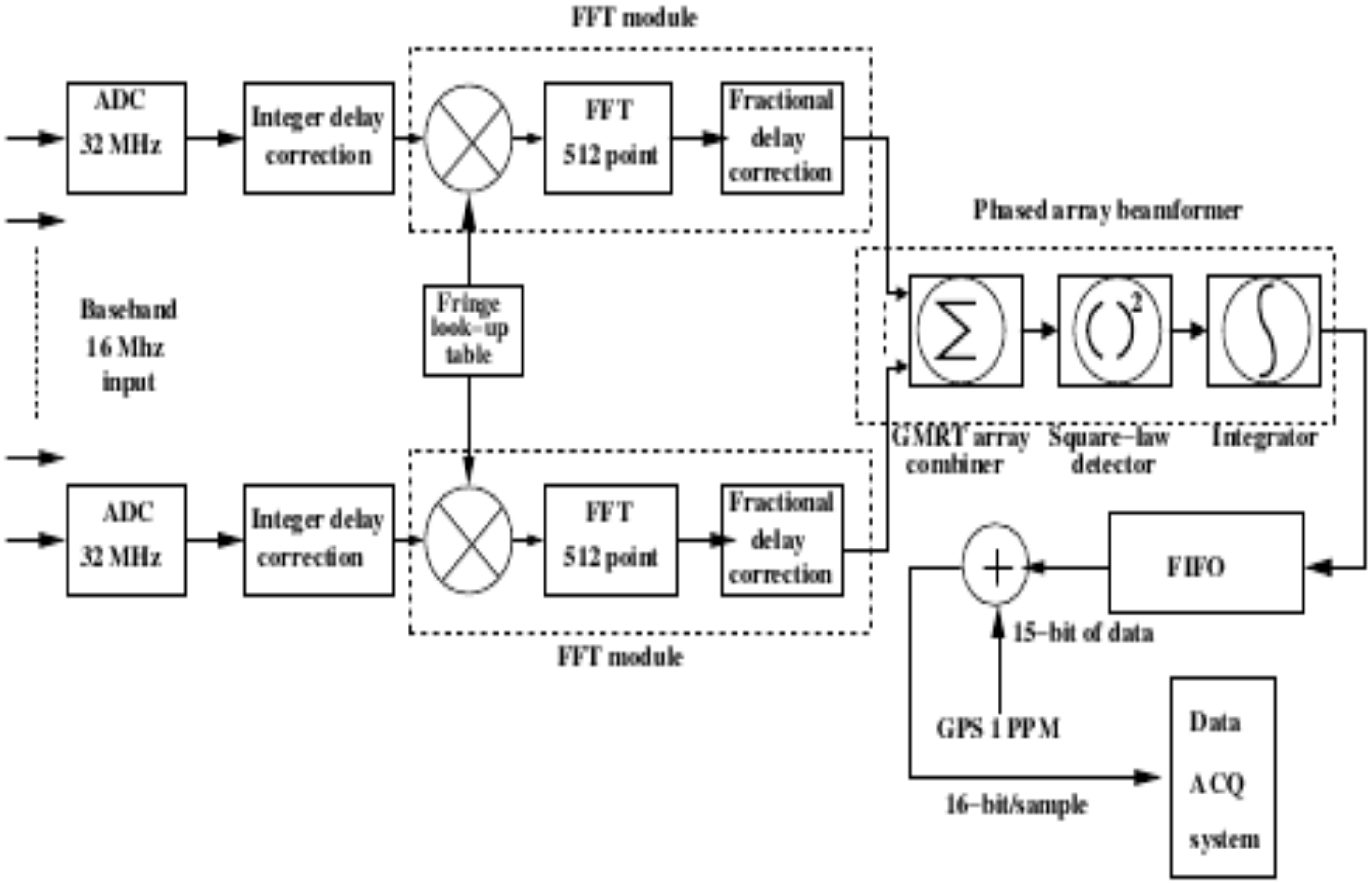
Visibility phases for a single spectral channel at 1280 MHz for a duration of 8.5 hrs



