The Ooty Wide Field Array

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The Ooty Radio Telescope

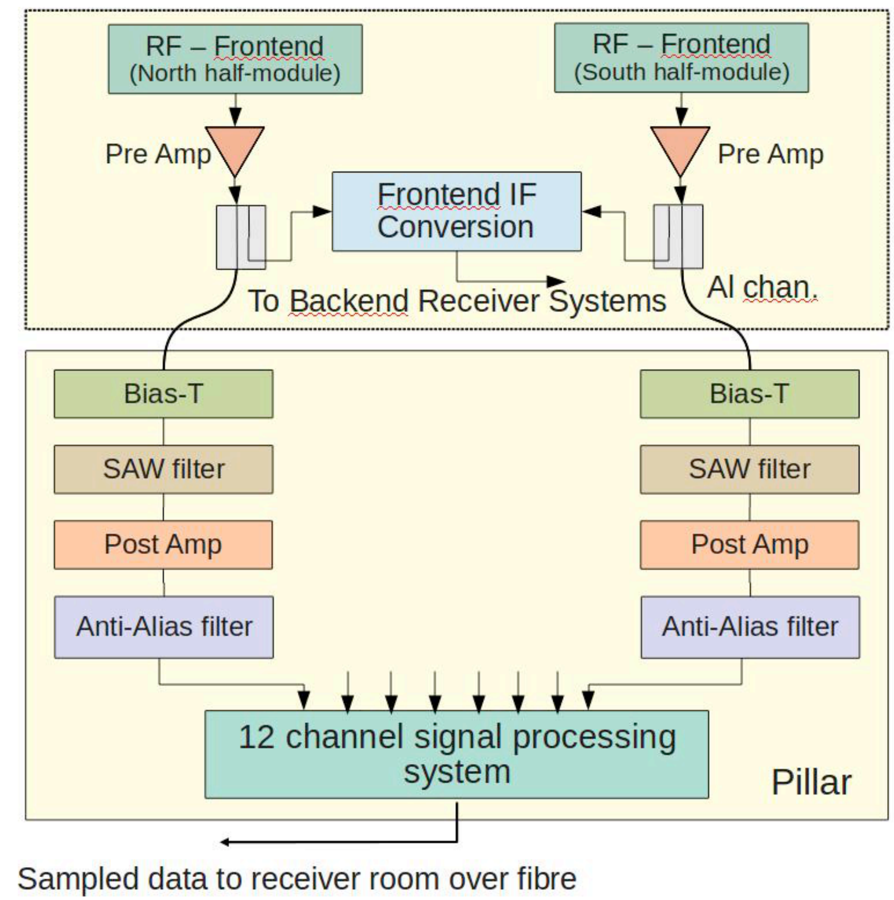
- Cylindrical parabola (530mx30m)
  - Been in operation since the early 1970s

- Mounted on N-S slope with slope~ l
  - Cylinder axis is parallel to earths rotation axis ("Equitorial mount")
  - Mechanical steering along E-W
  - Electrical steering to point in N-S

- Operates at a frequency of 330 MHz
  - Mainly used for space weather studies of the inner heliosphere
  - Also recently being used for pulsar studies.

The Ooty Wide Field Array (OWFA)

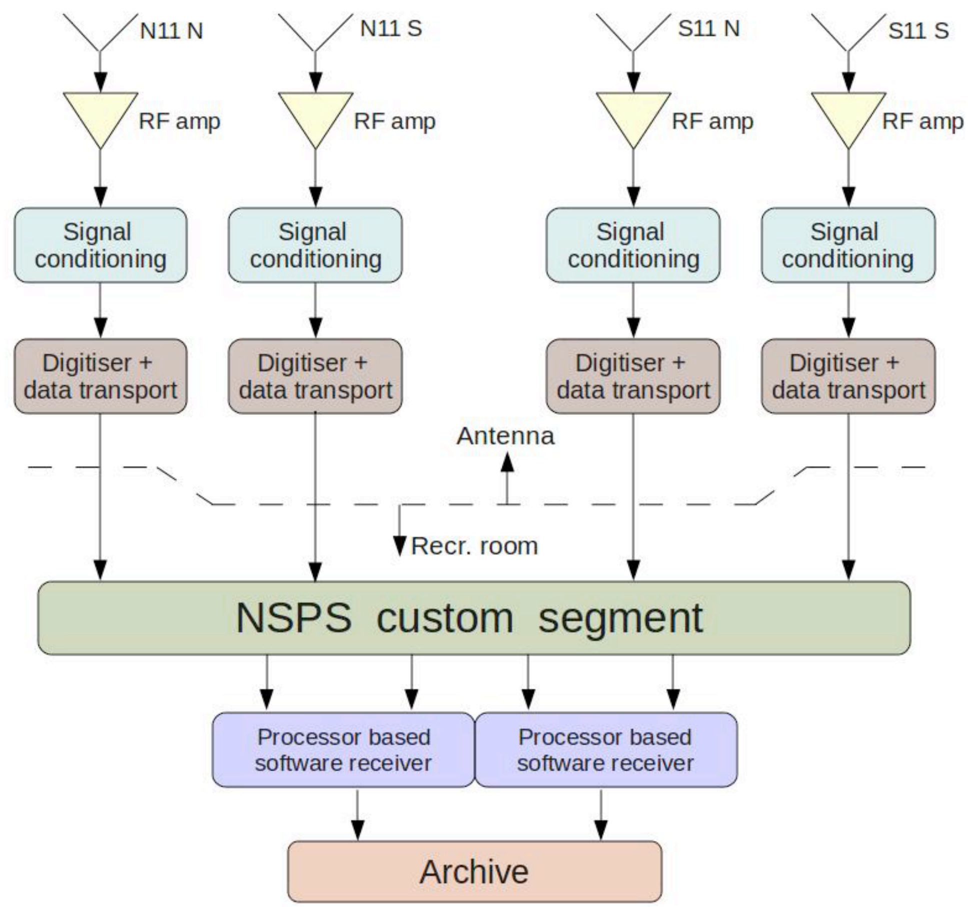
- ORT is being upgraded to become a modern versatile telescope
- RF signal is digitized in the field
  - *Digital signal is transported to receiver room via optical fiber*
- Two sets of digitized output are available
  - 40 el interferometer [Phase I, FOV 300’ x 115’]
  - *264 el interferometer [Phase II, FOV 1795’ x 115’]*
- The system is designed so that
  - *the legacy systems functioning is unaffected by the upgrade.*
  - *Phase II system can work in parallel with Phase I system*
  - *When installation is complete, Analog, Phase I and Phase II (OWFA) could all be simultaneously available.*



