Radio Astronomy signal processing back-end

Correlator and Pulsar receiver

Jayanta Roy

NCRA – TIFR, Pune, India

@ RAS on 7th July 2011

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

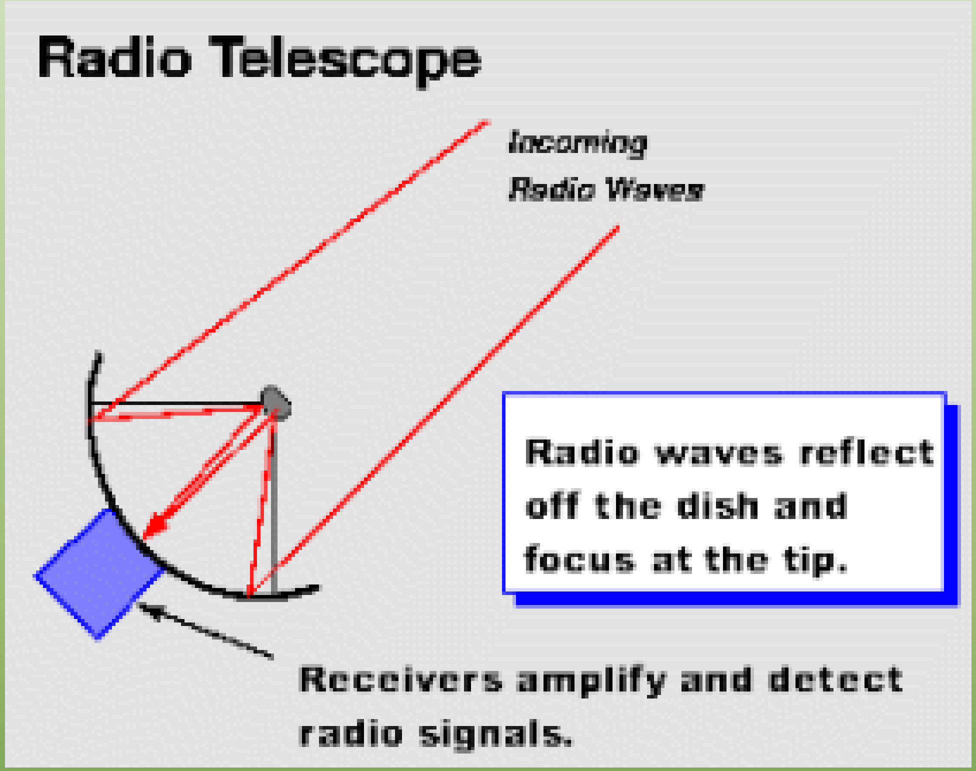
- For high sensitivity (to see faint sources out to the distant part of the universe)

  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



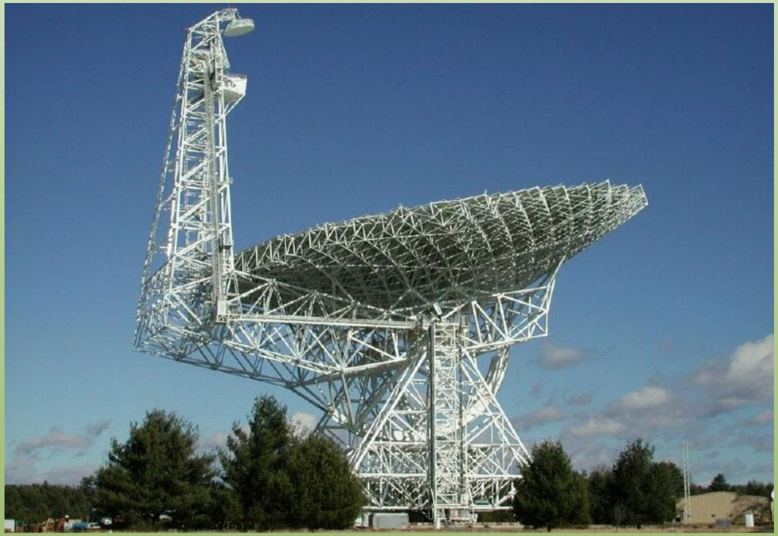
- Celestial radio signals are VERY weak ; unit of flux used is :
  $1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W} / \mathrm{m}^2 / \mathrm{Hz}$

- 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)



The new 100-m Greenbank Telescope

- 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 Very Large Array Telescope

Introducing a modern radio telescope array: The GMRT

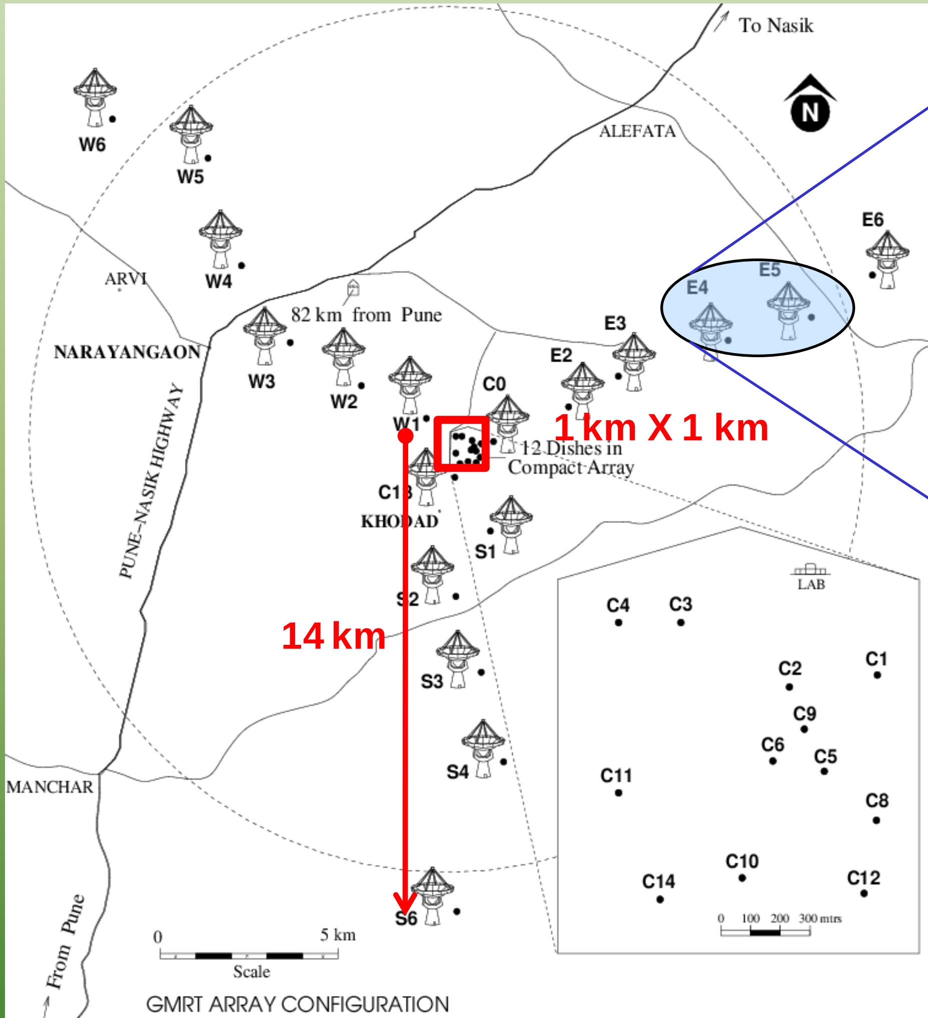
- The Giant Metre-wave Radio Telescope (GMRT) is a new, world class instrument for studying astrophysical phenomena at low radio frequencies (150 to 1450 MHz)

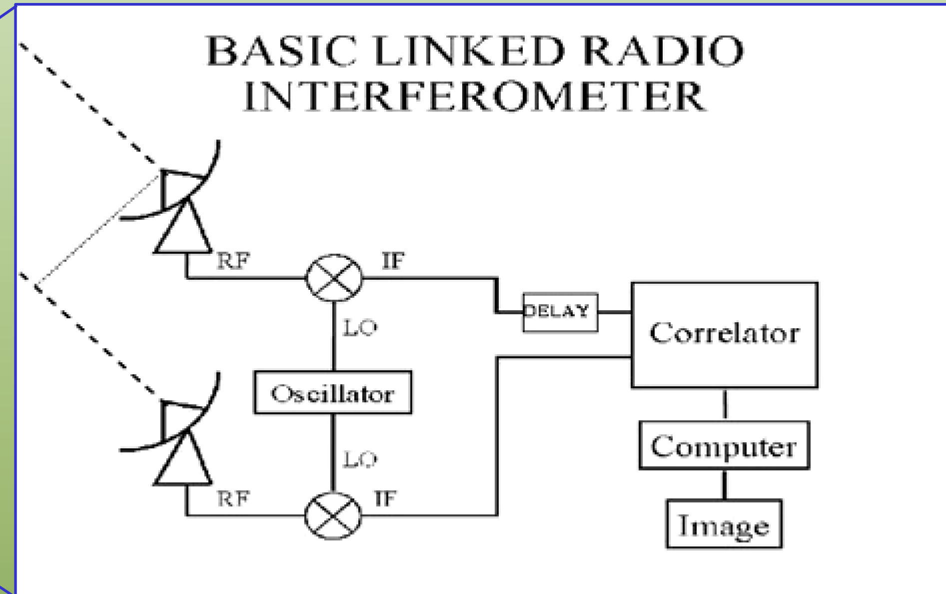
- Designed and built primarily by NCRA, a national centre of TIFR.

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

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^2 such instantaneous measurement s (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

Digitization of signals

Sampling

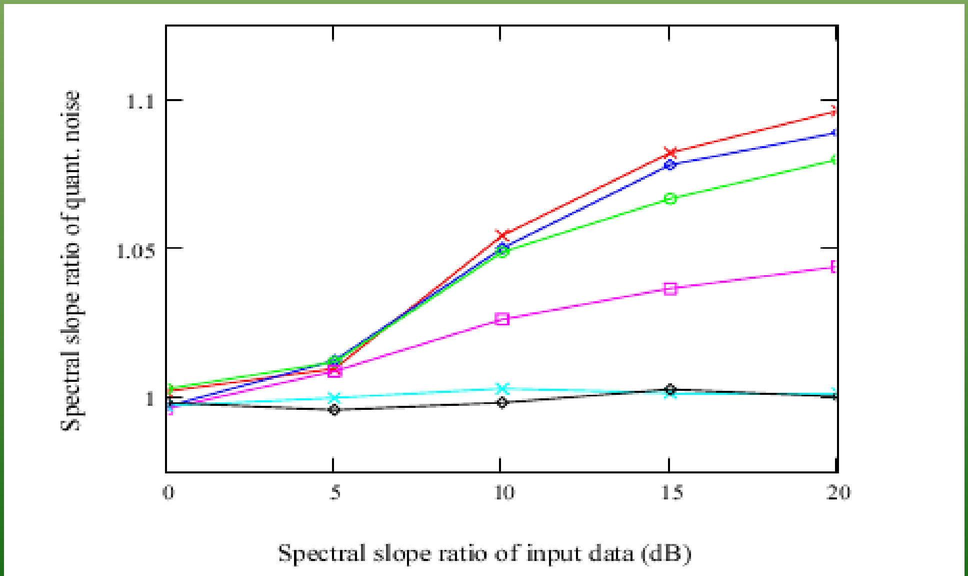
Band-limited signal down-converted to baseband sampled at Nyquist rate
32 MSPS with 8 bits per sample

