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The Ooty Wide Field Array

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Abstract. The Ooty Wide Field Array (OWFA) is a modern transformation of the mature Ooty Radio Telescope into a programmable synthesis telescope equivalent to a uniformly spaced linear array of 264 antenna elements each of size 1.92m × 30m, operating in a 38 MHz frequency band centred at 326.5 MHZ. The digitized response of each of the 264 elements is transported using a newly established fibre optic network to a central data partitioning hardware which distributes the data to realize a high degree of load balancing for a software correlator planned on an 8-node HPC. The 264-antenna real-time software correlator will provide 800 spectral channels with a spectral resolution of about 48 kHz. The required real time compute throughput of the OWFA correlator will exceed that of the present GMRT software correlator by more about a factor of 15. The OWFA is the first signficant application of the Networked Signal Processing System(NSPS) recently proposed for multi-element radio telescopes. With such a configuration, the OWFA will be a powerful platform for studying HI mass fluctuations at redshifts $\sim$ 3.3 as well as a variety of large scale surveys with goals ranging from space weather watch to transients searches.

Keywords : Software Correlator; Synthesis Radio Telescope; HI mass fluctuations; Baryonic Acoustic Oscillations

1. Introduction

The large collecting area, equatorial mount and linear feed array make the Ooty Radio Telescope (Swarup et al. 1970) a very powerful instrument for large scale sur-

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veys at metre wavelengths. In the last major upgrade of the telescope front-end (Selvanayagam et al. 1993) each of the 1056 dipoles of the feed array was equipped with an LNA and a centrally controllable phase shifter. However, practical limitations of the legacy receiver system make large scale surveys unfeasible with the legacy instrumentation. This makes the telescope highly suitable for reconfiguration as a wide field synthesis radio telescope by equipping it with a modern digital programmable receiver. A conceptual design for such a reconfiguration was first presented by Subrahmanya and Manoharan (2008). This was refined into the more elaborate and powerful system presented this paper.

In the legacy system, the phase-shifted dipole outputs are fed to a 48-way passive combiner tree in the field. Each such 48-dipole array forms a single beam which is frequency translated to a 30 MHz centre frequency and brought to the receiver room and fed to a 12-beam analog phasing system. For the present upgrade, front-end signals are tapped immediately after first branch of the combiner tree, i.e. a 4-way combiner forming a single beam from four consecutive dipoles. There are 264 such combiners along the focal line. Thus, the present upgrade reconfigures the Ooty telescope into a uniformly spaced linear array of 264 antenna elements, each of size 30m(east-west) × 1.92m(north-south). The instantaneous field of view of the new synthesis telescope (i.e. the primary beam of each antenna element) is $1.8^0 \times 28^0$ sec(δ) near zenith. In the field processing units, the responses of all these 264 elements are directly digitized at 76.8 MHz and delay-compensated. The delay compensated data are coded and packetized such that each frame consists of 1600 consecutive samples from a pair of antenna elements. The packetised data are transported to the centrally located digital receiver room over a network of 44 optical fibres operating at 2.5 Gbps each. In the digital receiver room, the signals received through optical fibres will be handled by a Networked Signal Processing System(NSPS, Prasad & Subrahmanya (2011)) to realize a 264-element, 800-channel FX correlator with a spectral resolution of 48 kHz.

Since the ORT is currently in regular use for a range of observations, one of the constraints on the design and installation of the OWFA was that the new system needed to co-exist with the legacy one. To avoid confusion with the co-existing legacy analog receiver system, the new system resulting from the above upgrade will be called the Ooty Wide Field Array (OWFA). The important system parameters of OWFA are summarized in Table 1.

Table 1. Configuration of OWFA.

Band centre	326.5 MHz ($\lambda 0.9182m$)
Element size	$1.92m$ = 2.087λ
Number of Elements	264
Nominal FoV(NS)	27.5^o / cos(δ)
Sampled pass band	307.2:345.6 MHz
Sampling Rate	76.8 Ms/s, 3-bit
Continuum Sensitivity	10 mJy/ $\sqrt{t_{sec}}$ rms
Spectral Resolution	48 kHz

Table 2. Equivalent OWFA parameters for cosmological studies.