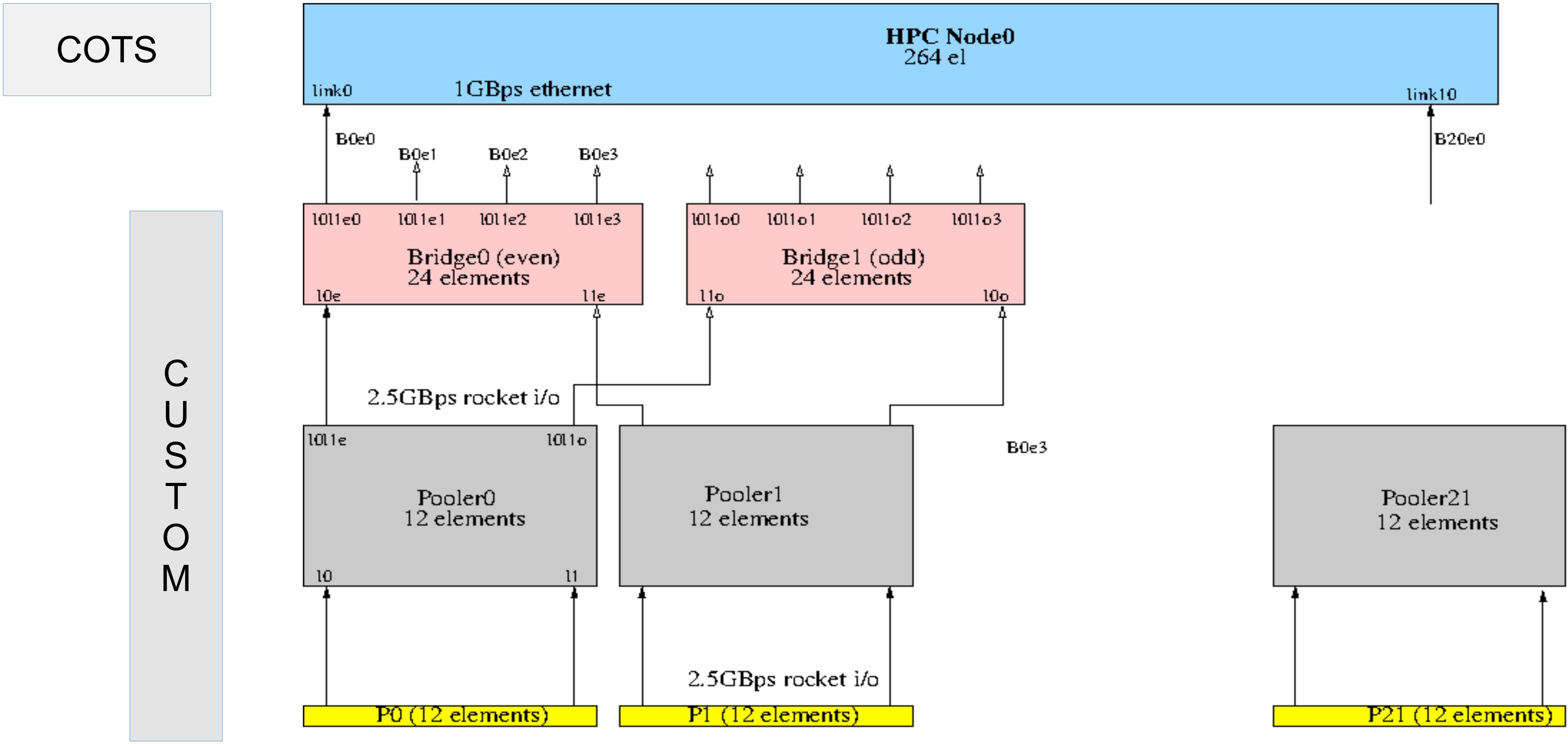
Networked Signal Processing System (NSPS)

Prasad & Subrahmanya Exp. Ast. (2011)

- OWFA receiver has 264 nodes ("antennas")
- New Architecture (NSPS) developed for this
  - treats this as a multi-sensor data fusion problem
- Receiver consists of a "custom" (FPGA) segment and a "commodity" (HPC) segment
- Custom segment "fuses" the data so that each HPC node gets one time-slice from all elements
  - Software correlator deals with an embarrassingly parallel problem



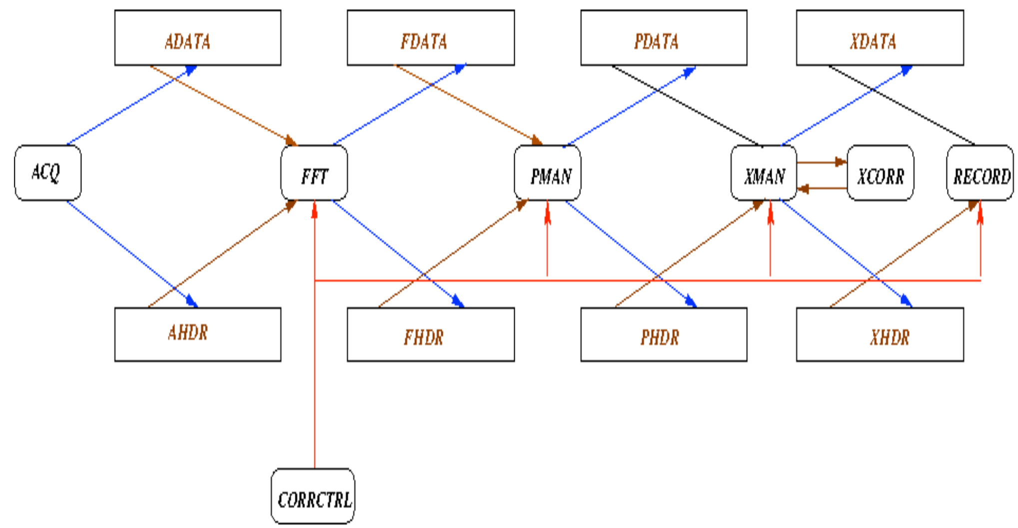
OWFA SIGNAL FLOW



- RF is digitised at the field (12 channel ADC per module)
  - Packetised data is sent via optical fiber to “Pooler cards”.
- Data is organized into 250ms wide time slices
  - “Bridge” cards send out the data via 1 G ethernet links
- Each HPC node gets 250 ms worth of data from all 264 elements
  - Via 11 x 1 GB ethernet links

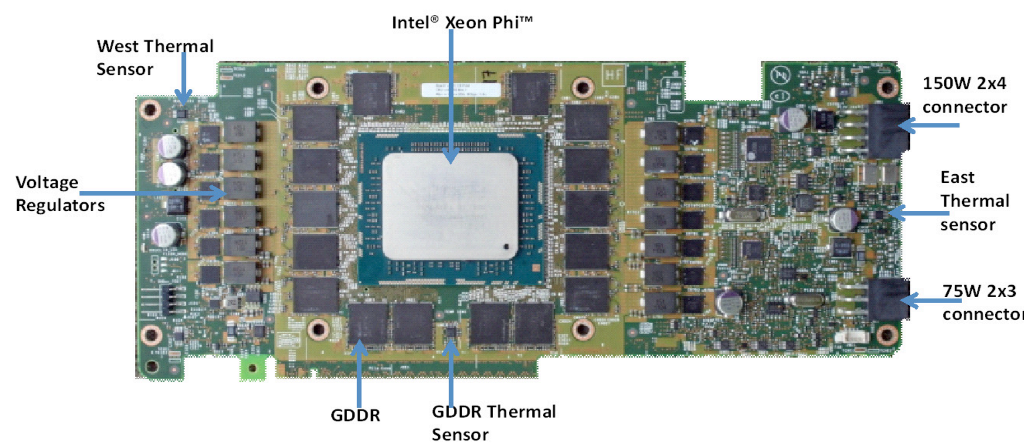
OWFA Correlator

- Correlator is designed as a 264 element 800 channel, ~40 MHz BW FX correlator



- Speced to run on an 8 node HPC
  - Each node has 2x18 core Haswell + 1Xeon Phi 3120 add on card