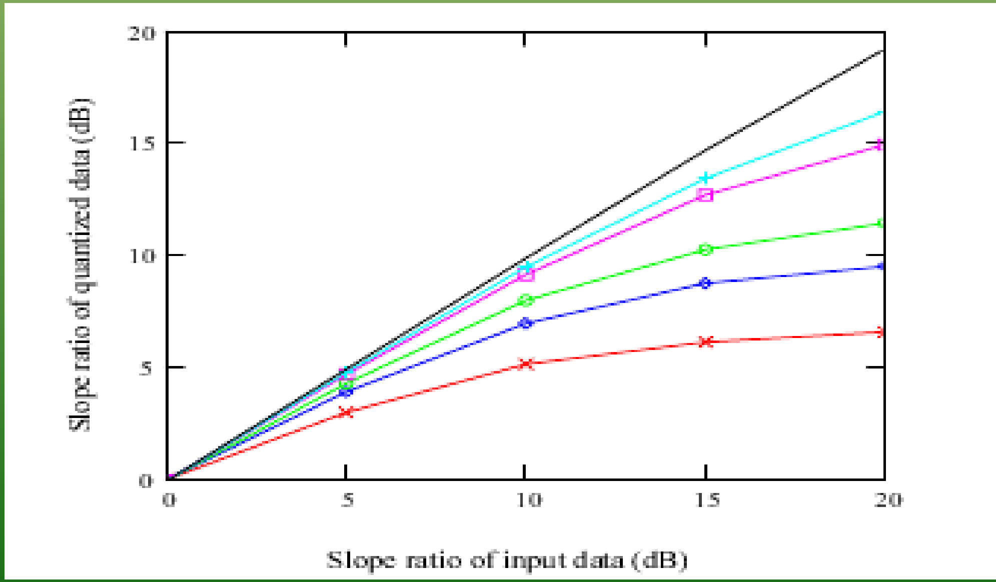
Quantization

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

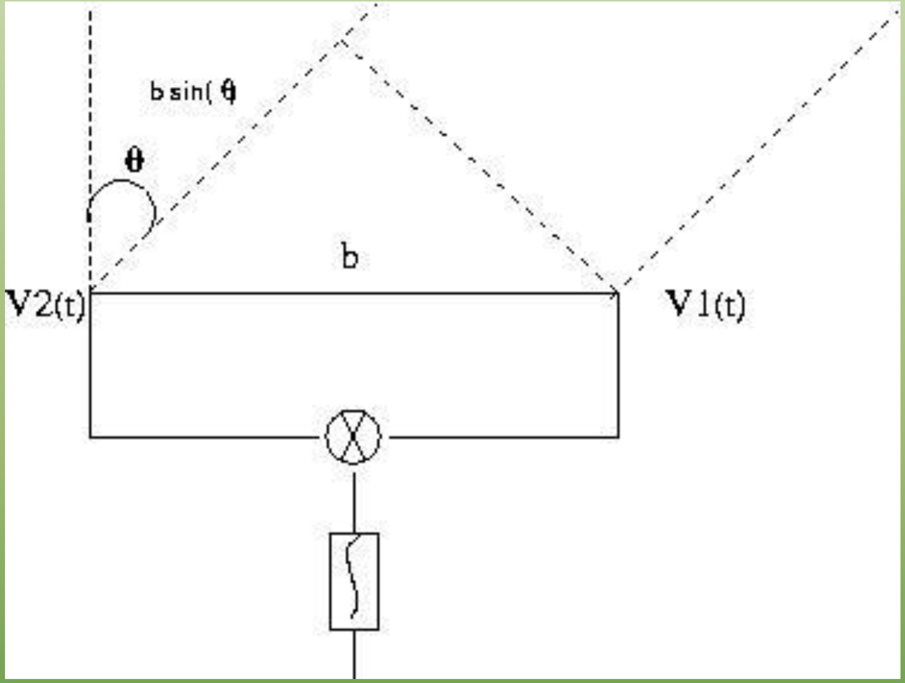
No. of levels	Quantize efficiency
3	80.9%
8	96.25%
16	98.84%
32	99.65%
256	99.99%





Delay and fringe correction

Interferometer measures the spatial coherence function of the incident electric field



τ = B/C Cos(θ)

dτ/dt = B/C Sin(θ) dθ/dt

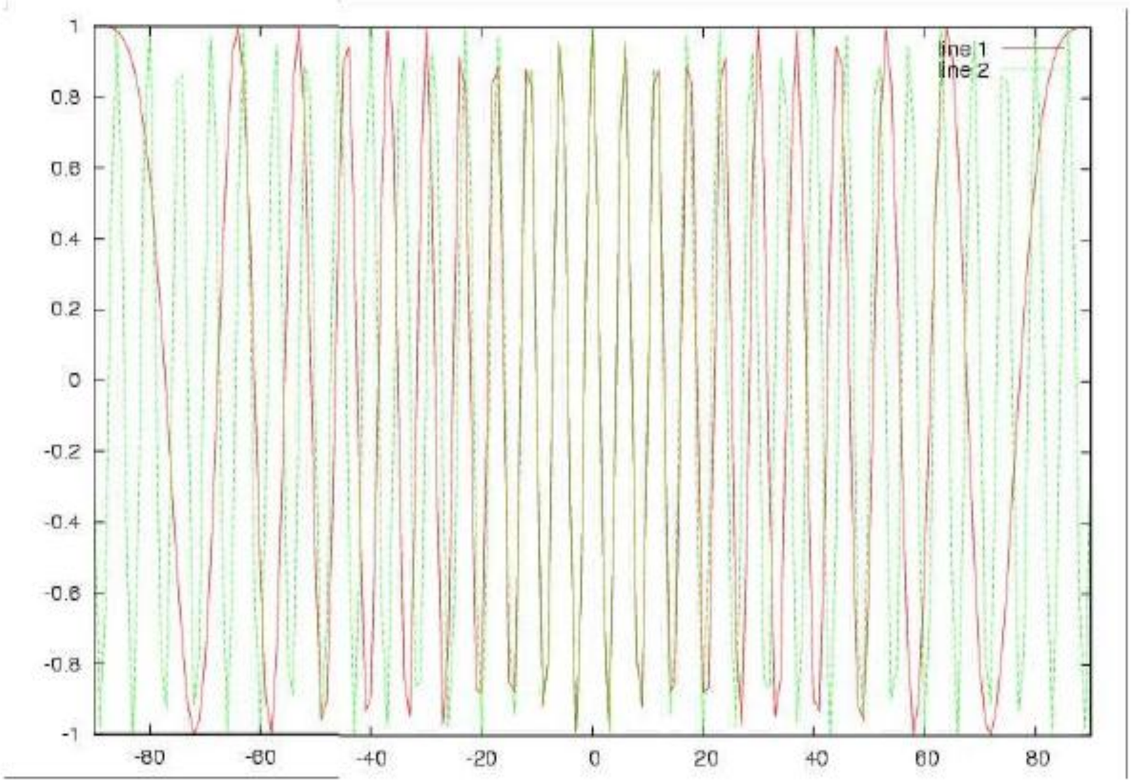
Signals arrive at Correlator from different Antennas have different *propagation* and *instrumental* delay.

Monochromatic radiation

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

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

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



Try with different b and ν combinations

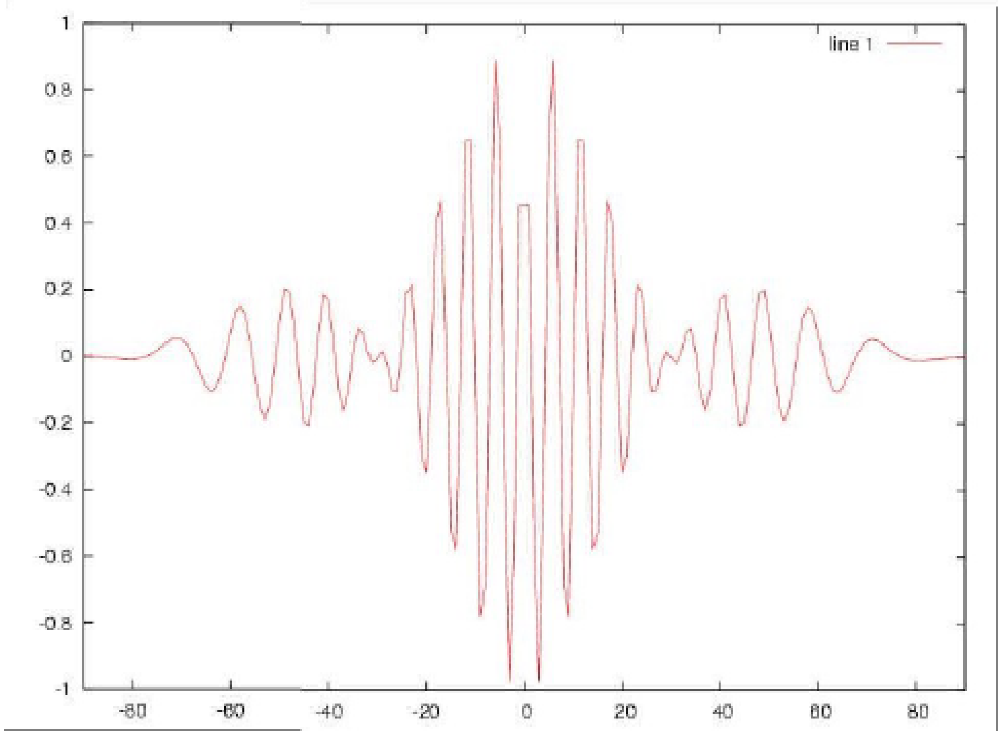
Fringe rate is maximum at zenith and minimum when source is rising or setting

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 : $\cos(2\pi\nu\tau_g)\dfrac{\sin(\pi\Delta\nu\tau_g)}{\pi\Delta\nu\tau_g}$



Increase $\Delta\nu$ to see how fringe amplitude decreases

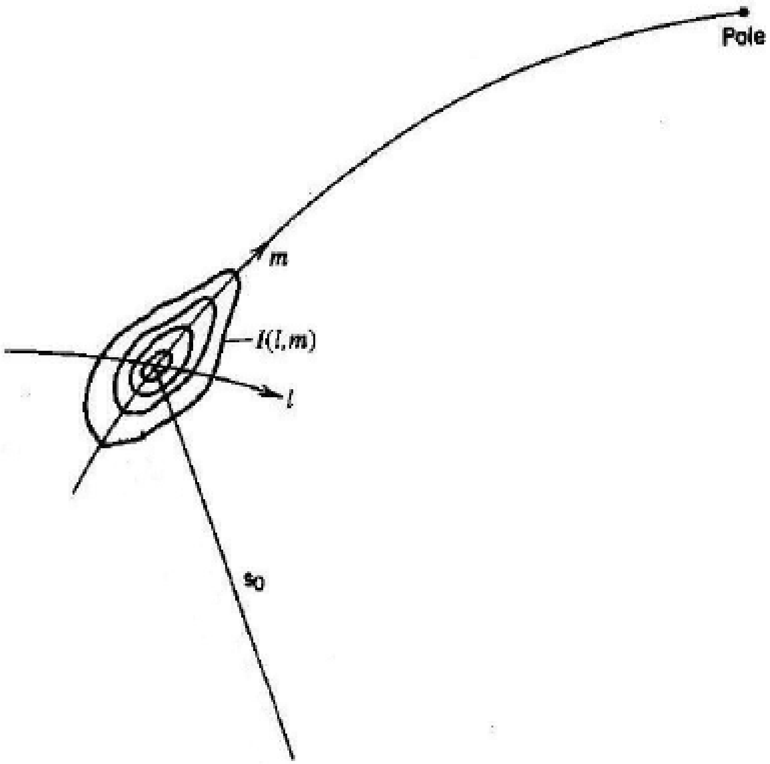
Increase $\Delta\nu$ without loosing fringe amplitude !!

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

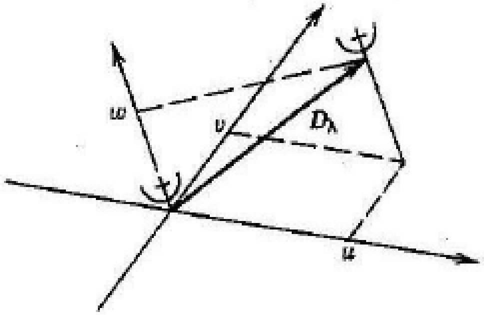
$$u_\lambda = X_\lambda \sin(H) + Y_\lambda \cos(H)$$

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

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



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 :

