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Review

The Receiver System for the Ooty Wide Field Array

C. R. SUBRAHMANYA[1], P. PRASAD[1], B. S. GIRISH[1], R. SOMASHEKAR[1],
P. K. MANOHARAN[2,*] and A. K. MITTAL[2]

[1]Raman Research Institute, C.V. Raman Avenue, Sadashivnagar, Bengaluru 560 080, India.
[2]Radio Astronomy Centre, NCRA-TIFR, P.O. Box 8, Ooty 643 001, India.
*Corresponding author. E-mail: mano@ncra.tifr.res.in

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Abstract. The legacy Ooty Radio Telescope (ORT) is being reconfigured as a 264-element synthesis telescope, called the Ooty Wide Field Array (OWFA). Its antenna elements are the contiguous 1.92 m sections of the parabolic cylinder. It will operate in a 38-MHz frequency band centred at 326.5 MHz and will be equipped with a digital receiver including a 264-element spectral correlator with a spectral resolution of 48 kHz. OWFA is designed to retain the benefits of equatorial mount, continuous 9-hour tracking ability and large collecting area of the legacy telescope and use of modern digital techniques to enhance the instantaneous field-of-view by more than an order of magnitude. OWFA has unique advantages for contemporary investigations related to large scale structure, transient events and space weather watch. In this paper, we describe the RF subsystems, digitizers and fibre optic communication of OWFA and highlight some specific aspects of the system relevant for the observations planned during the initial operation.

Keywords. Radio astronomy: radio telescope—receiver system—space weather watch: solar wind transients—cosmology: large scale structure of the Universe—fast radio bursts.

1. Introduction

Ooty Radio Telescope (ORT) is an equatorially mounted cylindrical radio telescope with a parabolic reflector of size 530 m × 30 m, which was commissioned in 1970 as a multi-beam radio telescope operating over a bandwidth up to $\sim$10 MHz centred at 326.5 MHz (Swarup *et al.* 1971). It is equipped with a uniformly spaced array of 1056 half-wave dipoles spanning 506 m of the focal line. It is located on a hill whose slope is equal to the latitude of the place, so that continuous tracking of a celestial object is enabled by mechanical rotation around a North–South axis. Using a centrally controlled phase shifter installed at each dipole, it is possible to establish a uniform phase gradient along the feed array to steer the beam in a desired North–South direction. The last major upgrade of its front-end was about 25 years ago (Selvanayagam *et al.* 1993), when each dipole was equipped with an LNA and an individually controllable phase shifter. The legacy receiver system consists of analog beam formation by phasing the array to form a set of 12 beams spanning $0.6^\circ \sec(\delta)$ in the North–South direction. A brief outline of the front end system is given below. This sets the context for the ongoing upgrade.

The legacy front-end of ORT is organized into 44 identical groups (half-modules) each spanning a 11.5-m section of the focal line (occupied by 24 consecutive dipoles) centred on a supporting frame. The output of each dipole is amplified using a Low-Noise Amplifier (LNA) and passed through a (user-controllable) phase-shifter. The front-end electronics of each half-module is mechanically housed in identical enclosures, each catering to a set of 24 consecutive dipoles with LNA and phase shifter followed by a passive combiner tree as shown in Fig. 1. The final output of the combiner tree results in a half-module beam whose phase-centre is typically arranged at the centre of the module constituted by a pair of half-modules on either side of a supporting frame. A mixer unit is located on the supporting frame corresponding to each module, where the two half-module beams are brought together, combined and down-converted to form a module beam using a centrally distributed local oscillator at 296.5 MHz. The resulting module beams (centred at 30 MHz) are transported to a central receiver room using equal length coaxial cables. The entire range of receivers