- F engine runs on the host, while the X runs on the Xeon-Phi card



OWFA Specifications

Tab. 1: Configuration of OWFA

	OWFA	*OWFA-40*
Band centre	**326.5 MHz** ($\lambda 0.9182m$)	326.5 MHz
Element size	$1.92m = 2.087\lambda$	$11.52m$
Number of Elements	**264**	40
Nominal FoV(NS)	$27.5^o / \cos(\delta)$	$4.9^0 / cos(\delta)$
Sampled pass band	**307.2:345.6 MHz**	317.0:336.8
Sampling Rate	**76.8 Ms/s, 3-bit**	39.625 Ms/s, 3-bit
FFT bandwidth	$38.4\,MHz$ **(full)**	19.8 MHz (full)
correlator bandwidth	$\sim 35\,MHz$ **typical**	19.8 MHz (full)
Continuum Sensitivity	***10*** **mJy**/$\sqrt{t_{sec}}$ **rms**	***15*** **mJy**/$\sqrt{t_{sec}}$ **rms**
Spectral Resolution	**48 kHz**	48 kHz (fft_size=800)

HI at z ~ 3 with the OWFA

- Ideally suited for measurement of the HI power spectrum at z ~ 3
  - Lot of baselines at the angular scales where the signal is strong
    - Dense sampling of the central part of the u-v plane
  - Equitorial mount means that one is measuring the same sky Fourier component at all times (i.e. *coherent* integration)
  - Massive redundancy allows for excellent calibration.

Non linear redundancy calibration

- Traditional redundancy calibration algorithms are linear
  - Require large matrix operations
  - Biased unless the SNR is high

(Noordam & de Bruyn, 1982; Wieringa 1991, 1992)

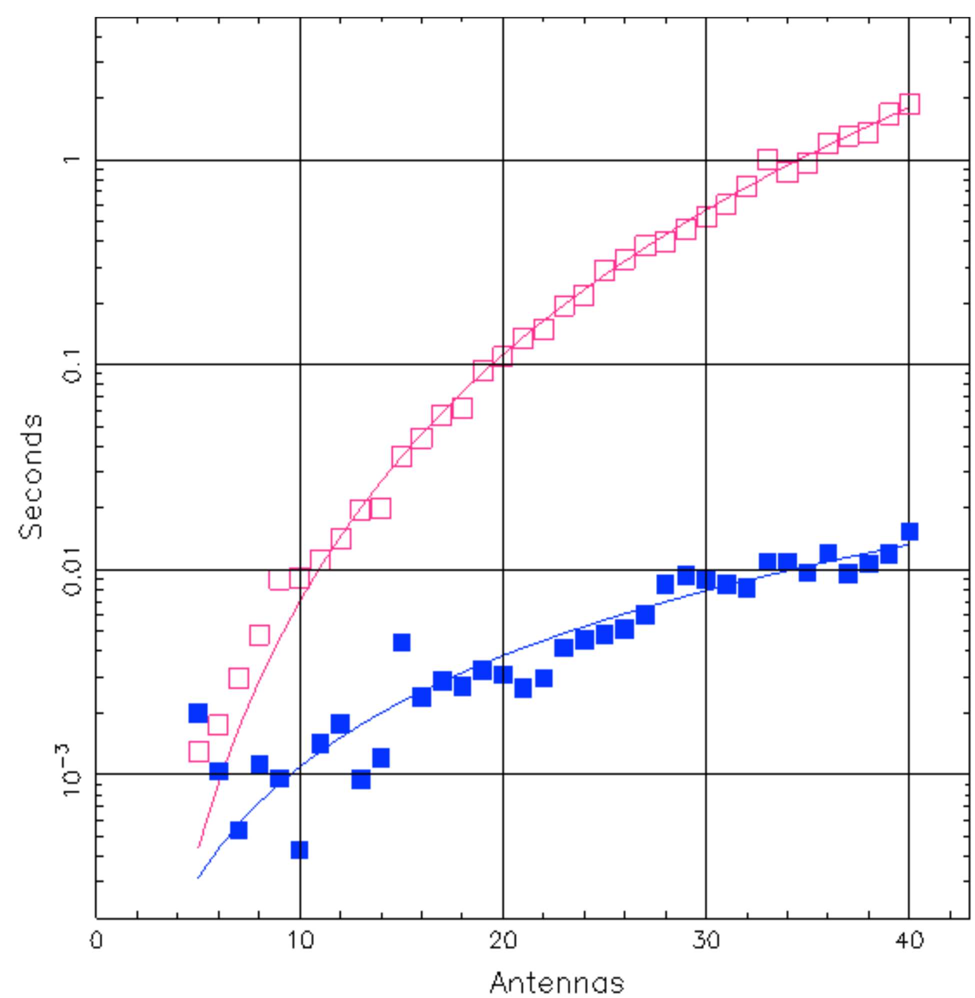
- Modified matrix based methods remove the bias
  - But are still expensive ~ N^4

    (Liu et al., 2010)

- Study in detail a non-linear algorithm
  - Unbiased
  - Optimal (achieves the Cramer-Rao bound)
  - Fast N^2 instead of N^4

- Should allow us to calibrate in near real time
  - Useful for space weather, searches for FRBs...

Marthi & Chengalur MNRAS, 437, 534, (2014)