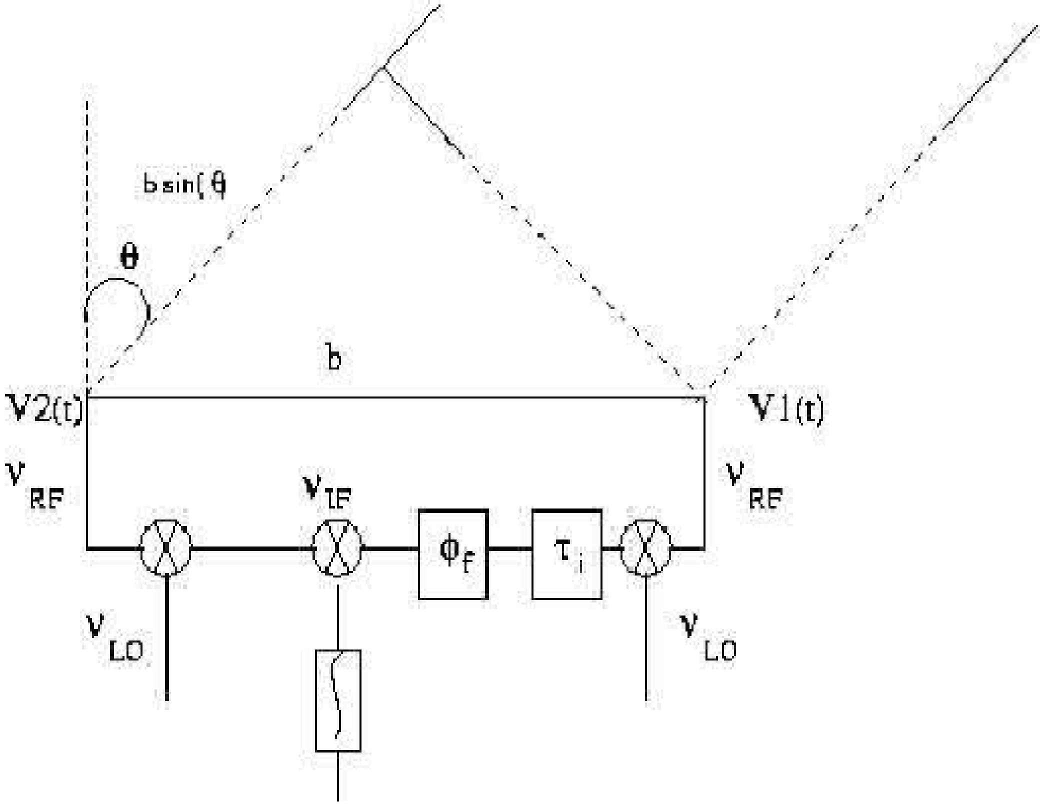
Delay $\tau_g = \frac{w}{c}$

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



<u>Delay suffered at RF frequency</u>

<u>Correction applies at IF frequency</u>

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

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

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

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

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

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

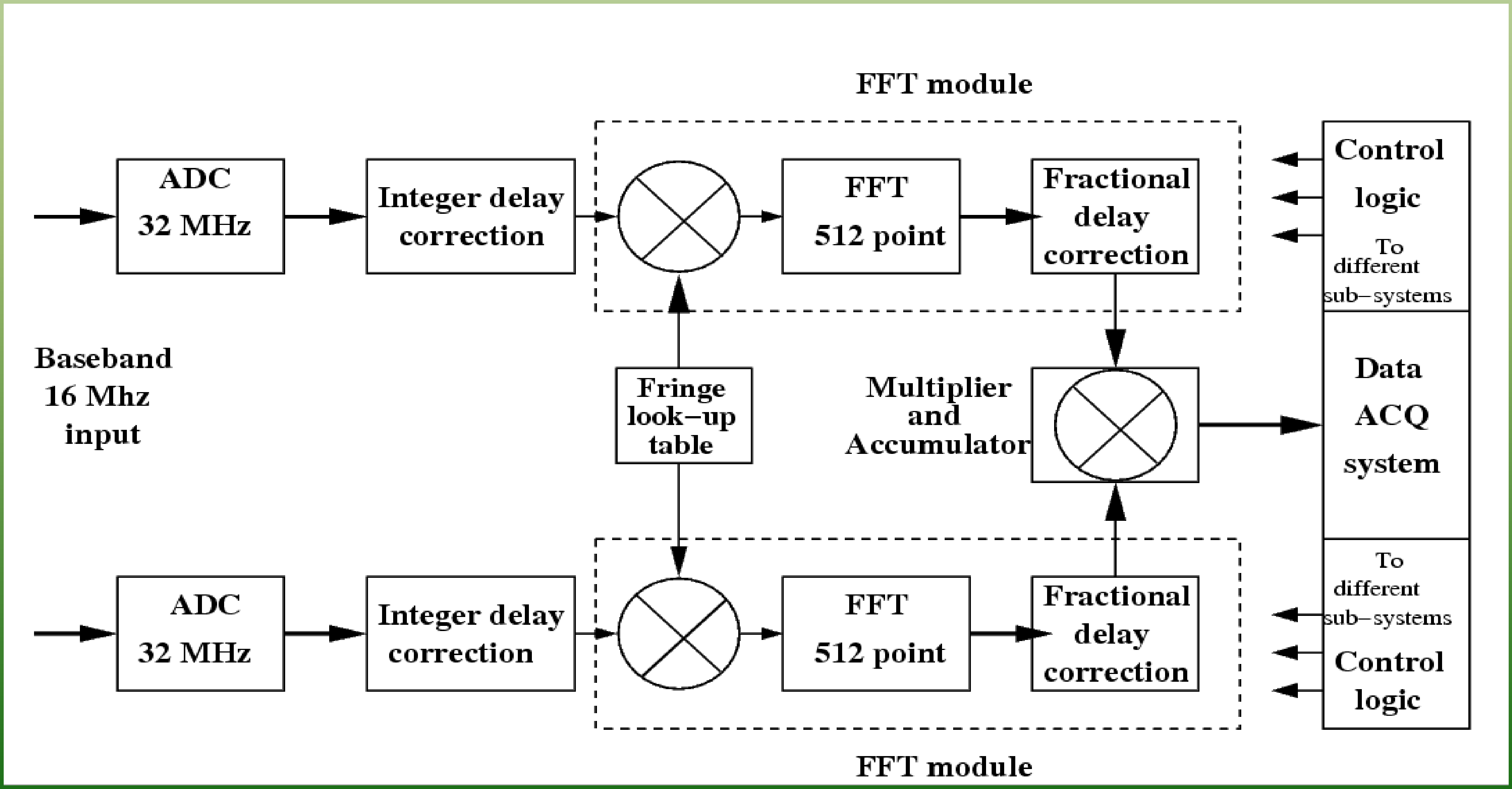
$$\boxed{(\tau)_{\max} = 150\mu s}$$

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

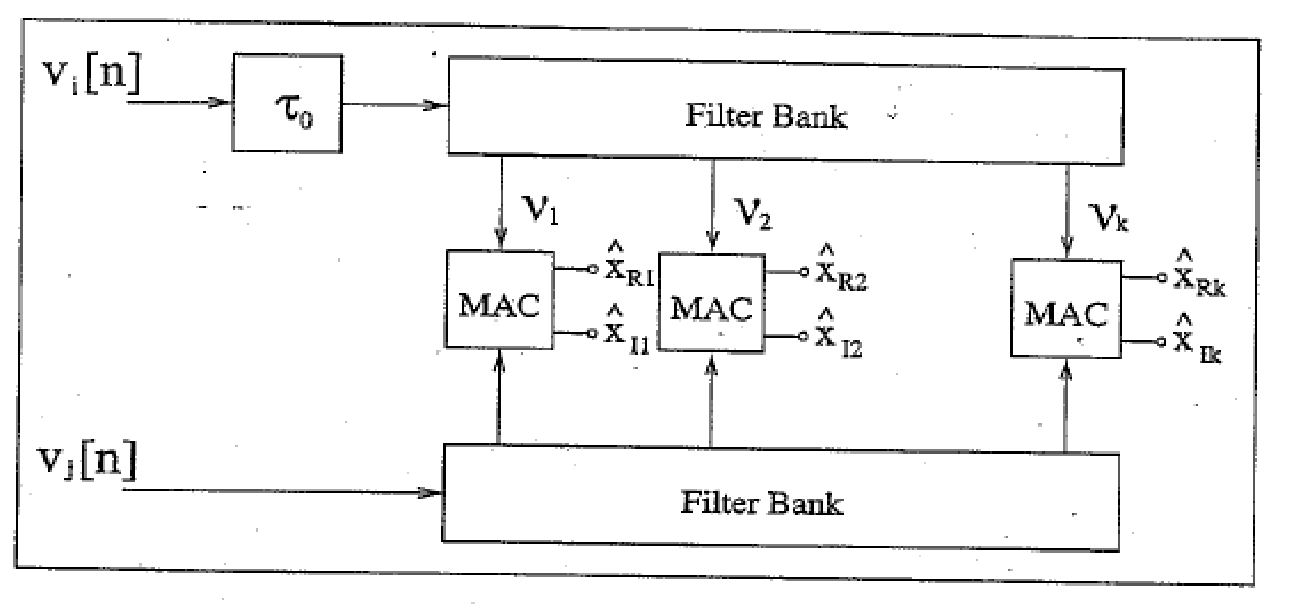
$$\boxed{\Delta\tau = 2ns}$$

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

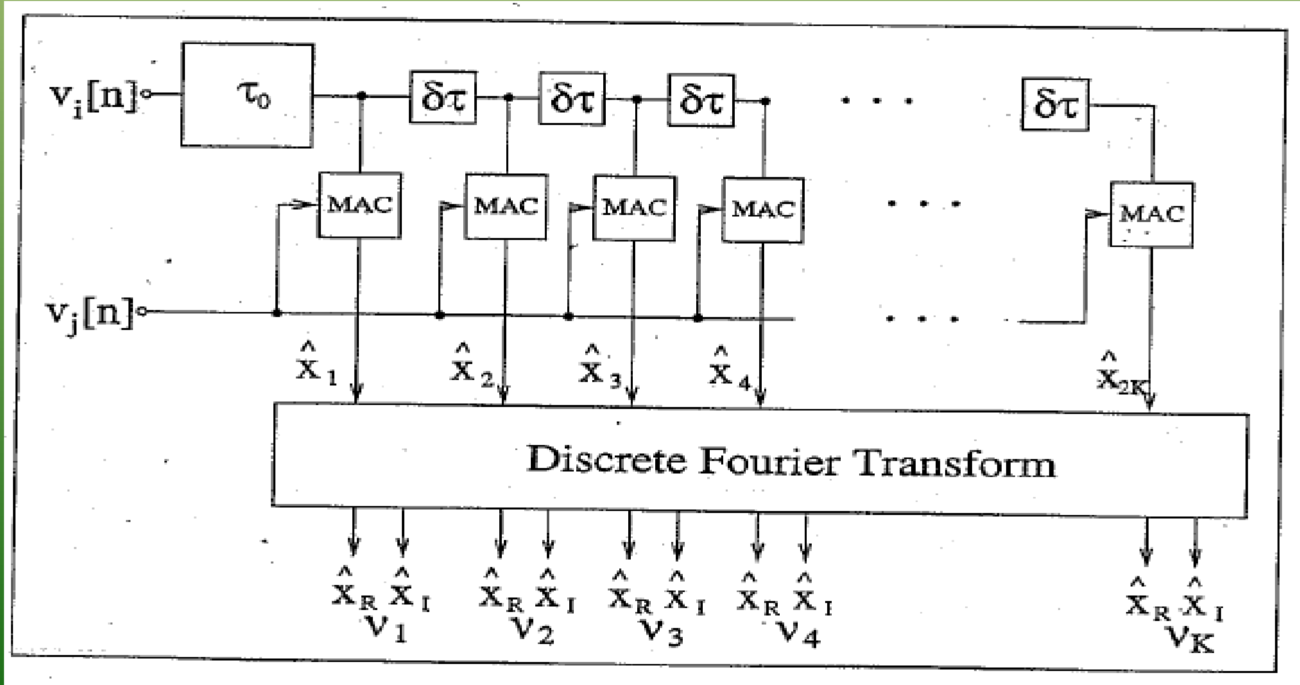


FX correlator

*~ 4*Na* BW * log(NFFT) +*

*2*BW * Na*(Na + 1)*

*= 4*Na*BW[log(NFFT)+(Na+1)/2] Cops*



XF correlator

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

[1 + log(NFFT)]

Cops

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

Compute loads of various functional blocks

- Simultaneous operation as
  - FX correlator as an Imaging instrument
  - Beamformer as a Pulsar receiver
- Input data rate : 2 Gsamples/s
- Required Compute load : 487 Gflops

FFT (181 Gflops
+
Fringe rotator (8.25 Gflops)

MAC (280 Gflops)

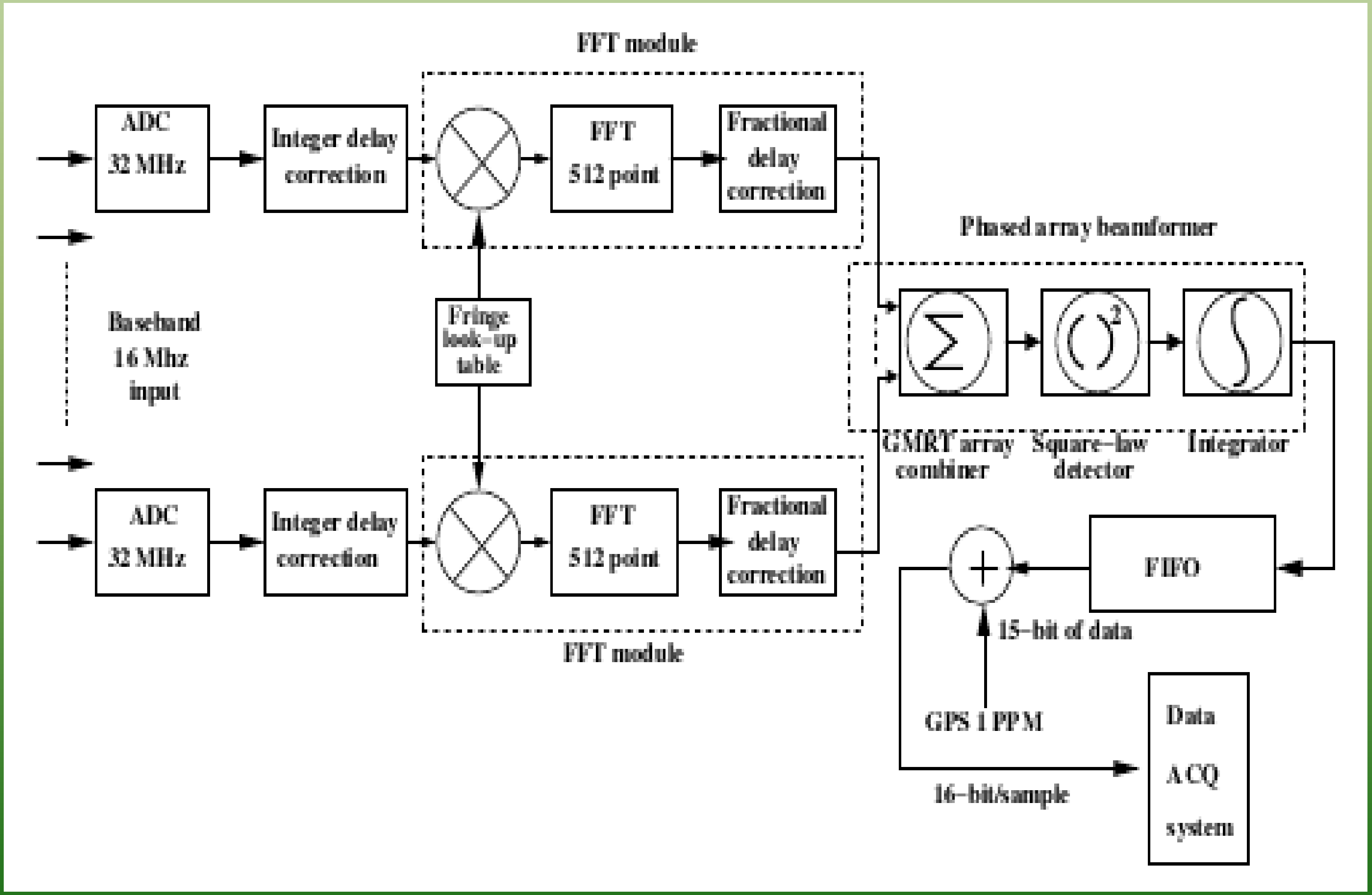
Beamformer (17 Gflops)