Array Beamformer : A pulsar receiver

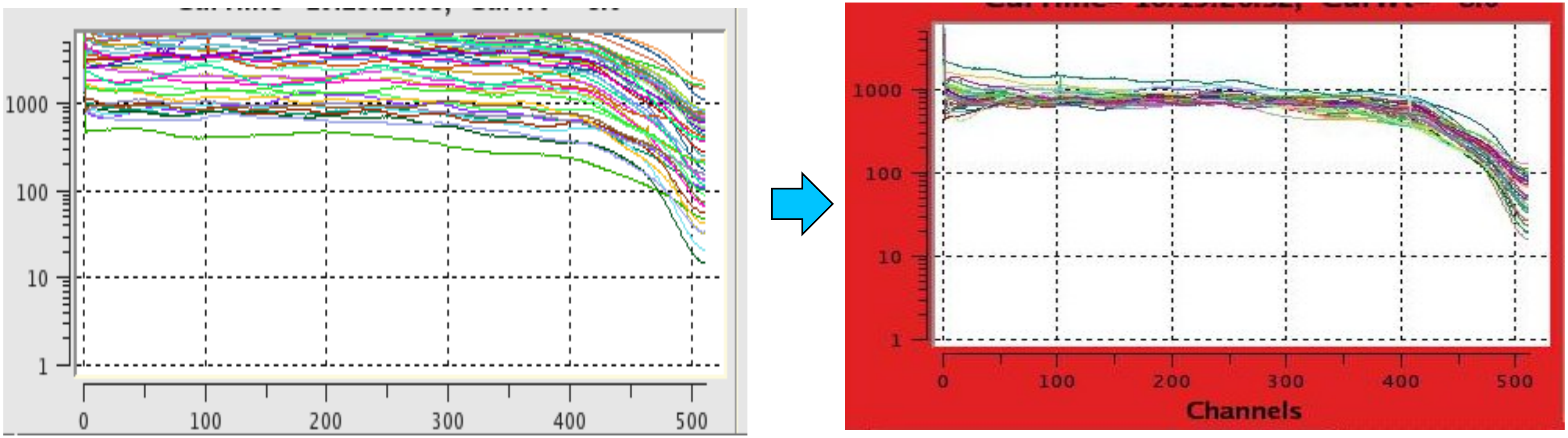
Incoherent array mode : signals from antennas are added in intensity

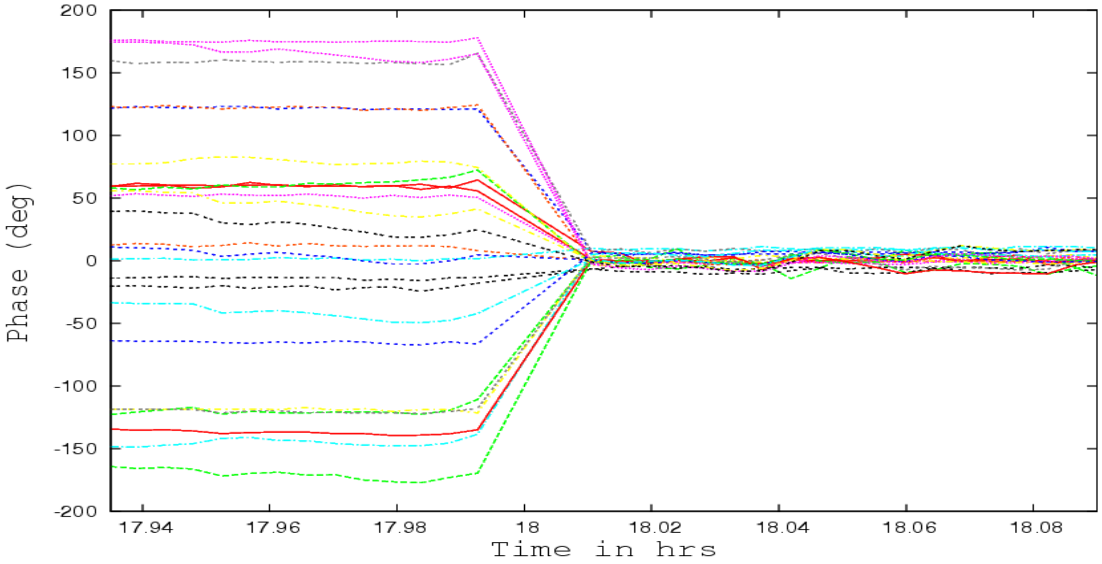
Phased array mode : Signals from antennas are added in voltage