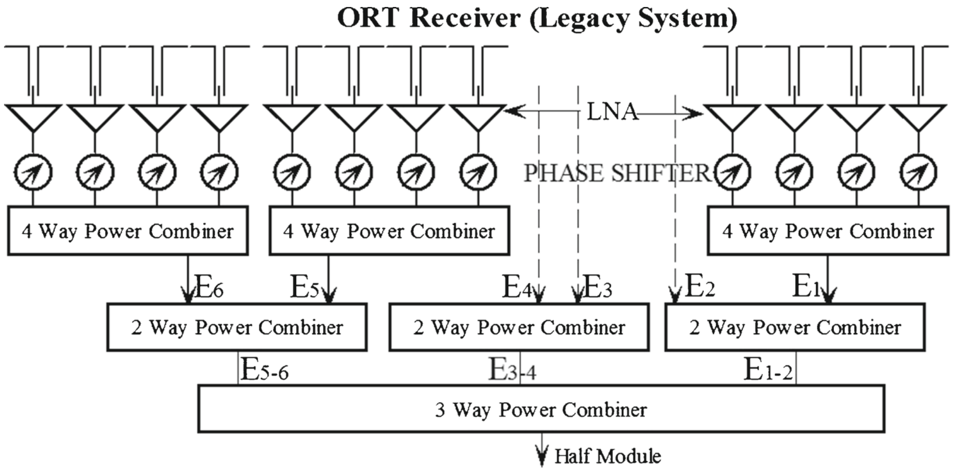

Figure 1. Legacy half-module.

used prior to OWFA corresponds to backend systems for these IF beams. The oldest and the most widely used receiver is an analog beam forming network for phasing the 22 modules in 12 different directions in the North–South direction spanning a total extent of $\sim 0.6^\circ \sec(\delta)$. For a summary of various projects undertaken during the initial decades of operation of ORT, we refer the reader to Swarup *et al.* (1991). Since then a digital receiver was built by Prabu (2011) for co-location with the analog beam forming network which allows one to record the digitized IF beams from all 22 modules and use an off-line processing to enhance the instantaneous field-of-view to $\sim 2.4^\circ \sec(\delta)$. Due to the combination of large collecting area, equatorial mount and the large number of phase-controlled dipoles along the focal line, one would expect to get a tremendous advantage for contemporary large scale surveys with the ORT. But these benefits have been completely offset by the severe limitation of instantaneous field-of-view imposed by the legacy receivers which treated the module beams available in the receiver room as the primary source of signal. Hence, we decided to give a new lease of life to the legacy telescope by carrying out a major revision of front-end as described in this paper. In particular, our efforts have led to a reconfiguration of the telescope into a synthesis telescope – the Ooty Wide Field Array (OWFA) – in which the phased sum of 4 consecutive dipoles along the focal line is treated as an individual antenna. This upgrade enables a range of different scientific programs including observations of the large scale distribution of neutral hydrogen at $z \sim 3$, observations of space weather in the inner heliosphere, and surveys for radio transients (for more details, refer to Subrahmanya *et al.* (this issue)).

The work related to OWFA began as an in-house activity at the Raman Research Institute (RRI) where conceptual design and prototyping were carried out with the help of a couple of small scale industries in Bengaluru. As part of a feasibility study, a preliminary design was undertaken for critical subsystems related to data acquisition and transportation to central computer. The hardware subsystems thus developed were adequate for working out the logistics for RF digitization, clock distribution, communication network topology and protocols as well as for a configurable correlator. They were used to re-configure the ORT as an array of 40 elements where the individual elements were half-module beams. For a detailed description of this precursor system (also called the ‘Phase I’ system) and some results from initial tests, we refer the reader to Prasad & Subrahmanya (2010) and Prasad (2012). This system was used as a test bed to work out a suitable communication network and a practical set of communication protocols useful for the digital receiver. Experience with this system was used to formulate a scheme called the Networked Signal Processing System (NSPS, Prasad & Subrahmanya 2011; Prasad 2012) which became the basis of an 800-channel spectral correlator for the 264-element OWFA. This includes a segment which provides a firmware interface to help realizing the software correlator on a many-core processor-based commodity High Performance Cluster (HPC) using a Single Program Multiple Data (SPMD) strategy.

In this paper, we give a detailed description of the RF and digitizer subsystems installed in the field and the fibre-optic communication system established to transport digitized data to the central receiver system as well as uplink signals related to time synchronization and command interface to the digitizers. Details of the software correlator will be provided elsewhere.