- Output data rate :
  - MAC output : 4 MB/s
  - Beamformer output : 128 MB/s
- Design scope : ASIC + FPGA or HPC

Array Beamformer : A pulsar receiver

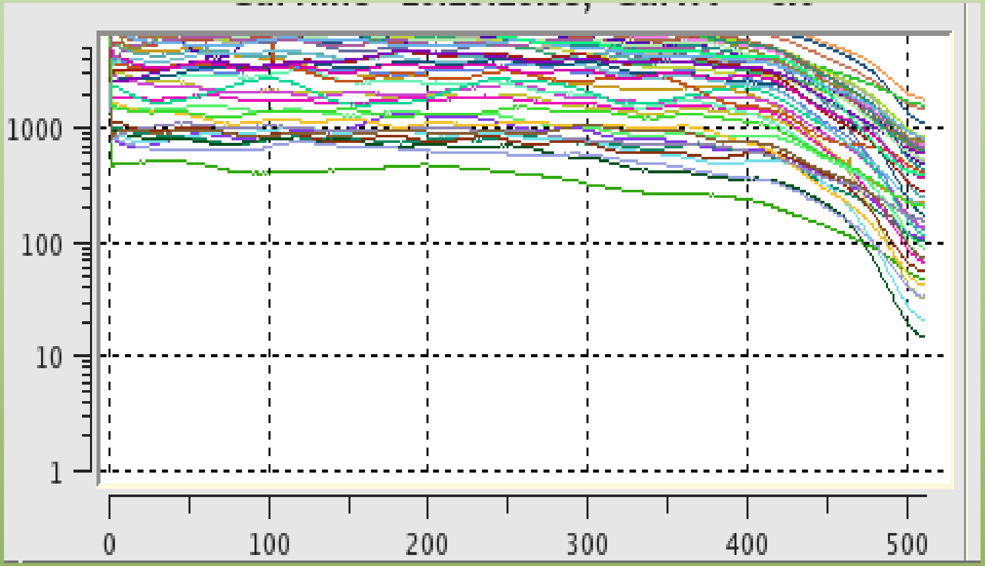
Incoherent array mode : signals from the antennae are added in intensity

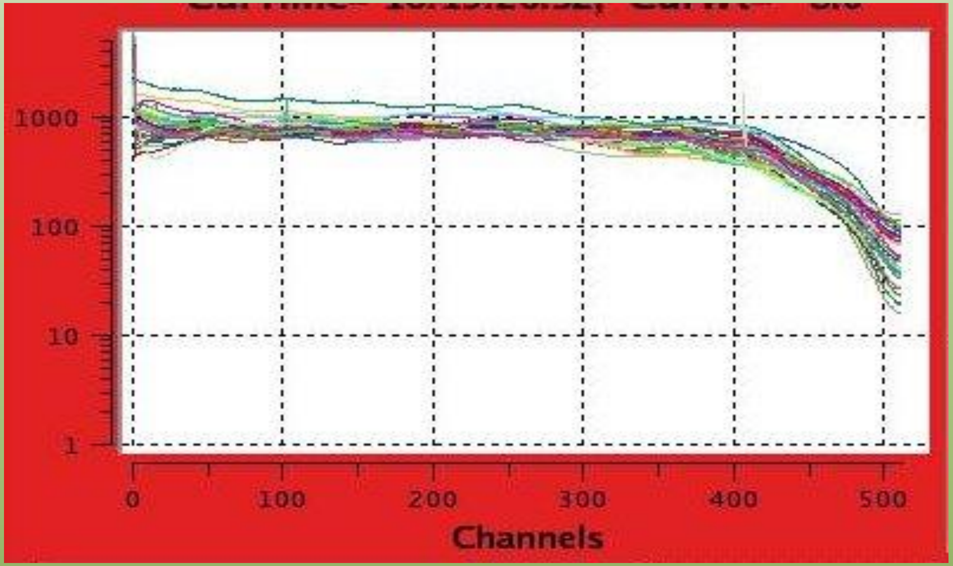
Phased array mode : Signals from the antennae are added in voltage

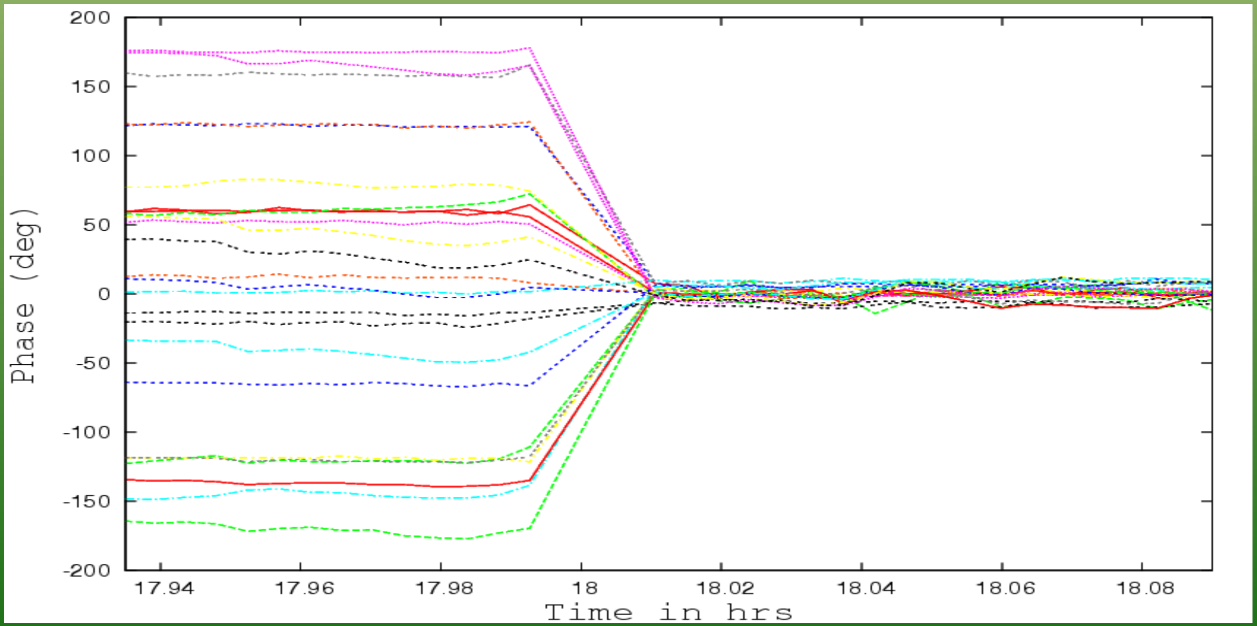


Amplitude and phase calibration for beamformer

Antenna based gain offset correction







Antenna based phase offset correction

Incoherent array Vs Phased array

In Incoherent array mode, the voltage samples from selected antennae are added after converting to intensities

$$V_{IA} = \left\langle \sum_{i=1}^{n} V_i \right\rangle^{2}$$

In coherent/phased array mode, the voltage samples from selected antennae are first added and then converted to intensities

$$V_{PA} = \left\langle \left(\sum_{i=1}^{n} V_i \right)^{2} \right\rangle$$

Mode	Sensitivity	Beam-width
IA	Sqrt(Na)	Primary beam
PA	Na	Synthesized beam

Highly sensitive, narrow phased array mode is used for detailed study known pulsars, whereas broader incoherent array beam is suitable for rapid surveying of the sky.

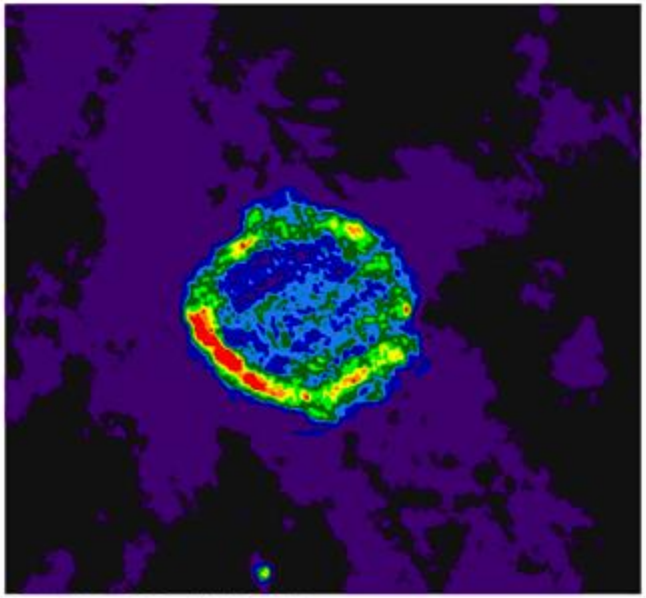
Sensitivity of a correlator

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

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

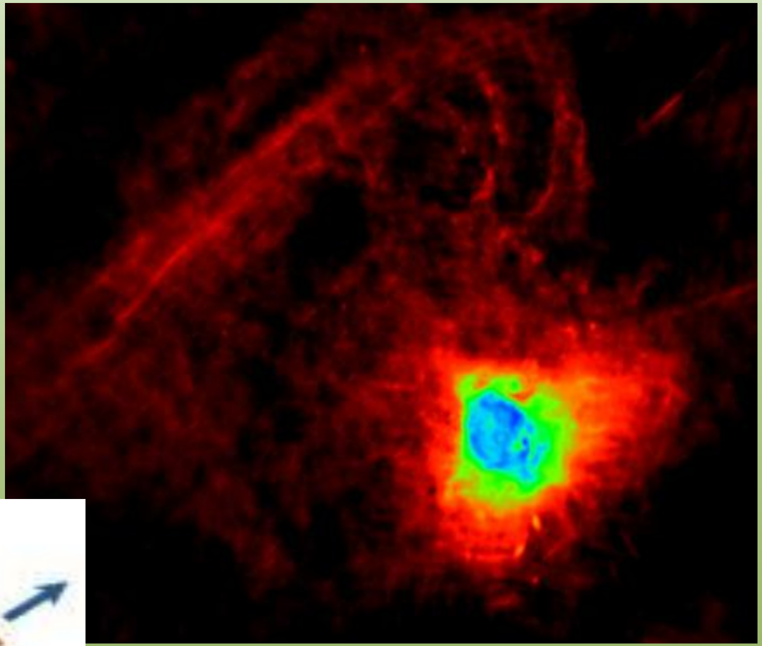
More sensitive array = large element array + wide-band system + low-noise receiver + large-efficient aperture telescope