Amplitude and phase calibration for beamformer

Antenna based gain offset correction

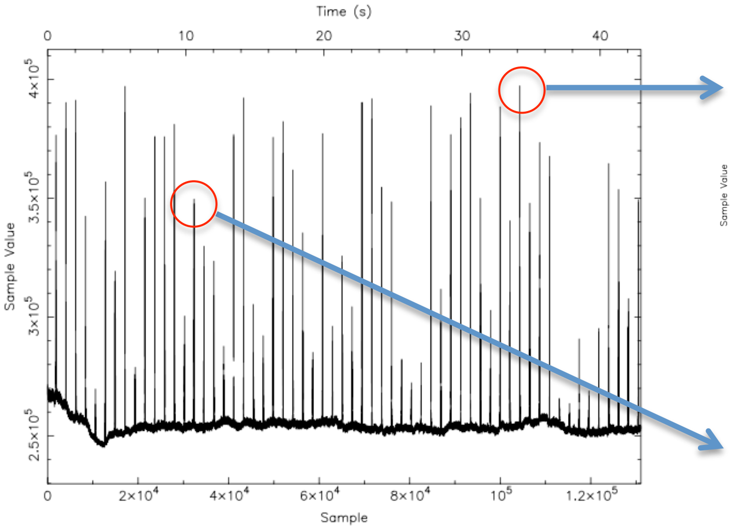


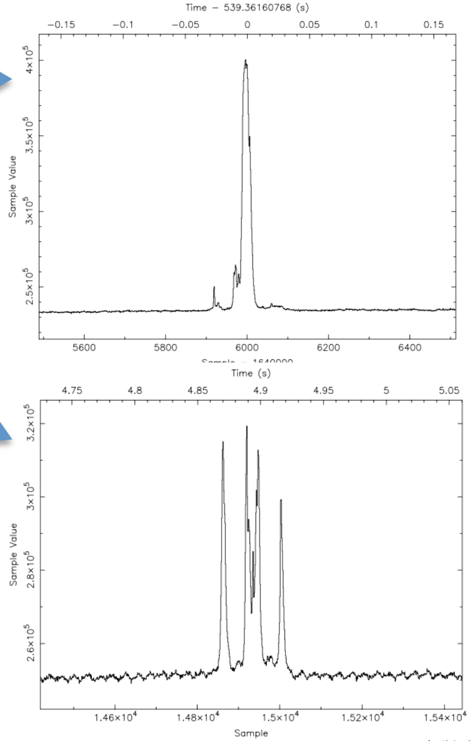


Antenna based phase offset correction

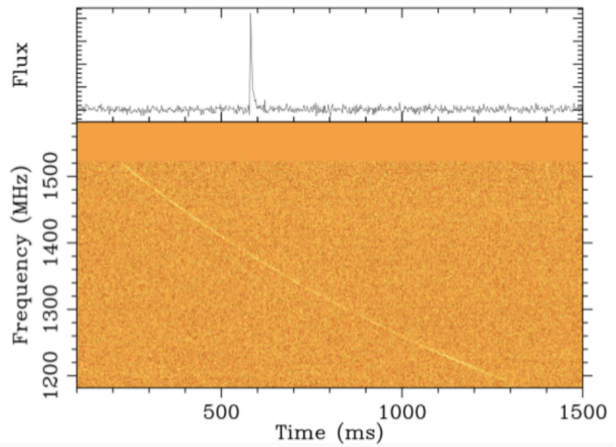
High time resolution beamformer

Single pulse time-series from PSR B0329+54

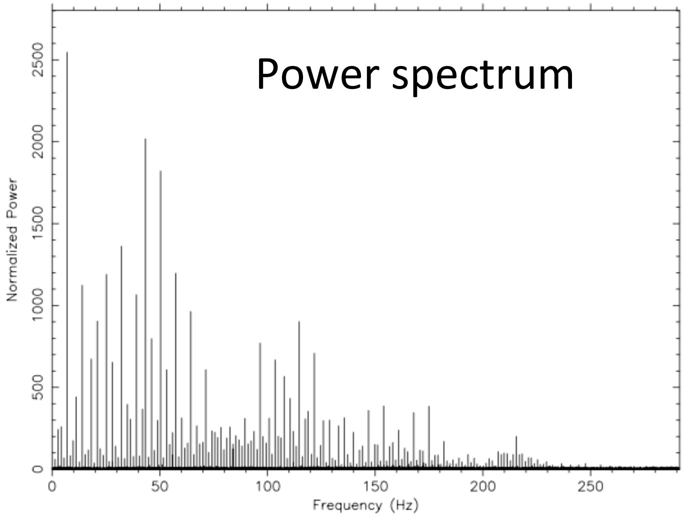




Dispersed single pulse from Fast Radio Burst



Power spectrum



