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Review

The Ooty Wide Field Array

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Abstract. We describe here an ongoing upgrade to the legacy Ooty Radio Telescope (ORT). The ORT is a cylindrical parabolic cylinder 530 m × 30 m in size operating at a frequency of 326.5 (or $z \sim 3.35$ for the HI 21-cm line). The telescope has been constructed on a North–South hill slope whose gradient is equal to the latitude of the hill, making it effectively equatorially mounted. The feed consists of an array of 1056 dipoles. The key feature of this upgrade is the digitization and cross-correlation of the signals of every set of 4-dipoles. This converts the ORT into a 264 element interferometer with a field-of-view of $2^\circ \times 27.4^\circ \cos(\delta)$. This upgraded instrument is called the Ooty Wide Field Array (OWFA). This paper briefly describes the salient features of the upgrade, as well as its main science drivers. There are three main science drivers viz. (1) observations of the large scale distribution of HI in the post-reionization era, (2) studies of the propagation of plasma irregularities through the inner heliosphere and (3) blind surveys for transient sources. More details on the upgrade, as well as on the expected science uses can be found in other papers in this special issue.

Keywords. Cosmology: large scale structure of Universe—intergalactic medium—diffuse radiation.

1. Introduction

This article describes the Ooty Wide Field Array (OWFA) which is an upgrade of the Ooty Radio Telescope (ORT). The ORT (Swarup *et al.* 1971) is an offset parabolic cylinder, 530 m × 30 m in size commissioned in 1970 (Fig. 1). The telescope is mechanically steerable about the long axis of the cylinder. This axis is mounted along a hill whose slope is the same as its latitude, effectively making the telescope equatorially mounted. The sky can hence be tracked by rotation about the cylindrical axis. The telescope has a line focus, along which is placed an array of 1056 dipoles. Each dipole is followed by a Low Noise Amplifier (LNA) as well as a 4-bit phase shifter (Selvanayagam *et al.* 1993). The dipoles are grouped into 22 'modules' with each module consisting of 48 dipoles. In the legacy system the phased output of all modules are combined with appropriate phase and delay correction to produce up to 12 equispaced beams covering $36'$ in the North–South direction. The delays and phases can also be adjusted to change the North–South position of the beam centroid. The telescope pointing is hence a combination of mechanical steering (along the East-West direction) and electrical steering (along the North–South direction). The legacy telescope had an operational frequency centred at 326.5 MHz and a usable bandwidth of ∼4 MHz.

Compared to the legacy ORT the OWFA has both a larger instantaneous bandwidth as well as a significantly larger field-of-view. The main science drivers behind this upgrade are (1) detection of the HI 21-cm emission from the large scale structure at $z \sim 3.3$, (2) monitoring of the weather in the inner solar heliosphere (via high cadence observations of a dense grid of scintillating extra-galactic radio sources) and (3) searches for transient sources. All three of these science drivers are described in more detail in other articles in this issue. Here we give an overview of OWFA itself and a summary of its effectiveness in achieving these main science goals.

2. The OWFA instrument

The OWFA (Table 1) operates as an interferometer, where each element of the interferometer consists of the phased output of 4 contiguous dipoles from the feed

Figure 1. The Ooty Radio Telescope is an offset cylindrical paraboloid, 530 m × 30 m in size. It is equatorially mounted. The Ooty Wide Field Array (OWFA) is an upgrade to the ORT, which digitizes the signals from every 4 dipoles along the feed line. These signals are then cross-correlated, leading to a very wide field-of-view interferometer. See text for more details.

Figure 2. Custom FPGA rack to handle the data from the north half of OWFA. There is a similar rack for the south half of the telescope. These cards re-organize the packetized data from the 264 elements into 8 time slices, with each time slice containing the data from all 264 elements. The time slices are transferred to 8 different HPC nodes via ethernet. This allows the HPC nodes to independently carry out the 264 element FX correlation for each time-slice.

array. This corresponds to a length of 1.92 m, so the geometric area corresponding to each element is 1.92 × 30 m. The effective system temperature is 150 K (Selvanayagam *et al.* 1993). The process of conditioning and digitizing this signal is described briefly below. The interested reader is referred to Subrahmanya *et al.* (2017) for more details.