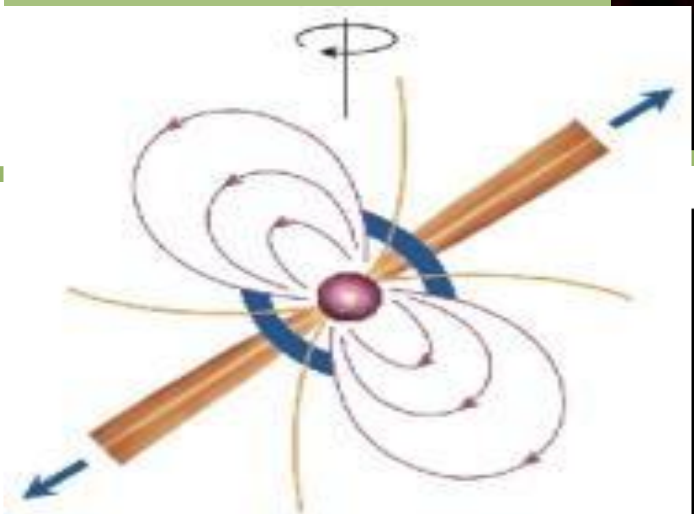
The world of Radio Astrophysics

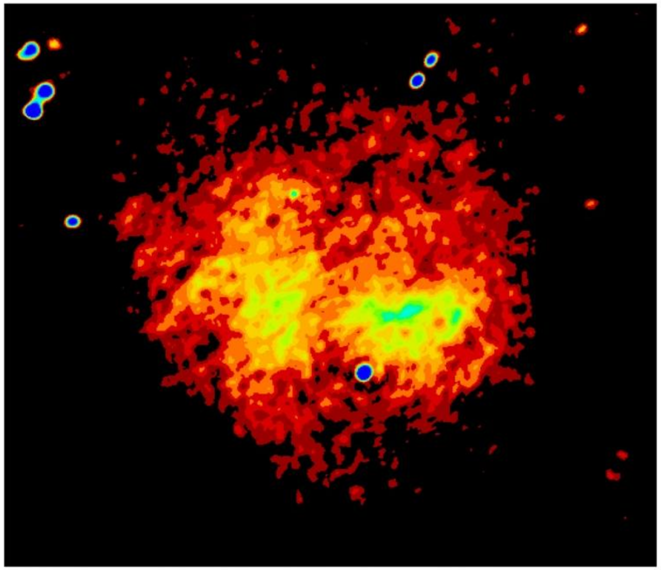


G11.2-0.3 OBS. ANIL SETH

- Supernova Remnants
- Centre of the "Galaxy"
- H II region
- Pulsars
- Radio galaxy

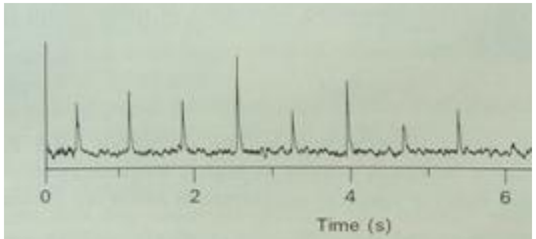




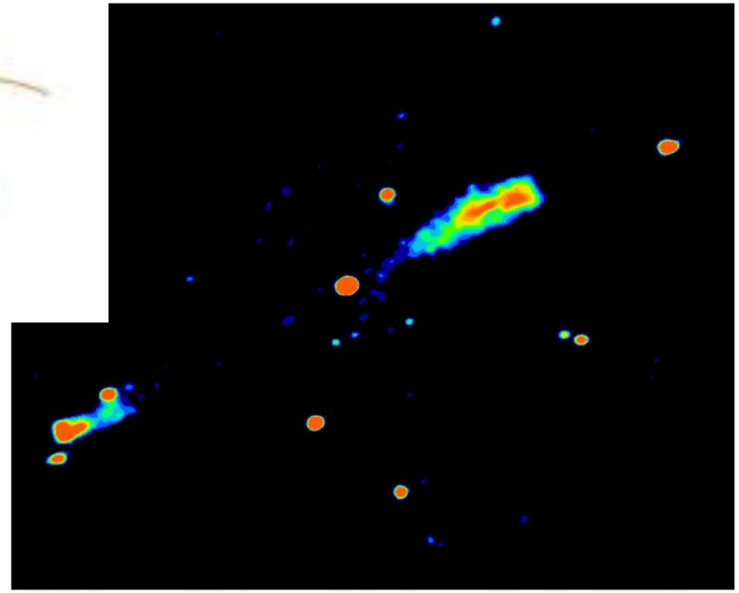


GMRT image of the H II region S184 at 325 MHz

(S. Roy, 29.07.99)



1-3 Chart record of individual pulses from one of the firs
discovered, PSR 0329+54. They were recorded at a f
410 MHz and with an instrumental time constant of
occur at regular intervals of about 0.714 s.



GMRT image of the largest Radio Galaxy 3C236 at 325 MHz

(S. Roy 18.08.99)

Rationale for a HPC back-end for Radio Astronomy

- Easy reconfigurability for higher frequency and time resolution
- More bits per sample ➔ possibility for better dynamic range : for better protection against radio frequency interference (RFI)
- Ability to add sophisticated algorithms to detect and filter out RFI signals at various stages in processing pipeline
- Ability to record raw voltage data from each antenna and play back with different options of parameter space
- Easy scalability for larger bandwidth and no. of antennae

HPC back-ends for Radio Astronomy :
Moving from Off-line to Real-time

Exponentially growing need for (highly energy-efficient and simple to manage) high performance storage and compute power within limited research funds.

- DiFX software correlator designed by Swinburne University of Technology, Australia is the first distributed computing instrument using off-line parallel processing (Deller et al 2007).

- GMRT software back-end (GSB) using a 50 nodes Linux cluster is the first implementation of a fully real-time software pipeline as a regular observatory back-end (Roy et al 2010) . Benchmarked to be 8 times faster than the DiFX.

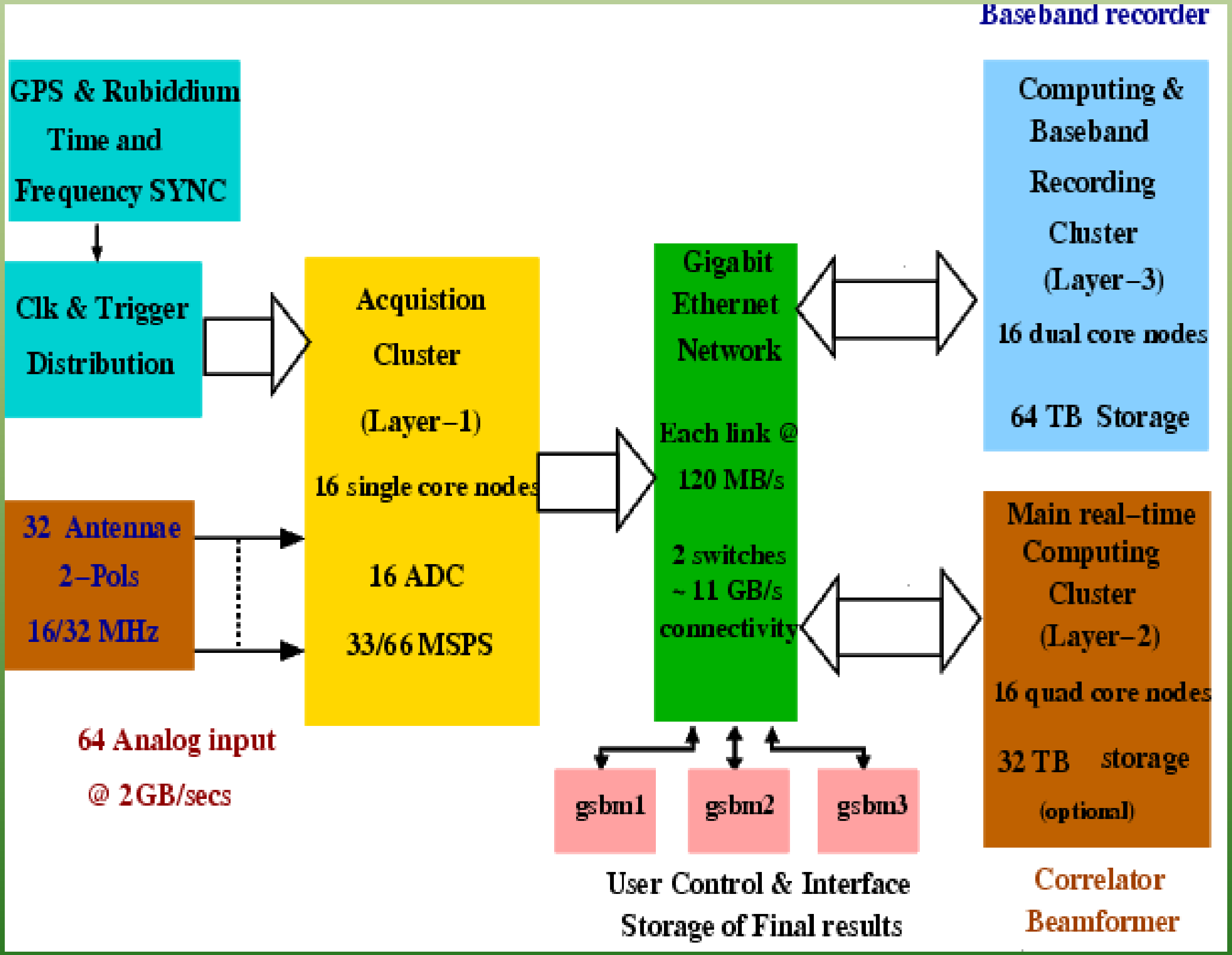
- Upcoming Blue-Gene based central processing unit for the LOFAR telescope at Netherlands will also be another such real-time back-end (Romein et al 2006).

- Proposed Peta-scale computing system for Square Kilometre Array (SKA)

GSB Schematic

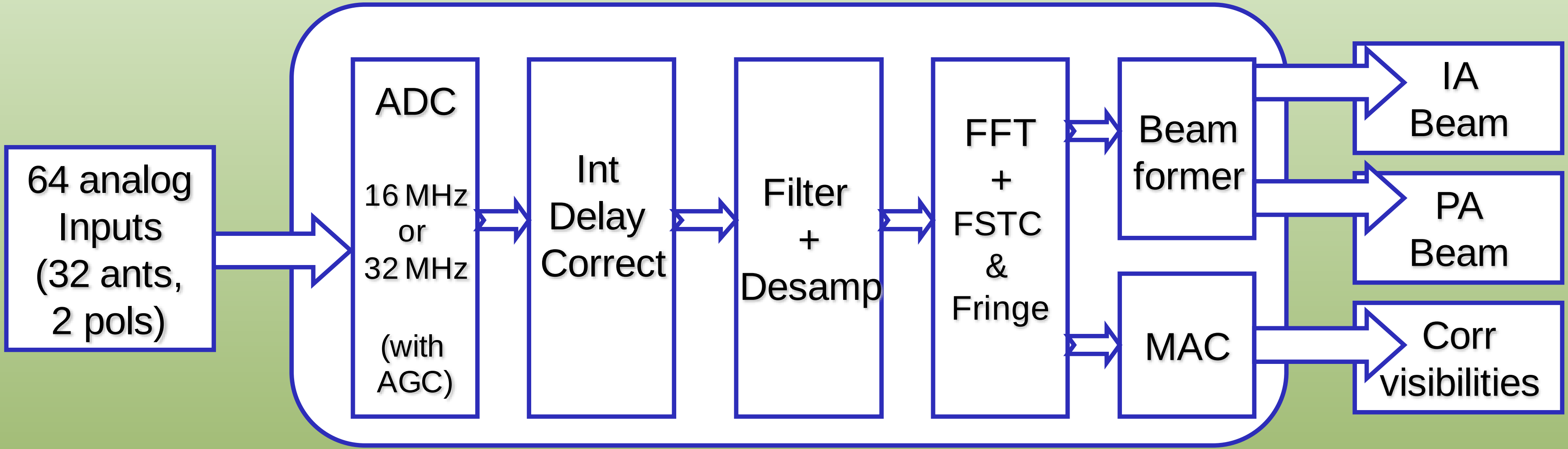
Input data rate :

- 32 antennae x 2-pols base-band analog inputs @ 16/32 MHz of bandwidth
  - 2 GSamples/sec (using 16 ADC cards with 4 analog inputs in each card)



- 232 cores Intel Xeon CPUs
- Each node with 2 GB RAM
- Dual GbE network interface for input data streaming
- Dual add-on GbE network interface for high time resolution output data streaming
- 3.9 Tflops @ 15kwatt
- Max output streaming ~ 3.5 TB/hour
- Storage : 128 TB