Sensitivity of a correlator

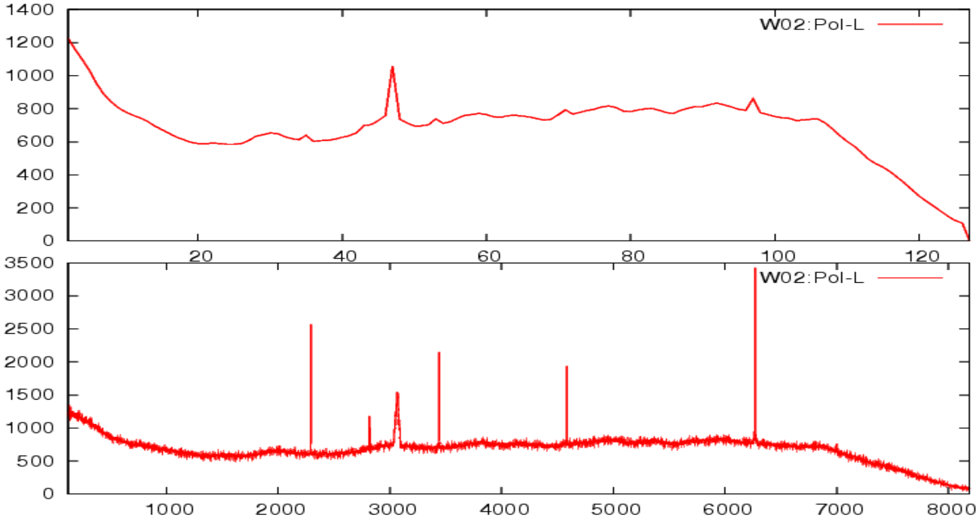
$$\frac{\sqrt{N(N-1)T\Delta\nu}\ GS}{T_s}$$

Array of N elements, Ts is the system temperature, Δv is the band-width, T is the integration time, G is the gain of the antenna, S is the source flux

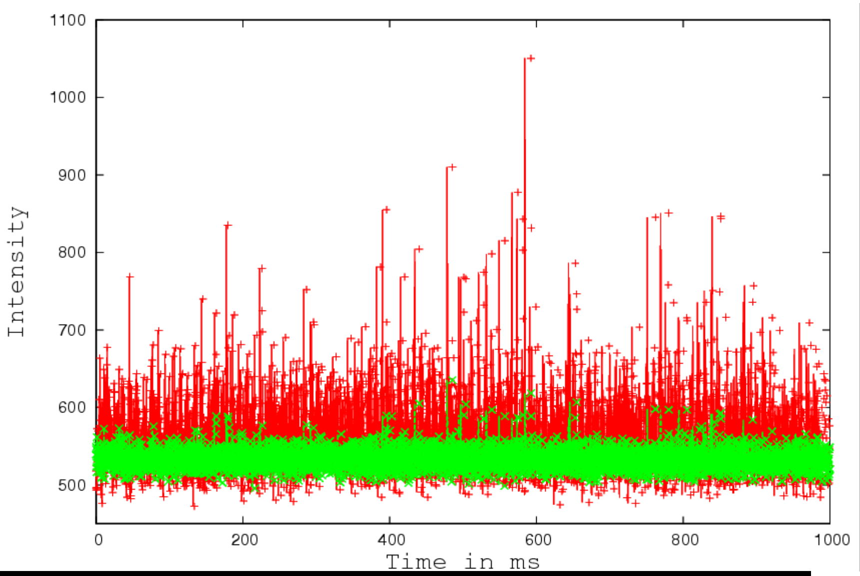
More sensitive array = large element array + wide-band system + low-noise receiver + large-efficient aperture telescope