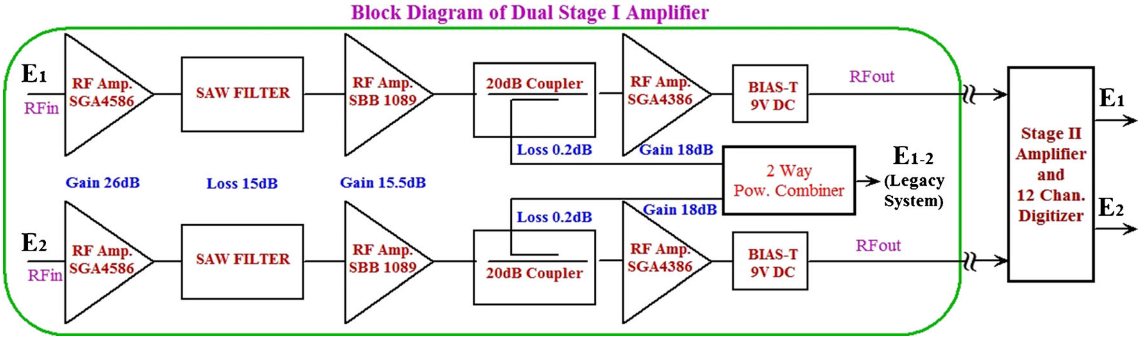

Figure 2. Dual stage-1 signal conditioner E1 and E2 respectively represent 1 to 4 dipoles and 5 to 8 dipoles combined outputs (refer to Fig. 1).

2. Ooty Wide Field Array

Due to limitations of in-house manpower, the detailed design and fabrication of all subsystems of OWFA were outsourced to small scale industries in Bengaluru. Augmentation of the infrastructure at the observatory and local logistics support required for system commissioning and testing were provided by the Radio Astronomy Centre, Ooty (Ooty is now known as Udhagamandalam). In order to minimize the telescope downtime and for efficient testing of new systems, the entire design paid attention to the feasibility of a concurrent operation of the legacy systems as well as the precursor (Phase I) system. In this section, we give a brief description of the field subsystems and communication system of OWFA.

2.1 *Array elements*

An antenna element of OWFA is defined as the phased sum of the signals received from 4 consecutive dipoles along the focal line. This corresponds to the output of a four-way combiner in the legacy system (Fig. 1) equivalent to an antenna of size 1.92 m × 30 m for the dipole spacing of 0.48 m. In contrast with the analog beam forming employed in the legacy system, the RF signals for OWFA are directly digitized in the field. Signal conditioning for digitization is done in two stages, with the first stage located inside the half-module enclosure while the second stage located below the reflector in a new set of metal enclosures (called pillars) installed close to the centre of each module.

The first stage of signal conditioners consist of 3 units mounted inside each half-module enclosure in place of two-way combiners of the legacy system. As shown in Fig. 2, each unit consists of a pair of identical sub-units, each containing a multistage amplifier band-limited to about 38 MHz centred at 327.5 MHz using a commercially available SAW filter. Coupled ports are provided from the individual amplifiers whose outputs are combined to form a signal fully compatible with that of the passive two-way combiner in the legacy system. The normal outputs of the amplifiers are brought out on SMA connectors to connect to a similar set of amplifiers located at the base of the antenna. Thus, a total of six 60-m cables from each half-module enclosure carry the RF to second stage signal conditioner. The stage-2 amplifier is similar to the first stage (but with a slightly higher gain) and includes a SAW filter identical to that used in stage-1. A current injector in stage-2 and a diplexer in stage-1 are used to transmit

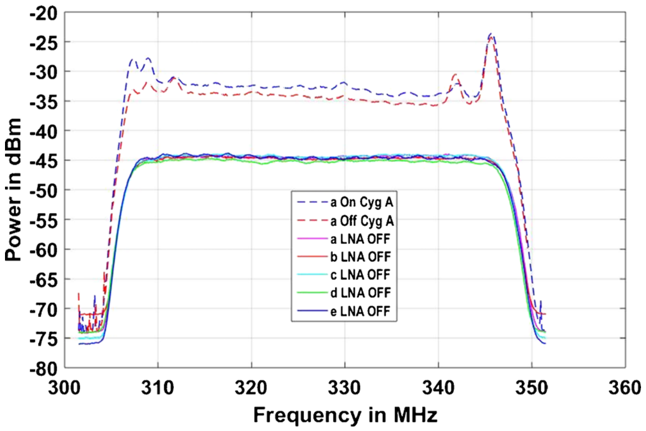

Figure 3. On source deflection for a single element. The long dash lines (ON Cygnus A (blue curve), and OFF Cygnus A (red curve)) show the total power received from a single element, respectively, when pointed towards Cygnus A, and away from Cygnus A, showing the increase in antenna temperature when looking at the bright source with a single 4-dipole element. The other continuous lines (a LNA OFF, b LNA OFF, c LNA OFF, d LNA OFF, and e LNA OFF) are for 5 different elements for which the LNA has been terminated, i.e., they do not receive any sky signal.