The phased output of the 4 dipole system is amplified and transported from the focal line to a set of 'pillars' located below the reflecting surface by co-axial cables. There is one pillar for each module, catering to 12 elements or a total of 48 dipoles. The set of 12 signals received at each pillar are amplified and then fed into a 12 channel ADC. SAW filters with a centre frequency of 327.5 MHz are used for image rejection, and the signals are bandpass-sampled to give an effective bandwidth of 38 MHz. The sampling clock in each of the pillars is locked to the central time and frequency standard of the observatory. A 1 pps signal is also distributed to all of the pillars to allow for synchronization. The digitized signals from the ADC are packetized using an onboard FPGA. These packets are transported to the central receiver room via optical fibre, using the Xlinx aurora protocol.

In the central receiver room the data processing is done using a Networked Signal Processing System (NSPS) (Prasad & Subrahmanya 2011) which consists of a set of custom FPGA cards (Fig. 2) and an HPC. The cards rearrange the data into sets of time slices, with each time slice containing 350 ms worth of data from all 264 elements re-framed as standard Ethernet UDP packets. These data are sent out using 1 GB ethernet links to an 8 node HPC, with each node receiving one time slice. Each HPC node consists of a dual socket Haswell server, along with an add on Intel Xeon-Phi 3510 card. This design allows for embarrassingly parallel data processing, with an 800 spectral channel, 264 element software FX correlator on each node with the F engine being on the mother board and the X engine on the Xeon-Phi cards.

There was a staged path to the realisation of OWFA. One of the first stages in the path was a precursor system (the so-called 'Phase I' system), which consisted of 40 elements, each corresponding to the combination of the signals from 24 dipoles (or half a module) and had a bandwidth of ∼19 MHz. The Phase I system did not include the two extreme modules of the ORT, and has been described in detail by Prasad (2011). Some of the papers in this issue also refer to this system. The Phase I system is no longer in active use. Since in the initial phases of observation there may be some advantages in testing algorithms using a simpler system where each element has a higher sensitivity and a smaller field-of-view, it is planned either that the Phase I system will be restored or that a similar functionality will be made available using the OWFA hardware.

The current status of the instrument is as follows. All of the RF amplifiers have been installed in the field

Table 1. System parameters for OWFA.

Parameter	Value
No. of elements	264
System temperature	150 K
Aperture area	30 m × 1.92 m
Field-of-view	1.75° × 27.4° cos(δ)
Shortest spacing	1.9 m
Longest spacing	505.0 m
Total bandwidth	38 MHz
Spectral resolution	48 kHz

and have been in regular use for some time. In fact (as detailed in Subrahmanya *et al.* 2017) these amplifiers now form a critical element in the path of the legacy system, and as such have been rigorously tested in the field. The digital systems (both in the field as well as in the central building) have been installed and interconnected by optical fibre links. The distribution of the sampling clock and the 1 pps synchronizing signals to the different pillars has been completed and tested. The data flow from the ADCs in the field to the HPC has also been tested. The key elements of the software correlator have been written, and it is expected that the instrument would be taking sky data by mid 2017.