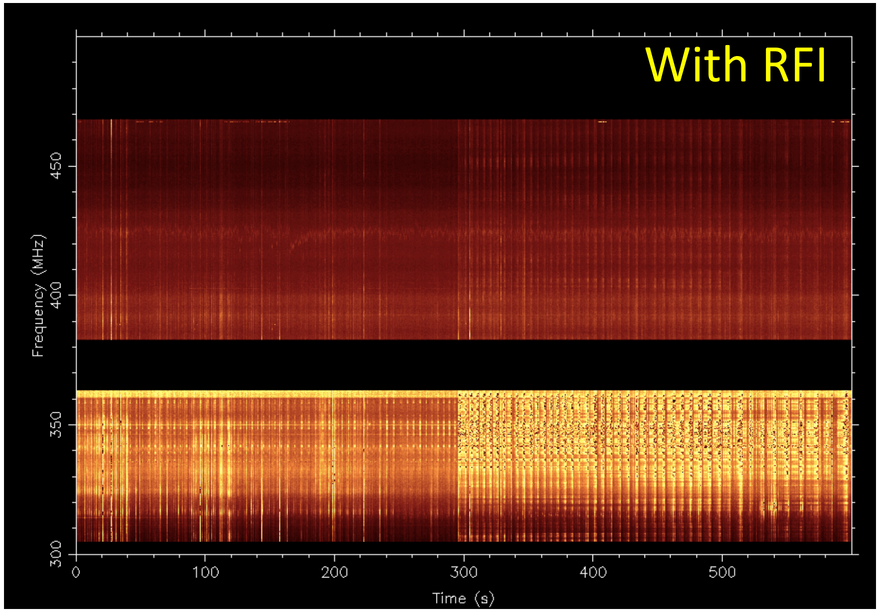
Detecting and mitigating RFIs

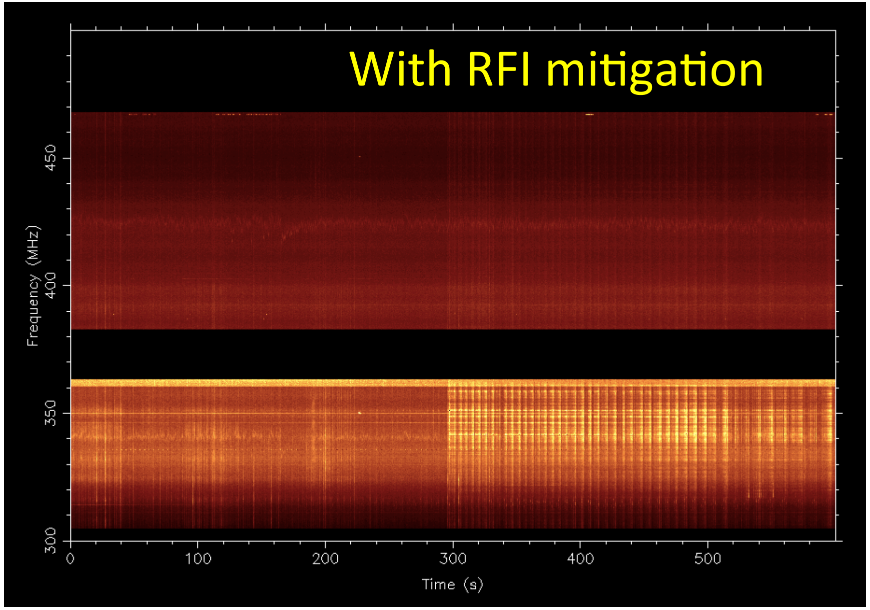
High spectral res



Pre detection RFI removal





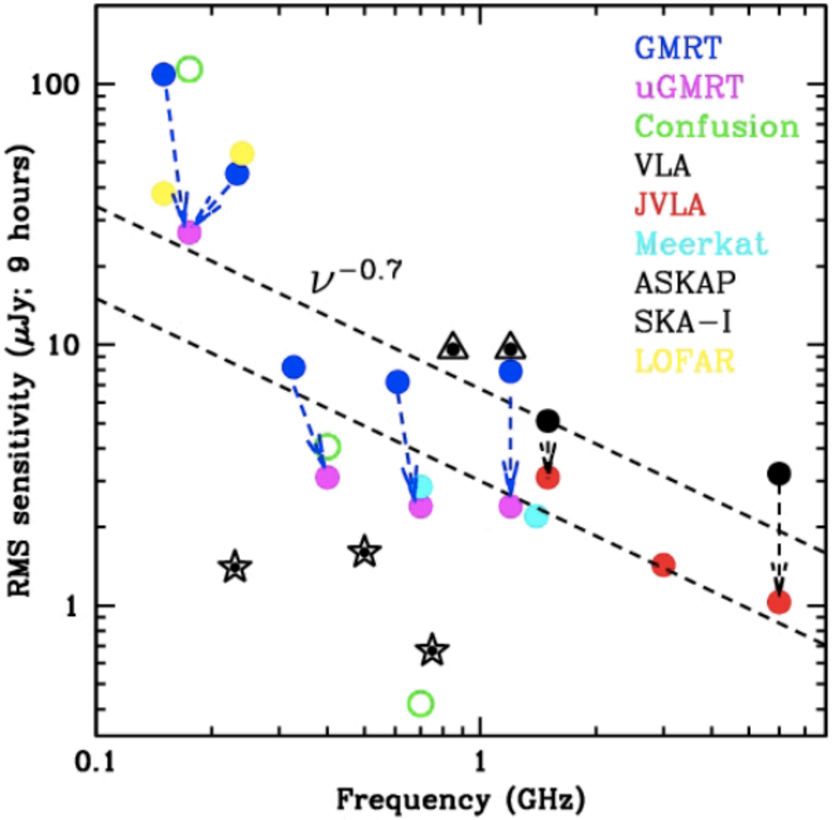


Comparison of some synthesis Radio Telescopes (cm & m wave)