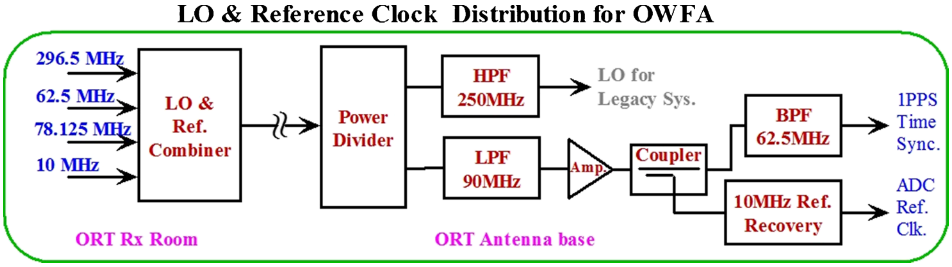

Figure 4. Reference and sync distribution.

supply for stage-1 system through the centre conductor of RF cable between the two stages. The output of second stage signal conditioners are directly fed to the 12-channel digitizer described below. The system response before digitization is shown in Fig. 3. It may be recalled that the bandpass is the result of cascading two SAW filters – one in stage-1 and the other in stage-2.

2.2 *Clock distribution, communication and control*

A GPS-disciplined rubidium oscillator provides a 10-MHz reference which is distributed to all the modules along with the local oscillator in the legacy system. A single cable originating from the receiver room branches into 22 cables in a Christmas tree configuration formed by a set of passive power dividers such that the relative phase difference between various modules in the transmission path is kept within a few degrees. At each module, a high pass filter passes the 296.5 MHz to the legacy mixer unit and a low pass filter passes frequencies below 100 MHz to OWFA subsystems located below the reflector. A combination of frequencies below 100 MHz is generated and combined with the legacy local oscillator for transmission through this chain (Fig. 4). One of these frequencies is the 10 MHz reference itself, from which the sampling clock is locally synthesized in the 12-channel digitizer described below. The other tones transmitted by OWFA system are meant for time synchronization and phase monitoring.

Time synchronization between various modules is carried out using a BFSK modulation with a phase-continuous frequency shift between 62.5 MHz and 78.125 MHz. The switching pattern is aligned to one pulse-per-second (1 pps) from a GPS receiver at the transmission end. For recovering the 1 pps at each module, BFSK is transformed into an ASK modulation by passing the signal through a 62.5-MHz filter to an rms detector (HMC10241). The output of the rms detector is converted to a sharp pulse using a Schmitt buffer and made available to the digitizer and control cards in the corresponding module as an external time sync.

2.3 *12-Channel digitizer*

As described earlier, at the base of each module, the RF signal elements from the two corresponding half-modules (6 elements/half-module) are passed through a second set of amplifiers (called stage-2 amplifiers) which include an anti-aliasing filter identical to the SAW filter in stage-1 amplifiers. The output of these signal conditioners are given to a 12-channel digitizer unit, whose functional blocks are shown in Fig. 5. It consists of 6 dual-channel ADC devices (AD9600) interfaced to an onboard FPGA (Spartan 6 SX45T). A pair of onboard synthesizers are used for generating the sampling clock from the centrally distributed 10 MHz reference available at each module. In addition to providing the 76.8 MHz sampling clock to the ADC devices, a spare output from one of the synthesizers is also connected to the on-board FPGA for its house-keeping operations. One of the house-keeping operations includes generation of local timer required for time-stamping data. The local timer generates a pulse per second (pps) used for internal logic. During initialization, the internal pps is aligned with the time sync recovered from the centrally distributed synchronization pulse. A user command is also available to adjust the internal pps by specified number of sampling clock ticks. This also provides a means for accommodating the small differences in propagation delays from the central distribution point to the recovery points in various modules.