GSB functional schematic



- *Correlator specs :* Spatial resolution = 250Hz – 125kHz

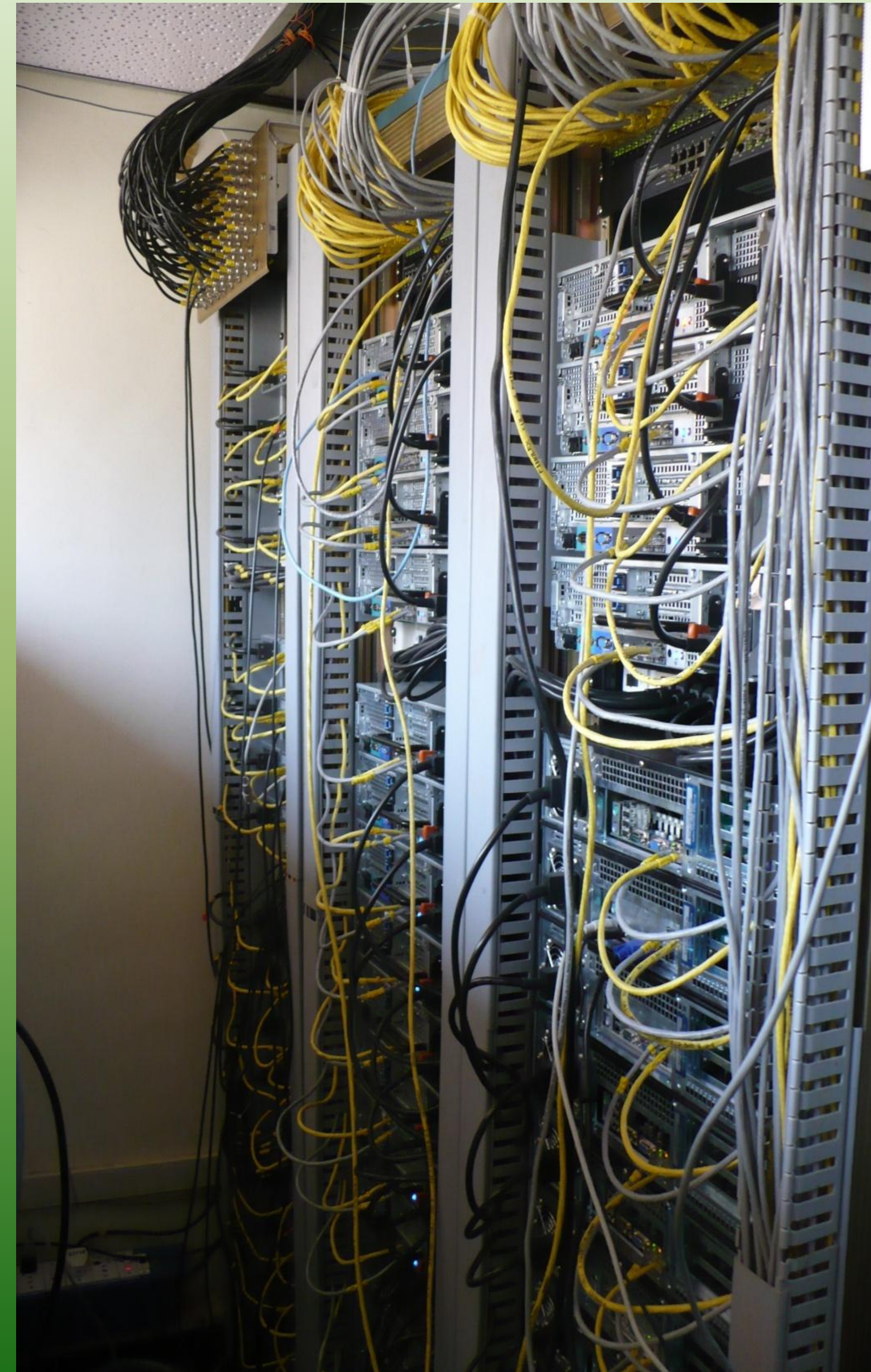
  Temporal resolution = 250ms – 16s

  Max output data rate = 28 GB/hour (512 ch, 528 baselines, 4 stokes @ 2s)

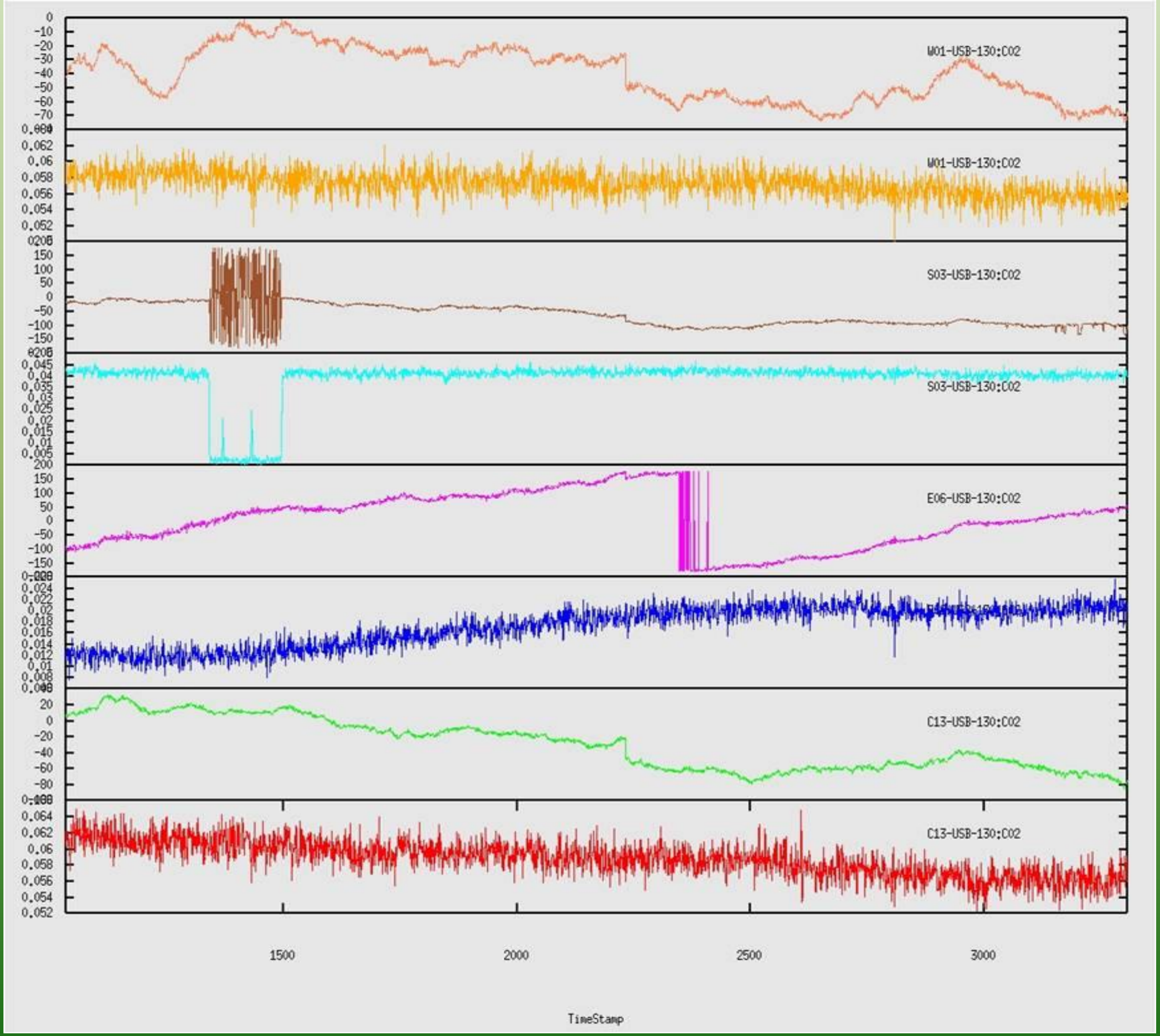
- *Beamformer :* Incoherent/Coherent intensity mode

  Temporal resolution = 30 us +

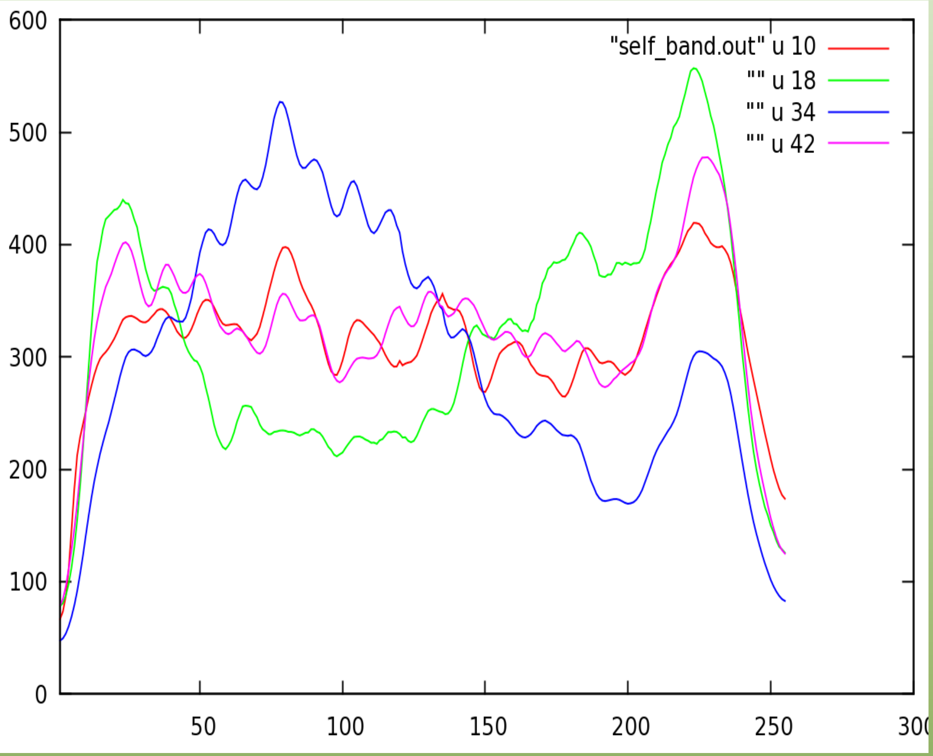
  Max output data rate = 225 GB/hour (512 ch, 4 stokes @ 60 us)