Synthesis Radio Telescope	**Location**	**No. of Antennas**	**Synth. Aperture.**	**Freq. Range**
❑ VLA	USA	27 x 25 m	33 km	1.4 GHz – 44 GHz (74 MHz & 327 MHz)
❑ WSRT	Netherlands	14 x 25 m	3 km	327 MHz – 8000 MHz
❑ ATCA	Australia	6 x 25 m	6 km	1.4 GHz – 44 GHz
❑ GMRT	India	30 x 45 m	25 km	120 MHz – 1460 MHz
❑ MERLIN	UK	6 x 25 m +1 x 76 m	400 km	408 MHz – 5000 MHz

The upgraded GMRT (uGMRT)

- ✓ Seamless frequency coverage from 150 to 1450 MHz
- ✓ Improved G/T_{sys}
- ✓ Increase of instantaneous bandwidth from 32 MHz to 200 MHz/400 MHz
- ✓ Expected increase in sensitivity by 3x
- ✓ Time-domain study simultaneously in 3-4 frequencies



Credit: Nissim Kanekar

Ref: Gupta et al. 2018

The uGMRT

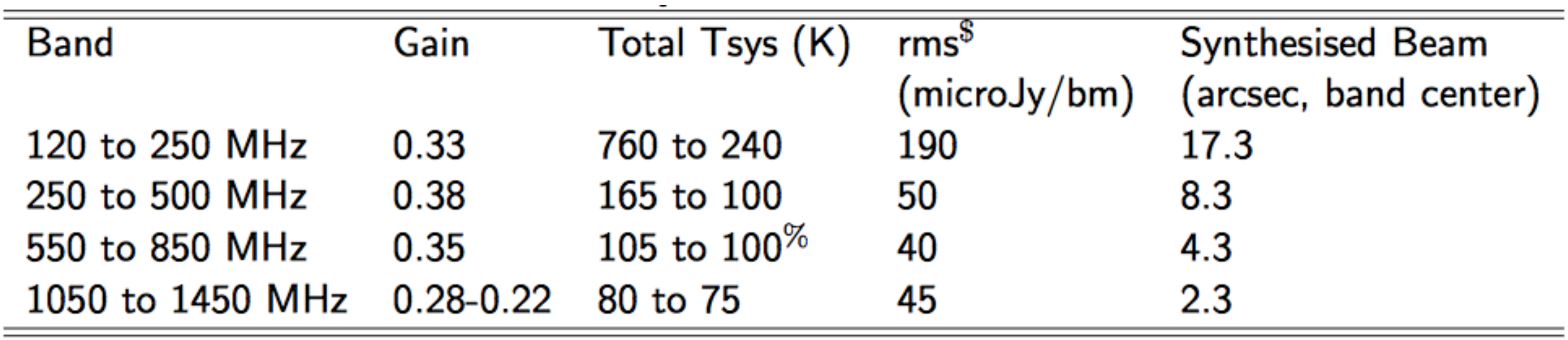
Currently four wide-bands of operations

120 – 150 MHz

300 – 500 MHz

550 – 850 MHz

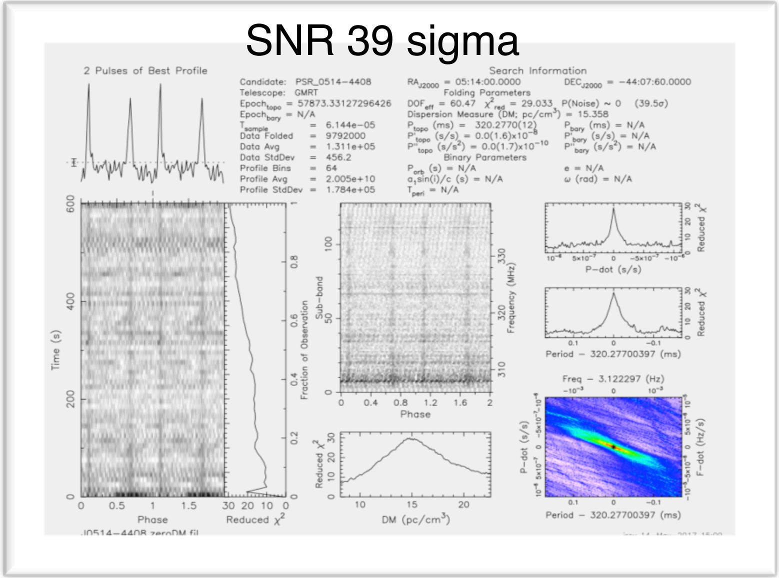
1000 – 1450 MHz



Band	Gain	Total Tsys (K)	rms$^{\$}$ (microJy/bm)	Synthesised Beam (arcsec, band center)
120 to 250 MHz	0.33	760 to 240	190	17.3
250 to 500 MHz	0.38	165 to 100	50	8.3
550 to 850 MHz	0.35	105 to 100$^{\%}$	40	4.3
1050 to 1450 MHz	0.28-0.22	80 to 75	45	2.3