HI redshift range	3.1 : 3.6
Proper length at z = 3.35	12.4 Mpc/beam(NS)
Comoving Dist Range	439 Mpc(550 kpc resolution)

For cosmological investigations, the frquency bandwidth of the OWFA can be used to define an effective redshift range or a comoving distance range. Some useful parameters translated to this redshift range are given in Table 2.

1.1 Motivation

As compared to the legacy Ooty radio telescope, the OWFA will provide the following major enhancements.

- Large instantaneous north-south field of view (28^0 with angular resolution 0.1^0);
- Bandwidth enhancement to 38 MHz - about 4 times that of ORT;
- Spectral resolution of 48 kHz ;
- Large number redundant baselines; and
- Provision for high time Resolution of a few milliseconds for the correlator.

With these enhancements, the OWFA can be expected to rate among the best facilities in the world for large scale surveys. The resulting survey speed and efficiency would benefit many observations with goals ranging from space weather watch to a wide range of transients and cosmological investigations of HI mass fluctuations. Indeed, one of the major driving forces for OWFA was to study HI mass fluctuations in the redshift range 3.1 – 3.6. for which the equatorial mount enables continuous tracking of a specific comoving volume ($\sim 3 \times 10^8 Mpc^3 = 0.3 Gpc^3$) for about 9 hours. The equatorial mount also results in the baseline spacings remaining unchanged as the sources is tracked. This is particularly important for statistical detection of HI fluctuations (including possibly BAO features) at high redshifts. Predictions for the expected signal at $z \sim 3.3$ as observed by the OWFA are available in Ali & Bharadwaj (2013), as well as in the article by Ali& Bharadwaj in these proceedings.

2. The OWFA Digital Receiver

Recognizing the role of the network for traffic shaping, data partitioning and load balancing for a software correlator, the concept of Networked Signal Processing System (NSPS) was proposed by Prasad & Subrahmanya (2011). A preliminary demonstration of the relevance of such concepts was provided by Prasad & Subrahmanya (2010) for the software correlator of the precursor to OWFA. A detailed description of NSPS and the proof of concept is given in Prasad (2012). The final digital receiver is the first significant implementation of NSPS (Prasad & Subrahmanya 2011) for a large array of antennas, in which the real time signal processing is viewed as a *Data Fusion Tree*, formed by interfacing the *root node* consisting of a high performance cluster (HPC) to a *custom segment* organized into three hierarchical levels. From a functional point of view, the custom segment performs traffic shaping, data fusing and packet routing while compute-intensive data processing like the software correlator is performed by the commodity segment constituted by the HPC. The HPC is planned as an 8-node cluster with each node equipped by Xeon Phi co-processors. This is interfaced to the custom segment through an unmanaged GigE switch. The three nodes of the custom segment can themselves be visualized as a *restricted* distributed system, depending primarily on stripped down lightweight networking protocols and the static routes set up during system configuration. In particular, the custom segment provides a hierarchical pooling system to reorganize the data into 8 sets of 11 GigE links in which each set has a contiguous burst (350 ms typical) of data from all 264 elements. This enables the realization of the software correlator using a Single Algorithm Multiple Data (SAMD) algorithm. The three nodes of the custom segment are summarized below.

Digitizer Node: The digitizer node consists of 22 identical digitizer boards. Each board digitizes 12 RF streams at 76.8 Ms/s, incorporates delay compensation and packs 1600 samples of a pair of RF streams into one *frame* using 3-bit coding with a common scaling for each frame. An pair of onboard transceivers in each board is used to transmit timestamped frames on single mode fibres at 2 x 2.5Gbit/s per link. This part of the custom segment of NSPS is located in the field, in metal enclosures below the reflector.