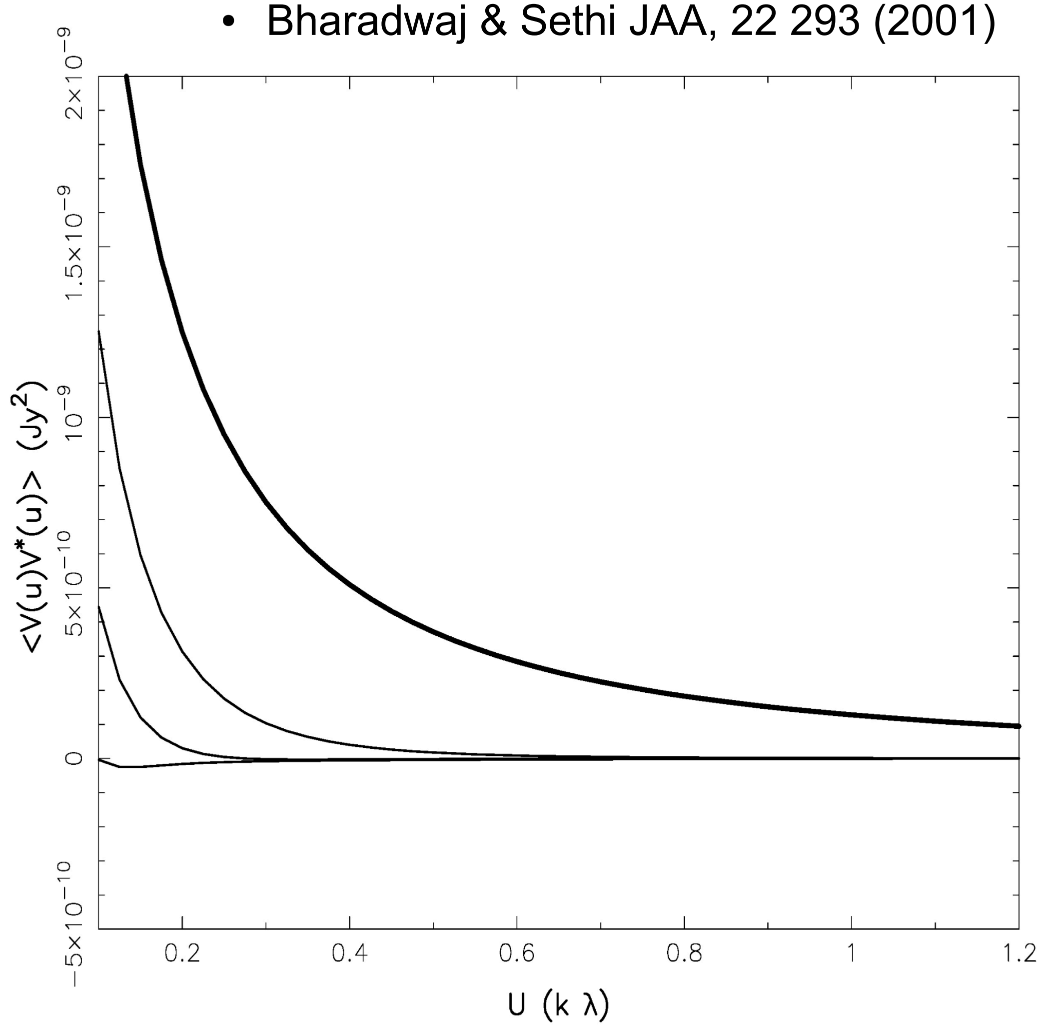
Detecting correlated HI emission from large scale structures

- The brightness of correlated part of the post-reionisation HI intensity fluctuations is relatively bright
  - Compared to the thermal noise

- In a series of papers Bhardwaj and collaborators computed expected signal strength for the GMRT
  - Bharadwaj, Nath & Sethi JAA 22, 21 (2001), Bharadwaj & Sethi JAA, 22 293 (2001)

- Proposed measuring the correlated HI signal directly from the visibilities
  - Avoids dealing with the non-linearities produced during deconvolution

- Bharadwaj & Sethi JAA, 22 293 (2001)



Measuring emission power spectra using an Interferometer

- The square of the visibility directly measures the emission power spectrum
  - The visibility square includes the system noise
  - Suitable only for situations where the SNR is large
  - e.g. Galactic HI emission

Dickey & Crovisier A&A 122 282 (1983)

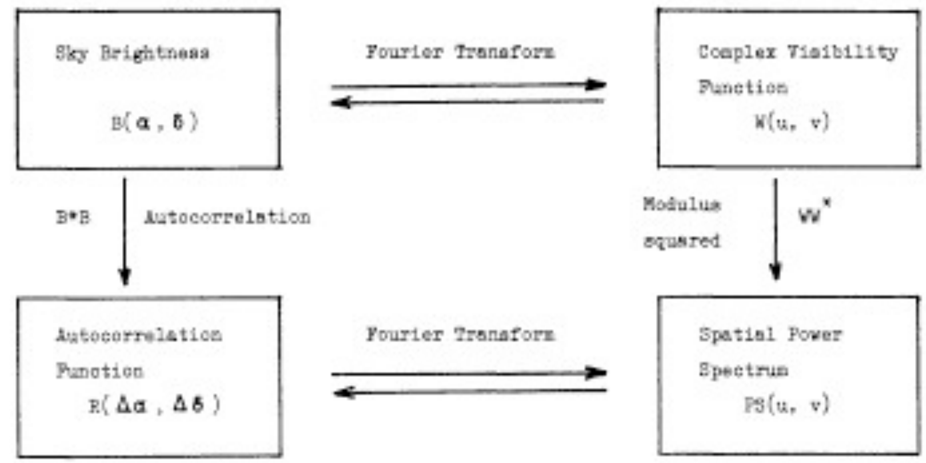


Fig. 1. The autocorrelation theorem applied to a brightness distribution

- At low SNR we can use a modified estimator
  - Correlate a given visibility with "nearby" visibilities
  - "nearby" within one antenna diameter

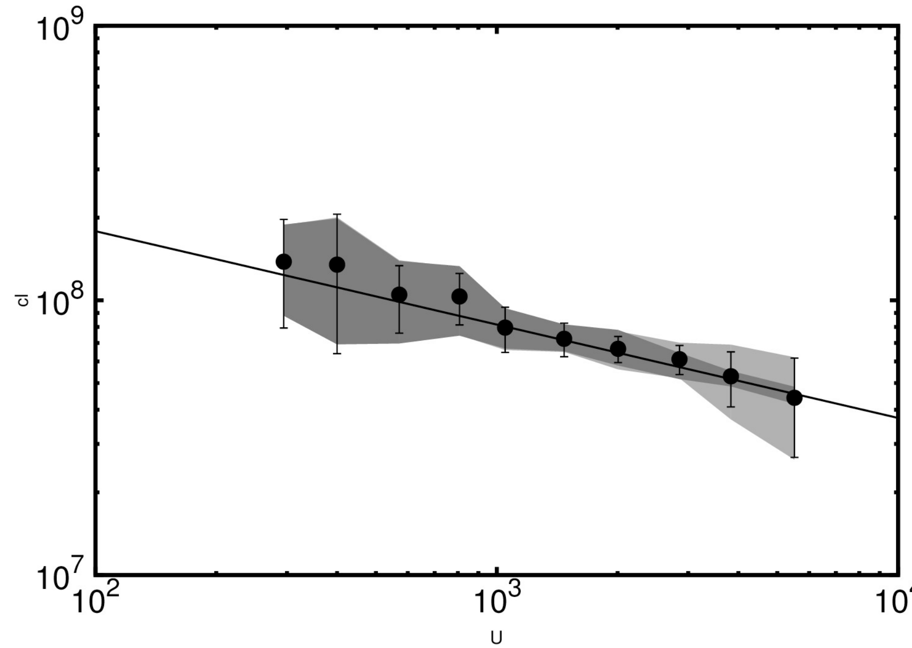
Begum, Chengalur & Bharadwaj, MNRAS 372, 33 (2006)

Characterising the estimator

- Simulations show that the estimator accurately recovers the input power spectrum

- Has been used in a wide range of studies
  - Power spectrum of
    - HI absorption in our galaxy,
    - HI emission in external galaxies,
    - Foregrounds for the HI signal....