From each ADC chip, the FPGA acquires data from the associated pair of signals, and delay compensates them using internal memory in the device. Delay-compensated data corresponding to 1600 consecutive samples from the two signals connected to an ADC device are stored in a memory block. For this buffering, data are compressed using a coding scheme which packs a total of 20 samples (10 from each input signal)

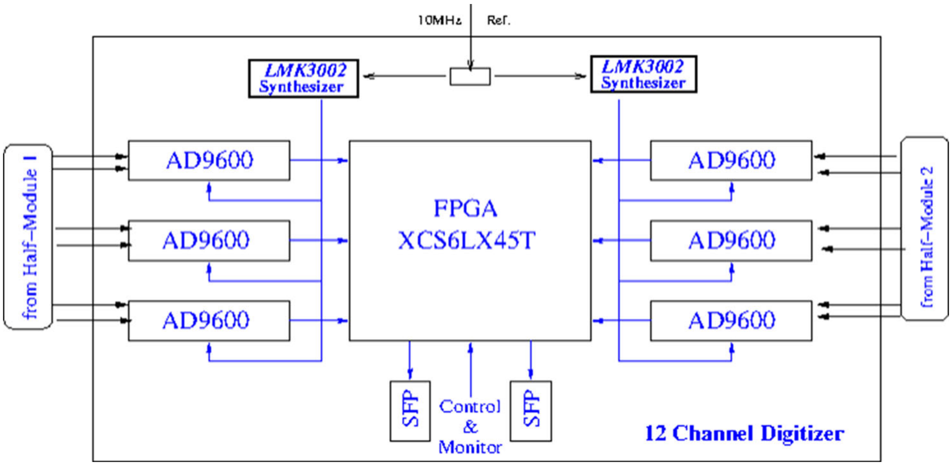

Figure 5. 12-Channel digitizer.

into a 64-bit word using a 3-bit coding and generating 4 control bits for each 64-bit word. This results in a 1280B word for 1600 consecutive samples from a pair of signals sampled by an ADC device. These are prefixed by a 32B preamble to form a frame buffer of size 1312B. Thus, at the end of 1600 sampling clock ticks, a total of 6 frames of constant size (1312B) are formed, where the 32B preamble in each frame contains meta-data containing useful information like sequence number, identification, timestamp, delays and project code. Double buffers are provided using on-chip memory (Block RAMs) so that while one set of 6 frames are being filled in, the previous set of 6 frames are transported to the central processing system. For transportation, the 6 frames are handled as two sets of 3 frames, where each set contains data from the 6 elements in a half-module. These frames are serialized and clock-encoded using Xilinx Aurora protocol and routed to two on-board transceivers for transmission at 2.5 Gbps link speed. The physical layer is based on standard off-the-shelf Small Form factor Plug-in (SFP) modules appropriate for single mode fibres.

The important system parameters resulting from this digitization are summarized in Table 1.

Table 1. OWFA system parameters.

Parameter	OWFA
Band centre	326.5 MHz ($\lambda = 0.9182$ m)
Element size	1.92 m = 2.087λ
Number of elements	264
Nominal FoV(NS)	$27.5^\circ \sec(\delta)$
Sampling rate	76.8 MS/s, 3-bit
Usable bandwidth	∼35 MHz typical
Continuum sensitivity	10 mJy/$\sqrt{t_{\rm sec}}$ rms
Spectral resolution	48 kHz

3. Conclusion

Conversion of the legacy ORT to an interferometer (the ‘Ooty Wide Field Array’, OWFA) will result in an instrument with high sensitivity as well as a large instantaneous field of view of $\sim 2^\circ \times 28^\circ \sec(\delta)$. The OWFA will be equipped with an 800-channel FX correlator with a spectral resolution of 48 kHz and a time resolution of a few milliseconds. This gives it a unique advantage for large scale deep surveys at metre wavelengths. The main science drivers are (1) observations of the power spectrum of HI emission from large scale structures at $z \sim 3.3$, (2) studies of the space weather in the inner solar heliosphere and (3) studies of transient sources. More details on the main science drivers behind the OWFA upgrade can be found in Subrahmanya *et al.* (this issue).

One of the major constraints in implementing this upgrade was the requirement that the ORT be kept in constant use, and hence it is necessary for the legacy receivers to continue to operate even as the upgrade proceeds. This constraint was met by introducing amplifiers in the path of passive combiner tree of the legacy system, from which one could tap signals for both the legacy systems as well as for the OWFA subsystems. If these amplifiers fail, the legacy system also will fail. The front-end of OWFA has been switched on for almost two years without affecting the legacy system. Thus, the entire front-end subsystem of OWFA has been undergoing field testing during this period and the successful operation of the legacy system indicates their robustness and stability.

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