Pooler Node: The Pooler Node consists of a set of 8 identical *pooler cards*, where each card accommodes 3 pooler blocks. Each pooler block consists of a an FPGA (*XCS6LX100T*) equipped with 4 multi-gigabit transceivers with optical fibre interface and 2 x 2Gb DDR3 onboard memory. Each pooler block accepts data coming from a 12-channel digitizer through two optical fibres and provides a double buffer using the on-board memory. The buffered data are read back and re-transmitted by re-ordering the frames such that output routed on each outgoing 2.5 Gbps link carries data from both the incoming links for half the time.

Bridge Node: This consists of 12 identical *bridge cards*, with each bridge card accommodating two bridge blocks. Each bridge block consists of an FPGA (*XCVLX50T*) equipped with 8 multi-gigabit transceivers with fibre-optic interface and a 2GB memory module. Each bridge block accepts two 2.5 Gbps links originating from independent pooler blocks. The buffered data from both the links are stored in the 2GB memory functionally organized into 4 partitions. Each partition accommodates frames corresponding to consecutive frames related to contiguous data from both the pooler blocks. The data from the four partitions are routed to independent Gigabit ethernet (GigE) links using on-board transceivers such that each GigE link has data corresponding to 350 ms (typical) bursts of contiguous samples from a total of 24 antenna elements.

3. The OWFA software correlator

The correlator being implemented for OWFA will be a 264-antenna, 800-channel spectral correlator, equivalent to a *27 million channel correlator!* operating at 76.8 MHz. The hierarchical pooling and partitioning of the digitized data in the custom segment enables us to use a Single Algorithm Multiple Data (SAMD) approach for real time processing. The specific SAMD design uses 8 identical subsystems, making the effective data rate into each node to be 76.8/8 = 9.6 Ms/s. Each node gets the real time data from a set of 11 GigE links, where each set carries the entire digitized time series at 76.8 Ms/s for all the 264 streams in bursts of contiguous data. The NSPS can provide a maximum contiguous burst interval of *0.35 second* for each node with the interval between bursts being precisely 8 times the burst-duration. The burst-duration, or its convenient submultiple defines a typical short term accumulation (STA) for the correlator outputs within a node. Keeping in mind the practical disk capacities and speeds, our current plan is to provide an STA of *0.07second*.

All subsystems in NSPS have memory to store-and-forward many packets. No subsystem needs to be made source synchronous, be it at the hardware or the software level. The custom segment of NSPS has enough buffer capacity to move data in blocks of contiguous samples over 0.35s (about 7 x 264 Gigasamples) to each node over a time interval of 2.8 sec. The latency tolerance for computing is increased further by using adequate (>256GB) on-board memory available in HPC nodes.

In each node, the computational load of the software correlator is shared by the host and a pair of Xeon Phi based coprocessor boards attached to each node. The spectral decomposition (FFT) will be handled by the host along with the input/out, data partitioning and other management activities, while the coprocessor performs the cross-correlation. In effect, the host sustains about 130 Gigaflops/node for FFT while the coprocessor sustains about 1.7 Teraflops/node. The algorithm being developed for the correlator shapes the computing to take advantage of vector instructions and group data to maximise arithmetic density while the data are in the hardware cache.

4. Current status

All the boards related to the NSPS custom segment hardware are available at site along with two nodes of the HPC. The correlator control is currently under development and the firmware for bridge and pooler blocks have been outsourced. They are likely to be available by mid-2014 for final integration and testing. During the latter part of 2014, it is planned to have system integration completed to a level adequate for taking bursts of data required for software testing, system characterization working out procedure for routine operations. Significant progress has been made in developing efficient algorithms for calibration (Marthi & Chengalur (2013), see also the contribution by Marthi & Chengalur in these proceedings). Detailed simulations of the expected OWFA signal from HI in large scale structures are also ongoing, and the first estimates the expected HI signal at the OWFA have been made by Ali & Bharadwaj (2013) and by Jasjeet Bagla and Bharat Gehlot (private communication).

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