Chowdhury et al. MNRAS 445, 4351 (2014)



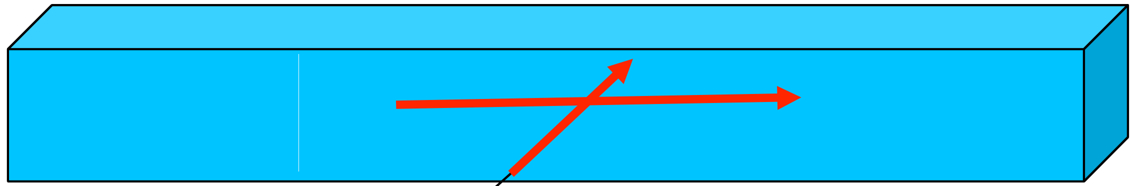
Roy et al. MNRAS 404, L45 (2010)
Dutta et al. MNRAS 398, 887 (2007)
Ghosh et al. MNRAS 411, 2426 (2011)

OWFA

$r\vec{\theta}$ - 3.2 Gpc

$r'_{\nu} = 11.33 \, \mathrm{Mpc} \, MHz^{-1}$

0.2 Gpc



$r'\nu$ 0.34 Gpc

Z=3.35

$r_{\nu} = 6.67 \, \mathrm{Gpc}$

$$k = \mid \mathbf{k} \mid = \sqrt{k_{\parallel}^2 + k_{\perp}^2}$$

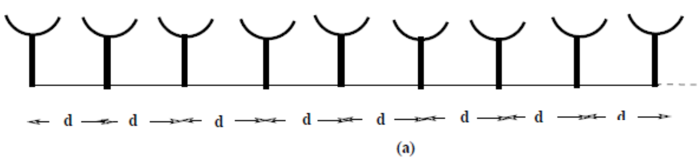


Table 2. The $k_{\perp}$ and $k_{\parallel}$ range that will be probed by the different Phases of OWFA.

Mpc^{-1}	Phase I	Phase II	Phase III	Phase IV
$k_{\perp}[min]$	1.1×10^{-2}	1.9×10^{-3}	9.5×10^{-4}	4.8×10^{-4}
$k_{\perp}[max]$	4.8×10^{-1}	5.0×10^{-1}	5.1×10^{-1}	5.1×10^{-1}
$k_{\parallel}[min]$	3.0×10^{-2}	1.8×10^{-2}	9.1×10^{-3}	4.6×10^{-3}
$k_{\parallel}[max]$	2.73	2.73	2.73	2.73

Parametrization of the HI Power Spectrum

$$P_{\mathrm{HI}}(\mathbf{k}) = A_{HI}^2\, \bar{T}^2\, \left[1 + \beta\, \mu^2\right]^2\, P(k)$$

$$A_{HI} \;=\; \bar{x}_{\mathrm{HI}}\, b_{HI} \qquad\qquad \beta \;=\; f(\Omega)/b_{HI}$$

$$\bar{T}(z) = 4.66\,\mathrm{mK}\,(1+z)^2 \left(\frac{\Omega_b h^2}{0.022}\right)\left(\frac{0.67}{h}\right)\left(\frac{H_0}{H(z)}\right)$$

$$\bar{x}_{\mathrm{HI}} \;=\; 0.02$$

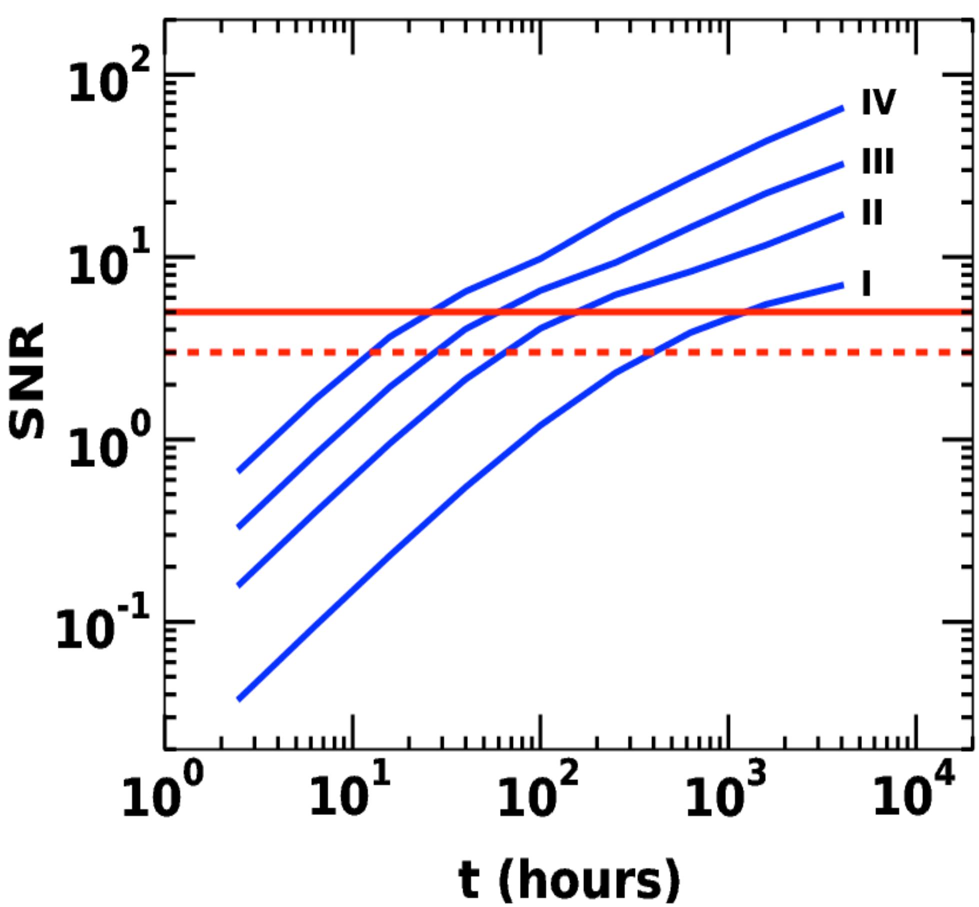
Zafar et al, 2013

$$b_{HI} \;=\; 2$$

Bagla et al.,2010

Measuring the Power Spectrum Amplitude

Sarkar et al (2015)