Time-domain sensitivity with uGMRT

SNR 39 sigma



Search Information

Candidate: PSR_0514−4408
Telescope: GMRT
Epoch_{topo} = 57873.33127296426
Epoch_{bary} = N/A
T_{sample} = 6.144e−05
Data Folded = 9792000
Data Avg = 1.311e+05
Data StdDev = 456.2
Profile Bins = 64
Profile Avg = 2.005e+10
Profile StdDev = 1.784e+05

RA_{J2000} = 05:14:00.0000
DEC_{J2000} = −44:07:60.0000

Folding Parameters

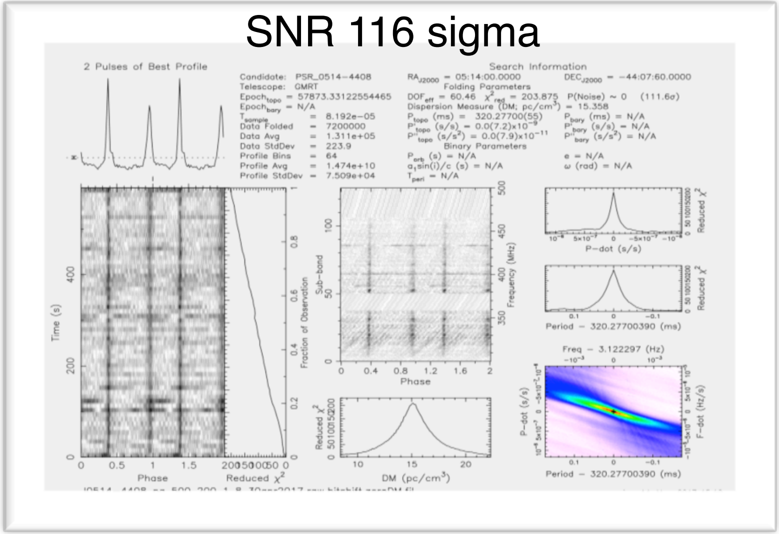
DOF_{eff} = 60.47 χ^2_{red} = 29.033 P(Noise) ~ 0 (39.5σ)
Dispersion Measure (DM; pc/cm^3) = 15.358
P_{topo} (ms) = 320.2770(12)
P'_{topo} (s/s) = 0.0(1.6)x10^{-8}
P''_{topo} (s/s^2) = 0.0(1.7)x10^{-10}
P_{bary} (ms) = N/A
P'_{bary} (s/s) = N/A
P''_{bary} (s/s^2) = N/A

Binary Parameters

P_{orb} (s) = N/A
$a_1\sin(i)/c$ (s) = N/A
T_{peri} = N/A
e = N/A
ω (rad) = N/A

P = 320 ms

SNR 116 sigma



Search Information

Candidate: PSR_0514−4408
Telescope: GMRT
Epoch_{topo} = 57873.33122554465
Epoch_{bary} = N/A
T_{sample} = 8.192e−05
Data Folded = 7200000
Data Avg = 1.311e+05
Data StdDev = 223.9
Profile Bins = 64
Profile Avg = 1.474e+10
Profile StdDev = 7.509e+04

RA_{J2000} = 05:14:00.0000
DEC_{J2000} = −44:07:60.0000

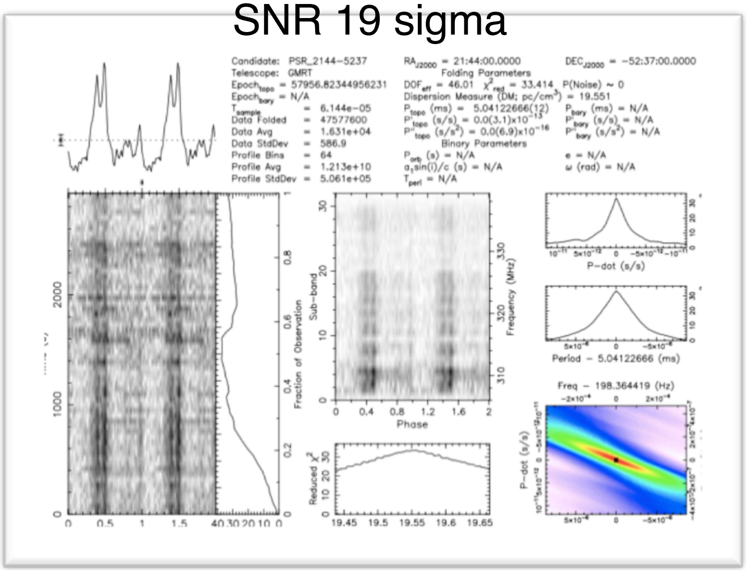
Folding Parameters

DOF_{eff} = 60.46 χ^2_{red} = 203.875 P(Noise) ~ 0 (111.6σ)
Dispersion Measure (DM; pc/cm^3) = 15.358
P_{topo} (ms) = 320.27700(55)
P'_{topo} (s/s) = 0.0(7.2)x10^{-9}
P''_{topo} (s/s^2) = 0.0(7.9)x10^{-11}
P_{bary} (ms) = N/A
P'_{bary} (s/s) = N/A
P''_{bary} (s/s^2) = N/A