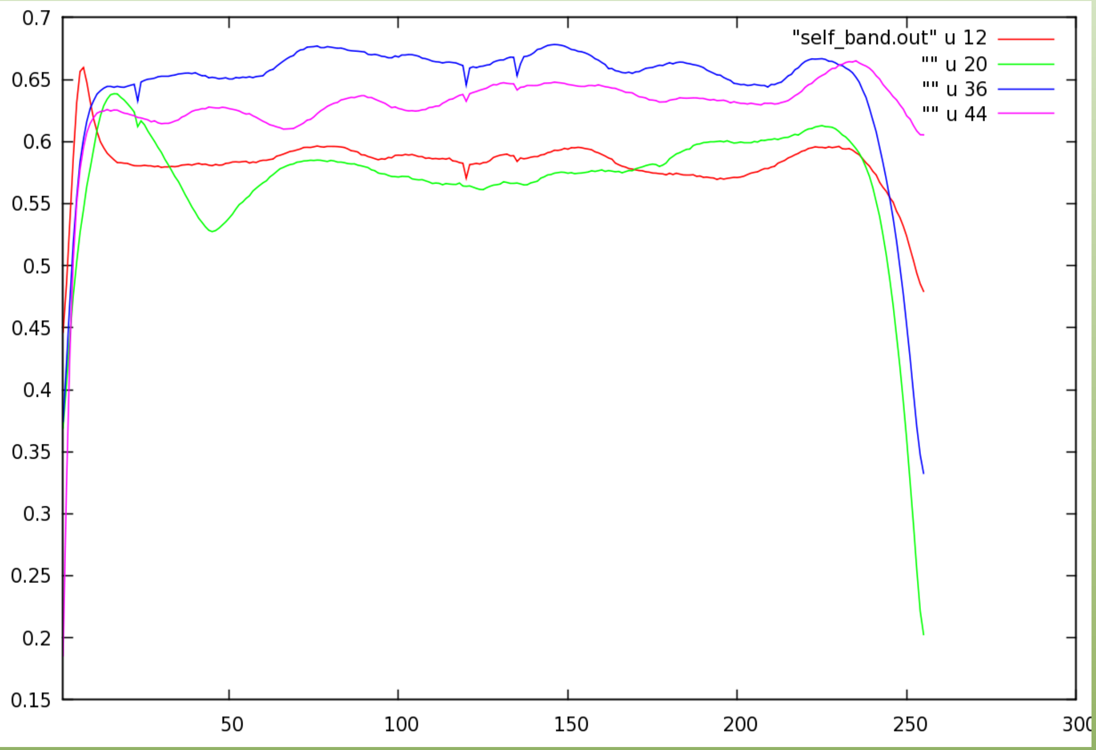


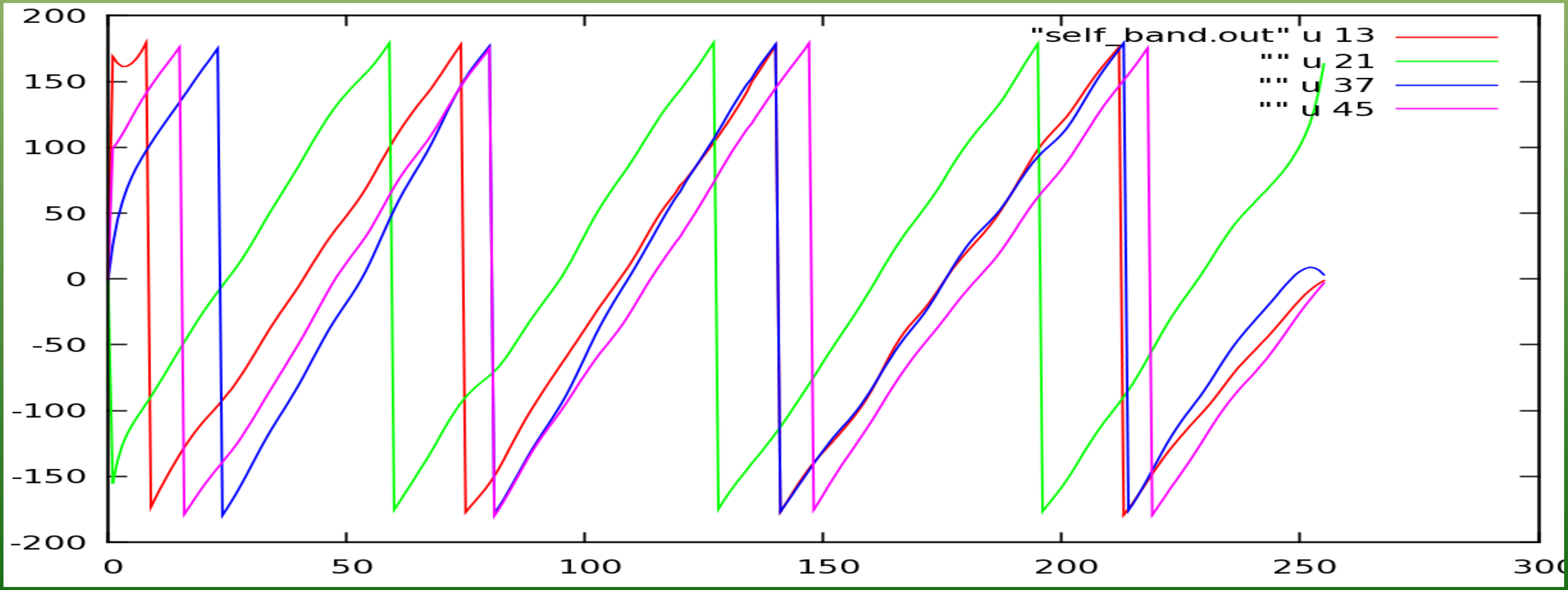
Cross correlation output



Cross spectrum in presence of correlated signals







High spectral resolution

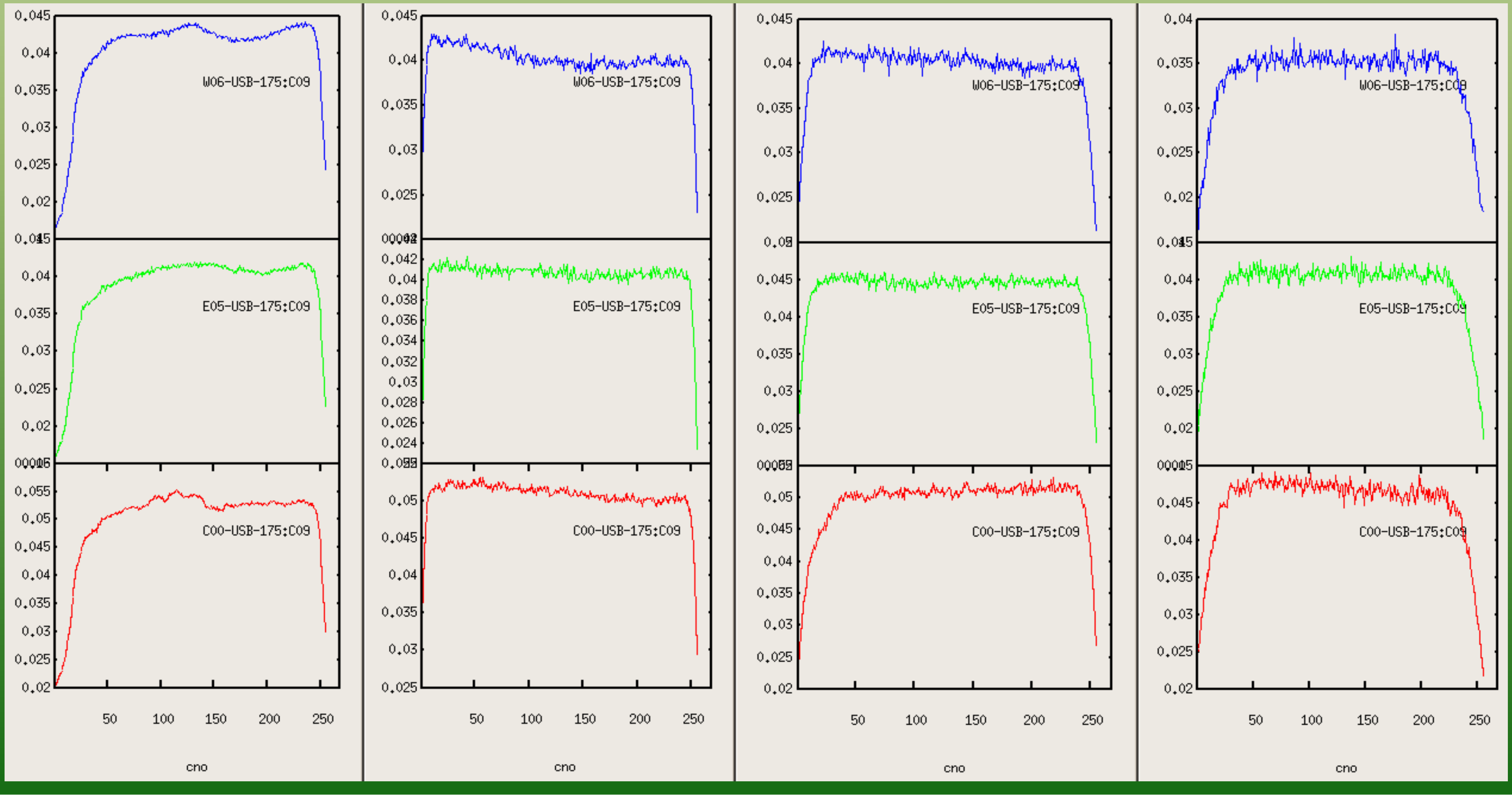
Modes / Flexibilities :

User selectable digital LPF / BPF / HPF

Choices of Spectral channels : 256 / 512

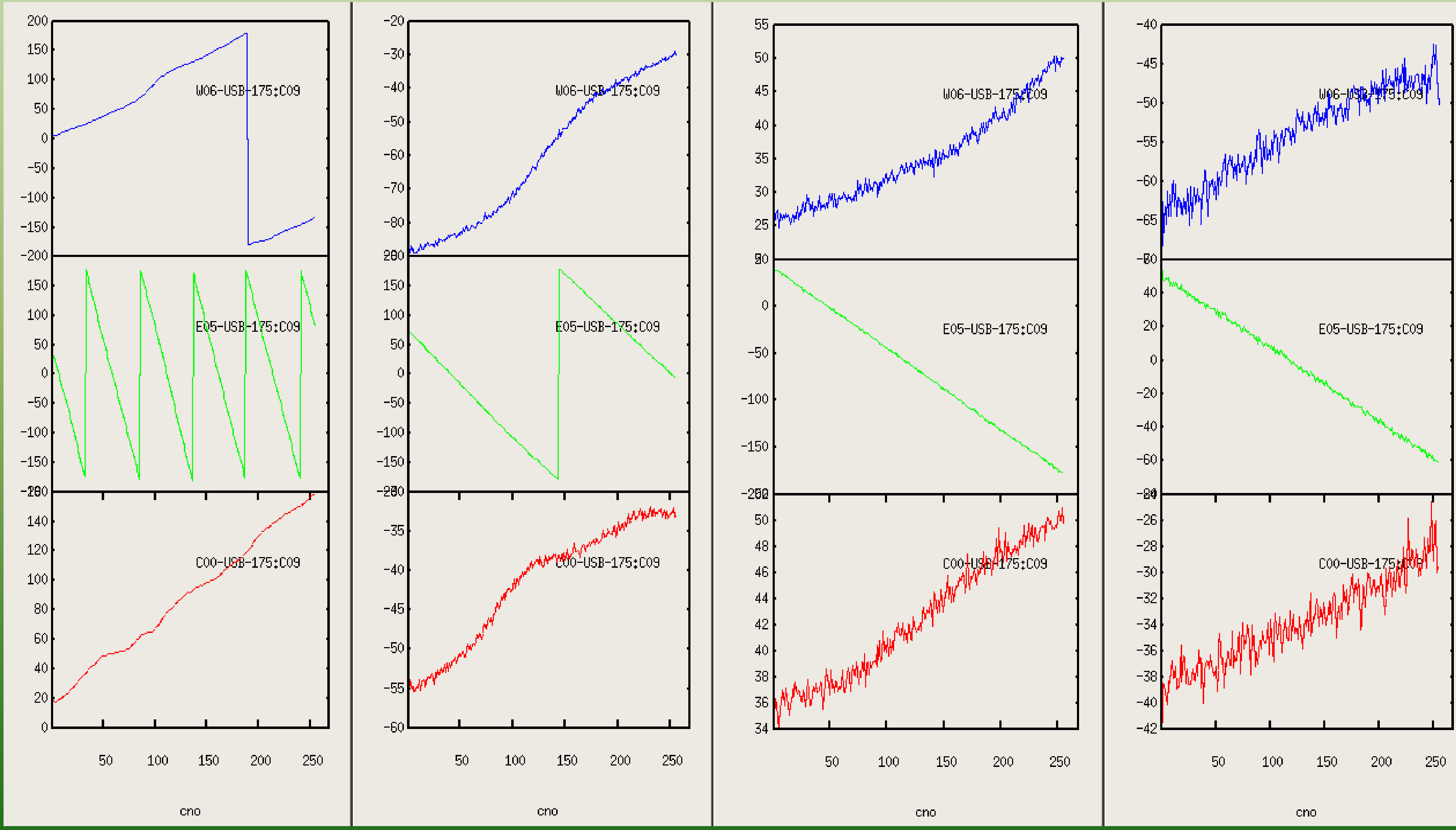
Choices of BW : 4 MHz to 125 KHz

Cross spectra amplitudes for 16 MHz / 4 MHz / 2 MHz / 1 MHz BW



High spectral resolution

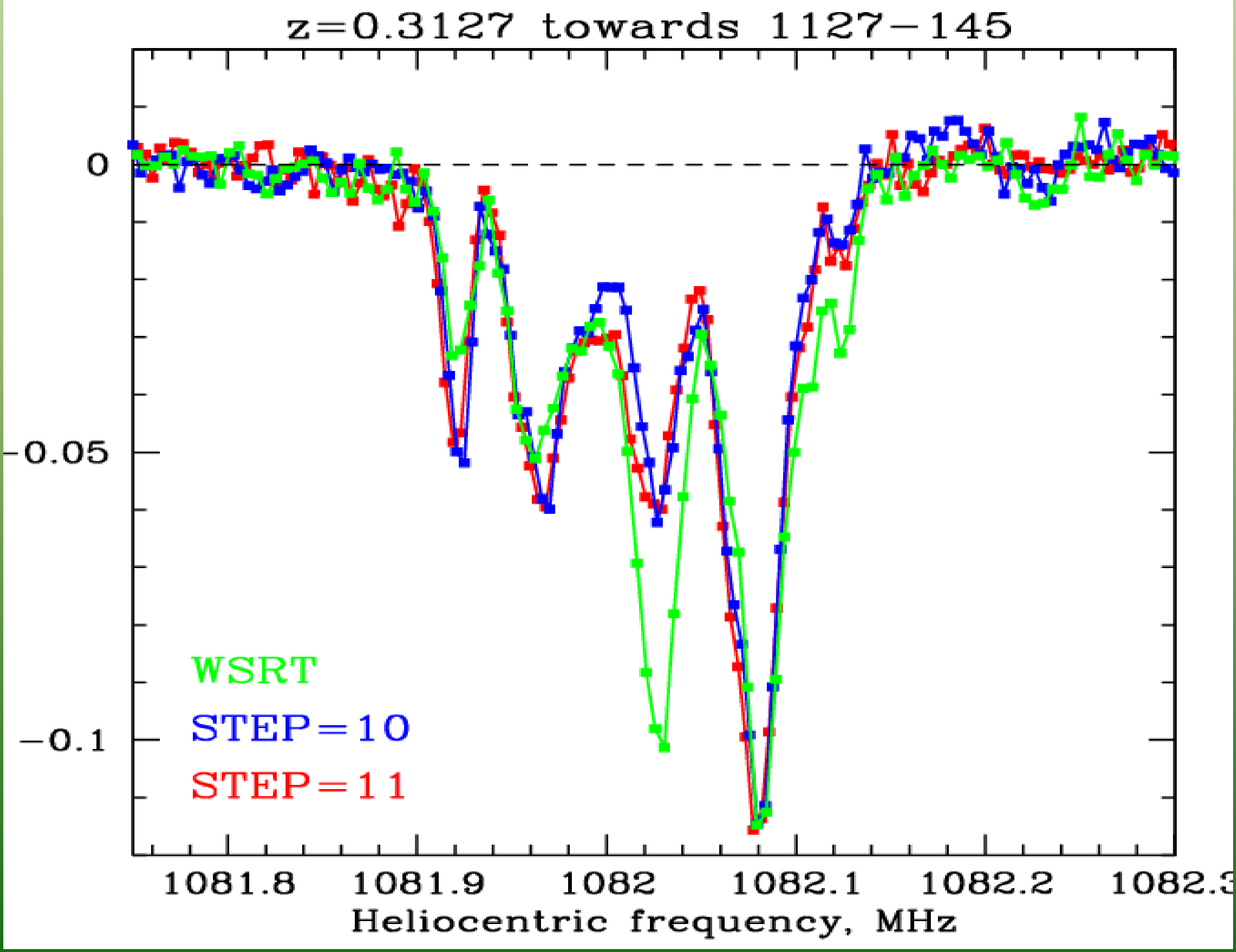
Cross spectra phases for 16 MHz / 4 MHz / 2 MHz / 1 MHz BW