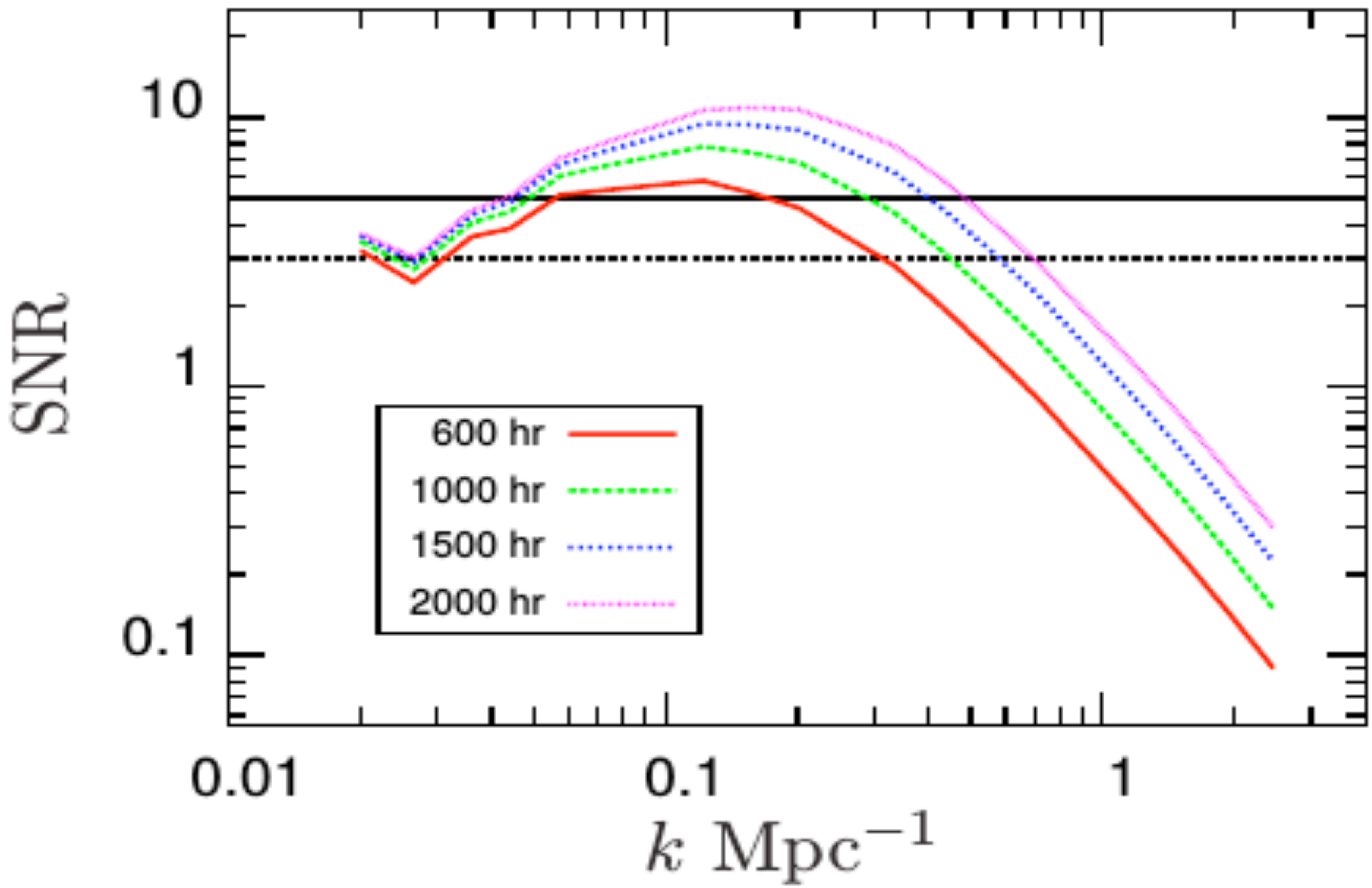
Prior

$$\beta = 4.93 \times 10^{-1}$$

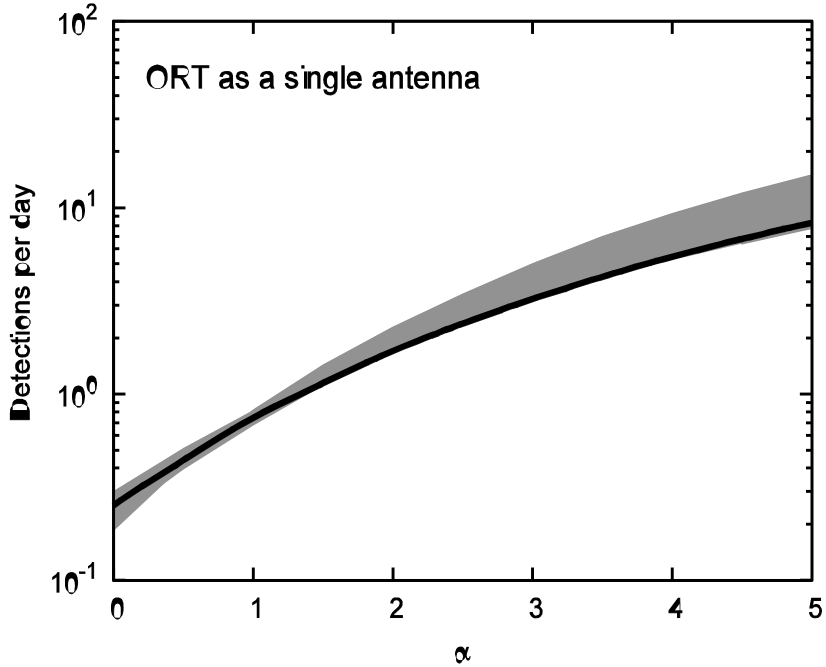
$$\text{SNR} = A_{HI} / \Delta A_{HI}$$

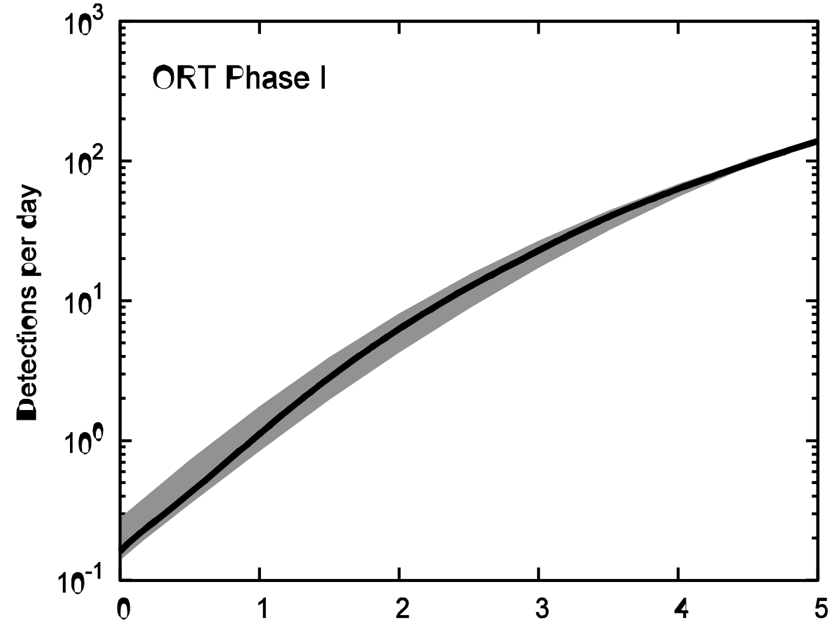
Measuring the binned Power Spectrum

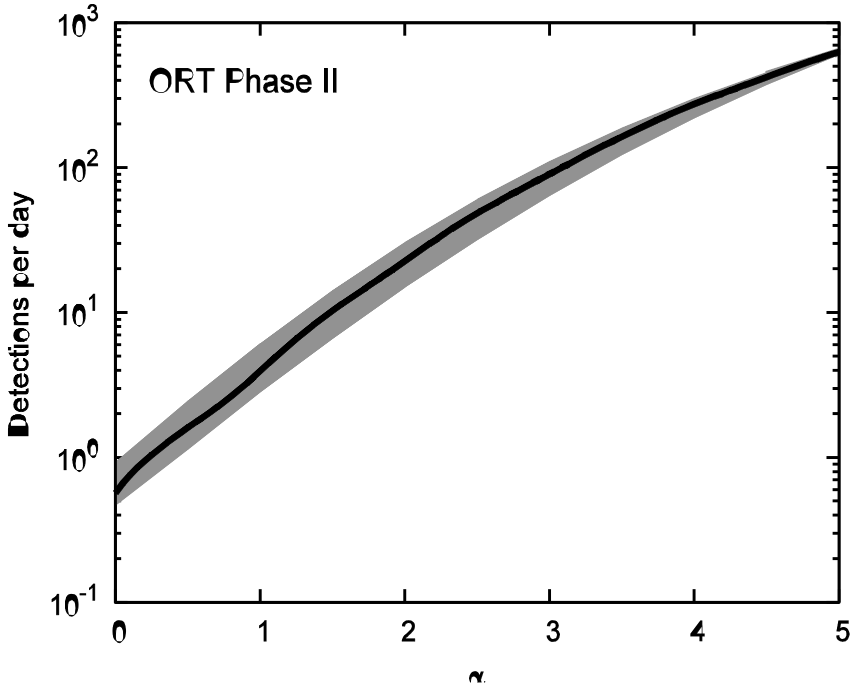
Sarkar, A. et al., (2015)



Predicted FRB event rates



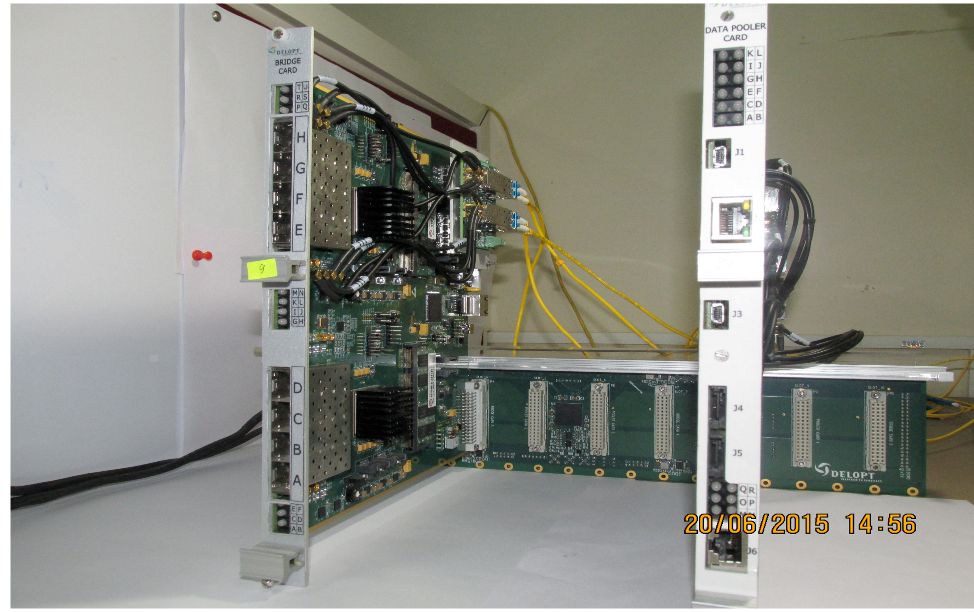


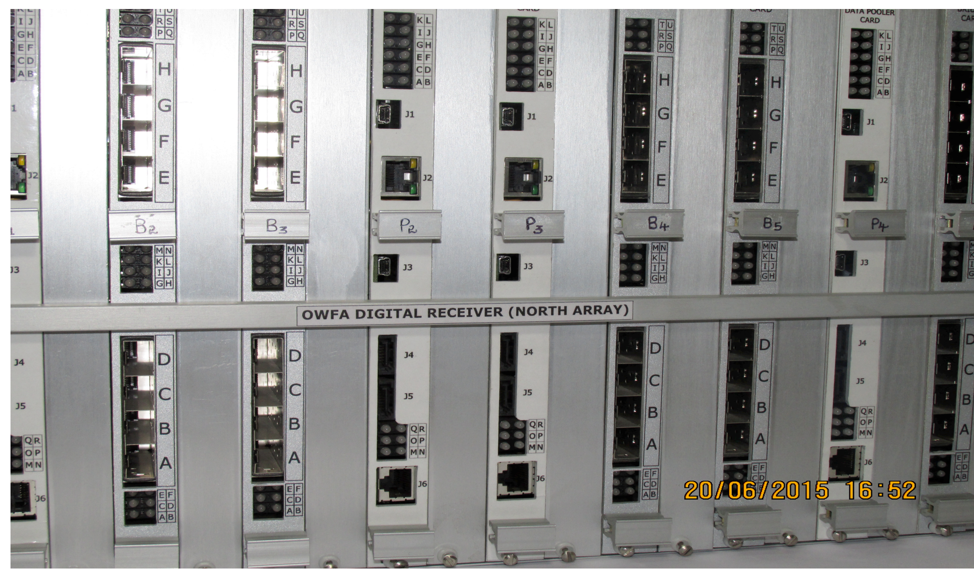


- Array is massively redundant
  - Only 264 unique baselines
- Allows for very efficient post correlation beam forming
- Beam forming on candidate events
  - confirm events
    - do rough localisation

Current Instrument Status

- All of the RF amplifiers have been installed
  - And running stably for quite some time
- All fibres between the field and receiver room laid and tested
  - Hardware and link for transport of reference clock and 1pps installed and tested
- All custom hardware cards are ready
  - Assembly of one sub rack (½ the telescope) done and being tested
- Code for the critical parts of the correlator (Xengine) written and timed
- Final HPC system (Xeon Phi based) is installed.
- Expect to be taking sky data by the middle of next year.