Binary Parameters

P_{orb} (s) = N/A
$a_1\sin(i)/c$ (s) = N/A
T_{peri} = N/A
e = N/A
ω (rad) = N/A

SNR 19 sigma



Candidate: PSR_2144−5237
Telescope: GMRT
Epoch_{topo} = 57956.82344956231
Epoch_{bary} = N/A
T_{sample} = 6.144e−05
Data Folded = 47577600
Data Avg = 1.631e+04
Data StdDev = 586.9
Profile Bins = 64
Profile Avg = 1.213e+10
Profile StdDev = 5.061e+05

RA_{J2000} = 21:44:00.0000
DEC_{J2000} = −52:37:00.0000

Folding Parameters

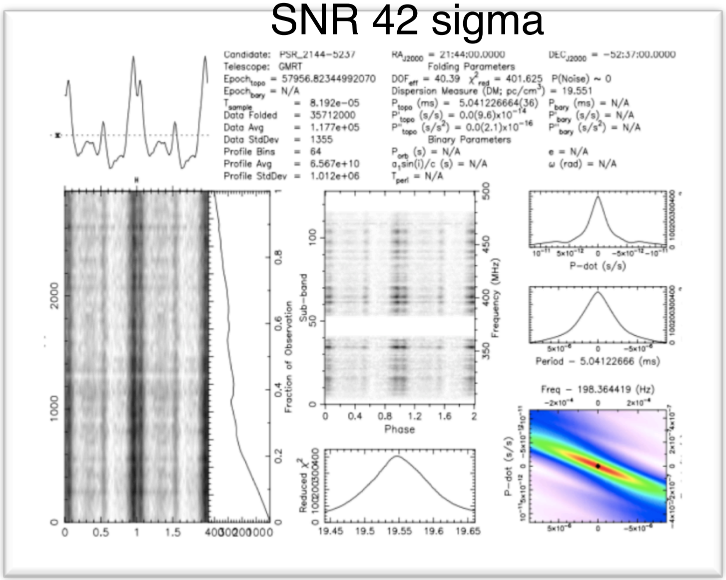
DOF_{eff} = 46.01 χ^2_{red} = 33.414 P(Noise) ~ 0
Dispersion Measure (DM; pc/cm^3) = 19.551
P_{topo} (ms) = 5.04122666(12)
P'_{topo} (s/s) = 0.0(3.1)x10^{-13}
P''_{topo} (s/s^2) = 0.0(6.9)x10^{-16}
P_{bary} (ms) = N/A
P'_{bary} (s/s) = N/A
P''_{bary} (s/s^2) = N/A

Binary Parameters

P_{orb} (s) = N/A
$a_1\sin(i)/c$ (s) = N/A
T_{peri} = N/A
e = N/A
ω (rad) = N/A

P = 5 ms

SNR 42 sigma



Candidate: PSR_2144−5237
Telescope: GMRT
Epoch_{topo} = 57956.82344992070
Epoch_{bary} = N/A
T_{sample} = 8.192e−05
Data Folded = 35712000
Data Avg = 1.177e+05
Data StdDev = 1355
Profile Bins = 64
Profile Avg = 6.567e+10
Profile StdDev = 1.012e+06

RA_{J2000} = 21:44:00.0000
DEC_{J2000} = −52:37:00.0000

Folding Parameters

DOF_{eff} = 40.39 χ^2_{red} = 401.625 P(Noise) ~ 0
Dispersion Measure (DM; pc/cm^3) = 19.551
P_{topo} (ms) = 5.041226664(36)
P'_{topo} (s/s) = 0.0(9.6)x10^{-14}
P''_{topo} (s/s^2) = 0.0(2.1)x10^{-16}
P_{bary} (ms) = N/A
P'_{bary} (s/s) = N/A
P''_{bary} (s/s^2) = N/A

Binary Parameters

P_{orb} (s) = N/A
$a_1\sin(i)/c$ (s) = N/A
T_{peri} = N/A
e = N/A
ω (rad) = N/A

Thank you