Science with high spectral resolution

HI 21 cm absorption line at z=0.3127

@ 1060 MHz with GSB BW = 1.04167 MHz with two different LO-4



All 5 main spectral components are Visible

Intrinsic line variability Can cause the difference In line depth

Courtesy : Nissim Kanekar

High time resolution beamformer

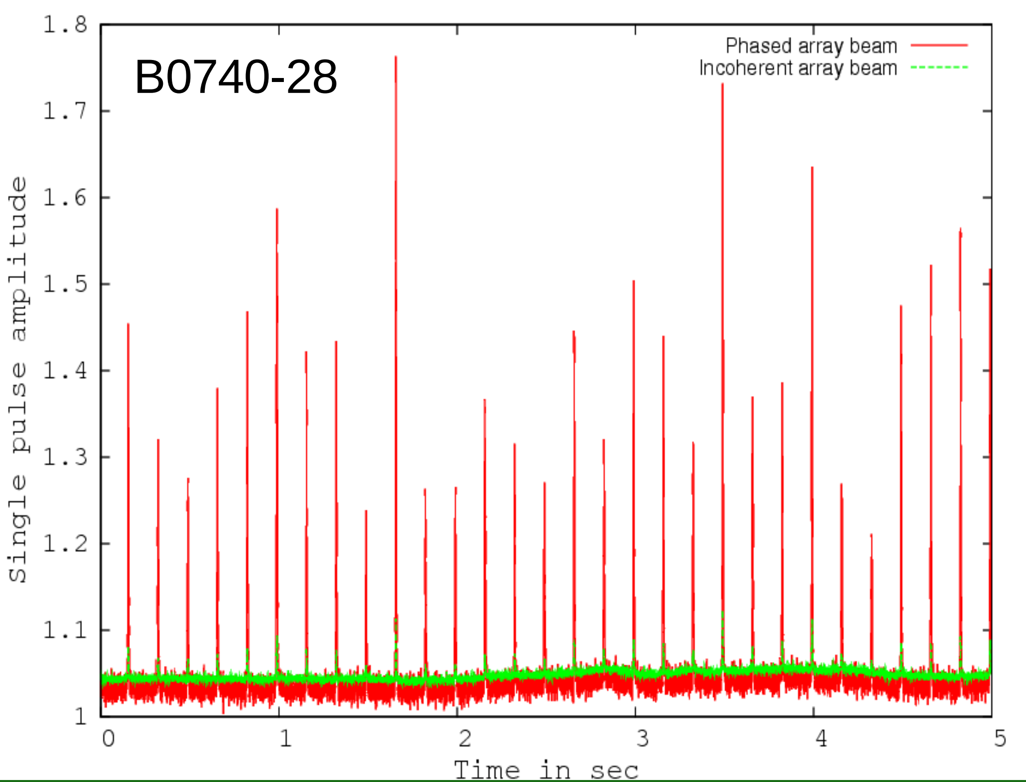
Modes / Flexibilities :

One/Two beams simultaneously

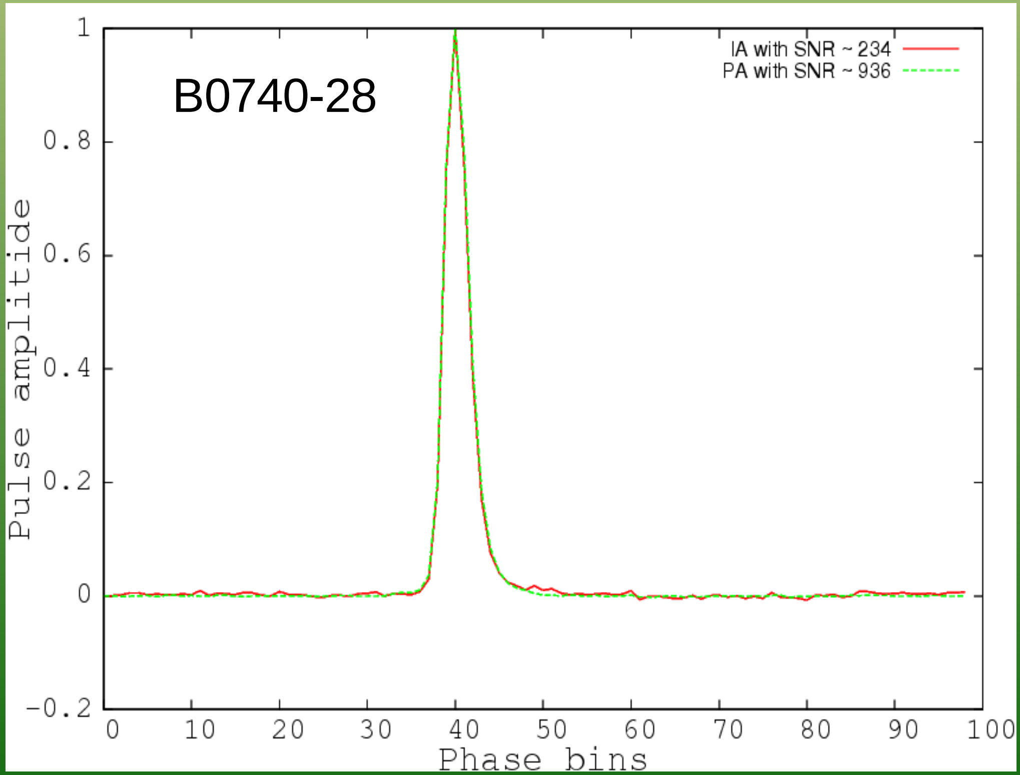
Op-1 : Only IA
Op-2 : Only PA
Op-3 : IA + PA (*default*)
Op-1 : IA + IA
Op-4 : PA + PA

Simultaneous 2 sub-array with full BW

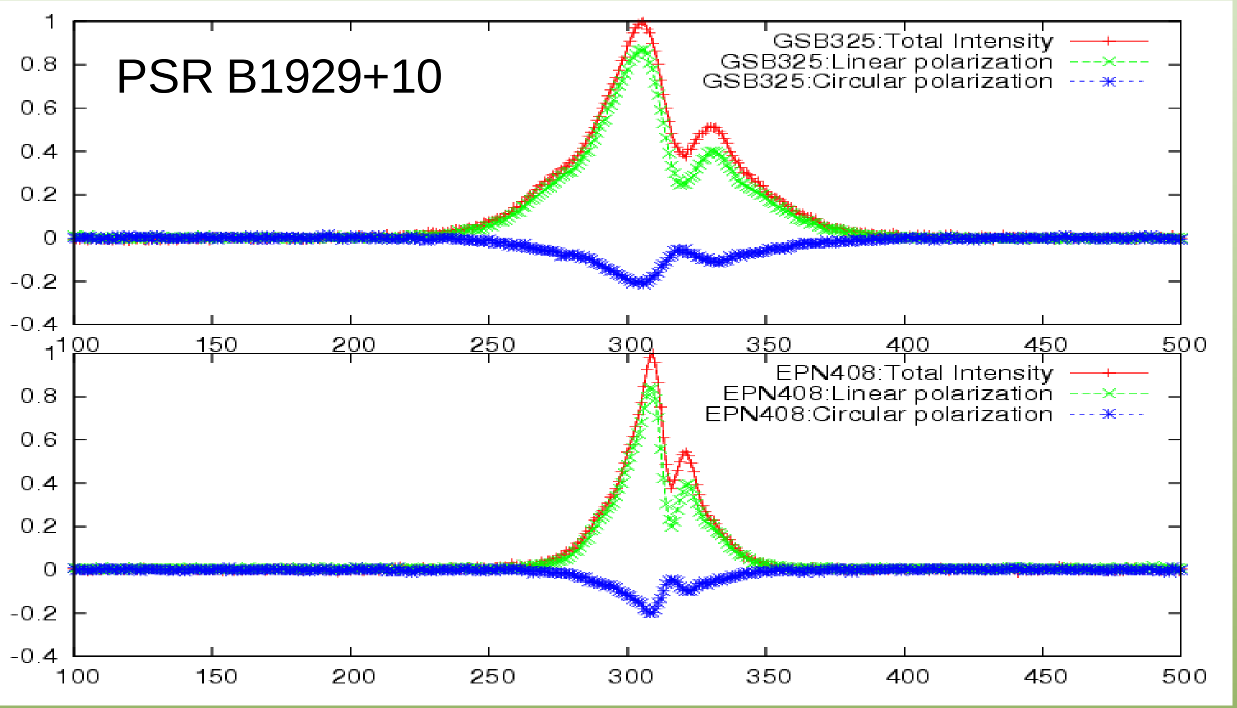
Single pulse time-series simultaneously from IA & PA at 325 MHz from PSR B0740-28



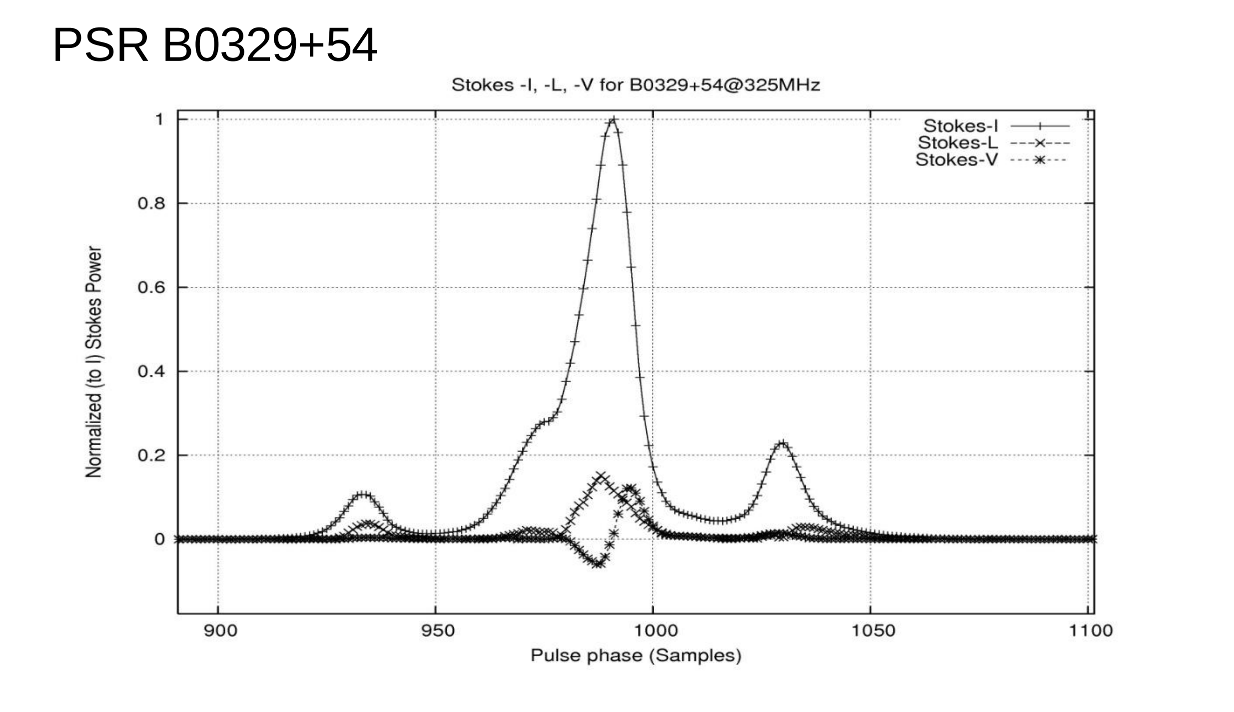
Averaged pulse profile using 15 antennae taken simultaneously with IA & PA at 325 MHz from PSR B0740-28 (*SNR improvement of ~ 3.9*)



High time resolution beamformer



Averaged pulse profile with linear & circular polarizations at 325 MHz from PSR B1929+10



Averaged pulse profile with linear & circular polarization at 325 MHz from PSR B0329+54

Looking ahead…..

The GMRT has already produced some interesting results and, even in the current configuration, will function as a competitive instrument for some more years.

However, it is time to start looking ahead at plans to upgrade the instrument in the years to come :

Provide *seamless frequency coverage* from ~ 30 MHz to 1500 MHz, instead of the 5 limited bands in this range at present. *This will require design of new feeds and a completely new receiver system to handle this frequency agility.*

Increase the instantaneous bandwidth coverage of the GMRT from the present maximum of 32 MHz to at least 400 MHz : this will provide a quantum leap in the sensitivity of the instrument for several kinds of applications. *This will require a radically new digital back-end receiver incorporating state of the art electronics and software processing techniques.*

Reduced receiver noise using high mobility transistorized LNA


Thank you