Thank you for your attention

Results: SNR plots

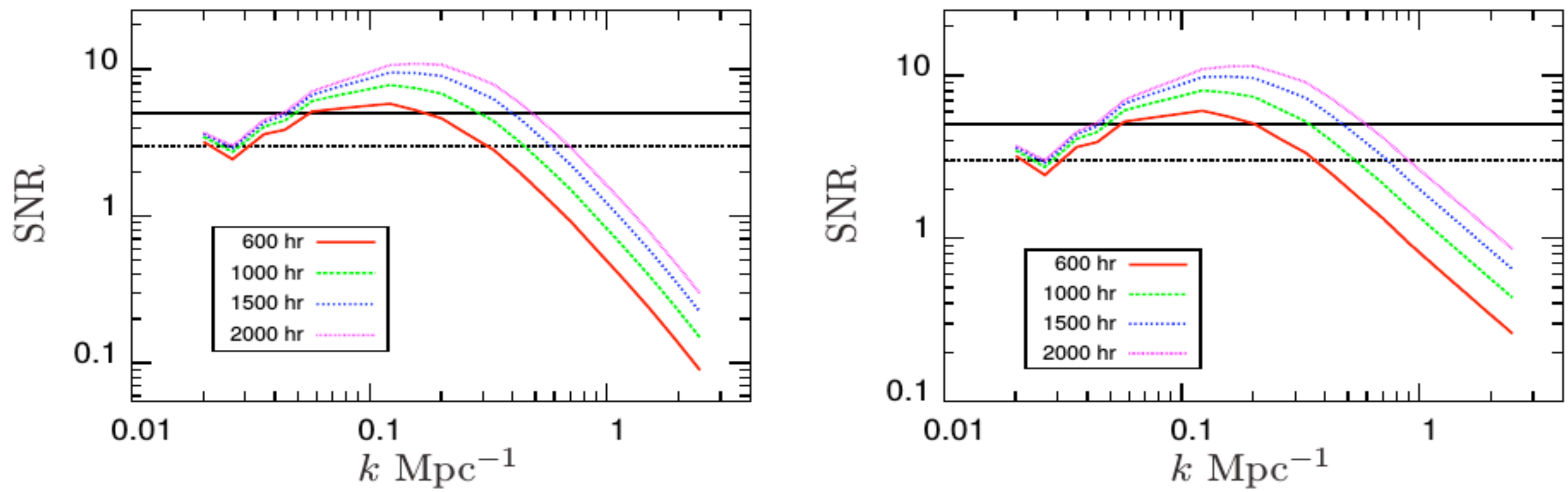
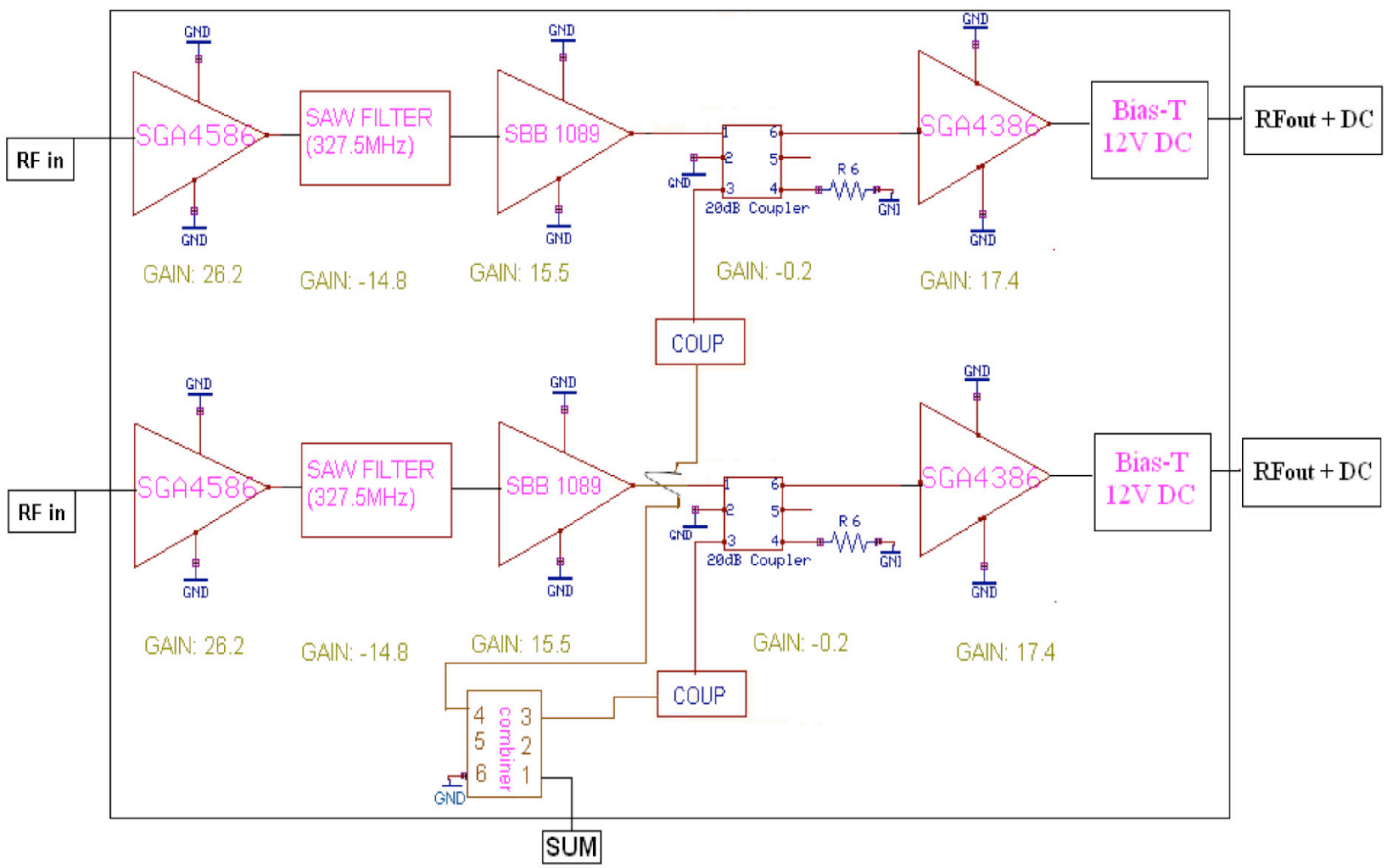


Figure 3. This figure shows signal-to-noise ratio (SNR) for HI power spectrum with scale-independent (left panel) and scale-dependent HI bias (right panel) as a function of k at different observing times (t) as indicated. The horizontal dashed and solid lines show SNR = 3 and 5 respectively for both panels.

OWFA Stage 1 amplifier BLOCK Diagram

Block Diagram of Dual Module Stage-1 Amplifier



Relation between the two visibility correlation and the power spectrum

$$V_2(\mathbf{U}_1, \nu_1; \mathbf{U}_2, \nu_2) = \langle V(\mathbf{U}_1, \nu_1) V^*(\mathbf{U}_2, \nu_2) \rangle$$

Relation between Two Visibility correlation (V_2) & MAPS $C_\ell(\Delta\nu)$

$$V_2(\mathbf{U}, \Delta\nu) = \frac{\pi\theta_0^2}{2} \left(\frac{\partial B}{\partial T}\right)^2 C_{\ell=2\pi U}(\Delta\nu)\, Q(\Delta\nu)$$

Measured

Quantity of Interest (MAPS)

Ali, S.S. et. al. , 2008 , MNRAS, 385, 2166

ORT Legacy Beam Former

- Consists of 22 modules
  - Each module is 23m x 30m in size
- Feed consists of a linear dipole array
  - Each module has 48 dipoles
  - Each dipole has an independent amplifier and phase shifter
- The dipole signals are combined together hierarchically to create the final output signal