3. Key science goals of OWFA

3.1 *HI at $z \sim 3.3$*

The HI 21-cm line is emerging as an important probe of both cosmological parameters as well as structure formation over a wide redshift range (see Pritchard & Loeb (2012) for a review). Importantly, the HI 21-cm line is the only available probe during the 'cosmic dark ages', i.e. before the formation of the first ionizing agents, and remains one of the most important probes through the 'cosmic dawn' era (when the first ionizing stars and black holes form) and the epoch of reionization. In the post-reionization era, neutral hydrogen is largely confined to dense collapsed objects but its large scale distribution remains an important probe of both structure formation and the evolution of cosmic parameters (see e.g. Bharadwaj *et al.* 2001, 2009; Bharadwaj & Sethi 2001; Chang *et al.* 2010; Bagla *et al.* 2010). The cosmology enabled using the HI 21-cm line (along of course, with other science drivers) has led to a re-awakening of interest in low-frequency radio astronomy, and a number of experiments are being planned in order to probe these different cosmic epochs. Experiments planned for the post-reionization era include CHIME (Bandura *et al.* 2014), BAOBAB (Pober *et al.* 2013) and Tianlai CRT (Chen 2011). The wide field-of-view, excellent sampling of the short baselines (where the HI signal is expected to be strong (Ali & Bharadwaj 2014)) as well as good sensitivity make OWFA also well suited for observations of the post-reionization HI signal. The highly redundant configuration of the OWFA interferometer also allows for efficient and high cadence redundant calibration (Marthi & Chengalur 2014), which is important in reducing systematics arising from foregrounds. Detailed calculations of the expected signal show that OWFA sensitivity is sufficient to make a $\sim 5\sigma$ detection of the amplitude of the power spectrum A_{HI} of the large scale distribution of HI emission at $z \sim 3.3$ in integration times of $\sim$150 h. Longer integrations ($\sim$1000 h, Sarkar *et al.* 2017; Ghelot & Bagla 2017), should have the sensitivity to measure the power spectrum at angular scales between $11'$ and $3°$ (or wavenumbers from $\sim$0.02 to 0.5 Mpc^{-1}). Two important astrophysical parameters that are constrained by these observations are the amplitude of the power spectrum A_{HI} (which in turn depends on the cosmic density of neutral hydrogen (Ω_{HI}), the neutral fraction (x_{HI}), and the bias parameter (b_{HI})) and the redshift distortion parameter β (Bharadwaj *et al.* 2015). As mentioned above, these measurements in turn also lead to constraints on the cosmological parameters (Bharadwaj *et al.* 2009). The expected HI 21-cm signal is however many orders of magnitude fainter than the radio emission from other foreground sources such as the diffuse galactic synchrotron emission and discrete extra-galactic radio sources. A detailed study of these foregrounds and their effect on the expected signal as observed by the OWFA are presented in Marthi *et al.* (2017, in preparation) based on a simulation package (described in Marthi 2017). These calculations include the HI signal, based on simulations of the expected cosmological distribution of HI. The HI simulations themselves are presented in Chatterjee *et al.* (2017). More details regarding the predicted outcomes of observations of HI with OWFA can be found in Ali & Bharadwaj (2014 and Bharadwaj *et al.* (2015), as well as in Sarkar *et al.* (2017). Ghelot & Bagla (2017) presented a similar study of the HI signal expected to be seen by OWFA and also compare OWFA with other instruments operating in this frequency range as far as suitability for detection of HI at $z \sim 3.3$ is concerned.

3.2 *Studies of the inner heliosphere*

Interplanetary scintillation (IPS) measurements are extremely useful to constrain the physical properties of the solar wind in the entire inner heliosphere (e.g., Manoharan 1993; Manoharan *et al.* 2001). For example, the legacy analog system of the ORT allows one to monitor IPS of about 600–1000 radio sources per day. Such observations have played a crucial role in studies of 3-D evolution of coronal mass ejections (CMEs), development of the associated interplanetary shocks as well as the acceleration of particles in the Sun–Earth space (e.g., Manoharan 2010; Manoharan & Agalya 2011). However, the Ooty 3-D reconstruction of both solar wind speed and density obtained from such monitoring has been limited to a latitude and longitude resolution of $\sim 10° \times 10°$ with about $10 R_\odot$ increment in heliocentric distance (Manoharan 2010). This restriction arises from the number of sources it is possible to observe in a given time. It also takes about half a day of observation to provide a 6-hour increment in 3-D views (Manoharan 2010; Kumar *et al.* 2011). In the case of OWFA, simulations show that the increase in sensitivity as well as the considerably more powerful beam-forming capabilities (as compared to the legacy system) would allow for a ∼5-fold increase in the number of sources that could be monitored in a given time (Manoharan *et al.* 2017). This allows for the imaging of CMEs and solar wind structures with much improved temporal and spatial resolutions. This in turn would provide a better understanding of the physical processes associated with the evolution of CMEs (for e.g. the associated shock, sheath and their influence on the ambient solar wind) and other solar wind transients.

3.3 *Transient studies*

The good sensitivity and very large field-of-view of the OWFA instrument make it an ideal instrument in blind searches for rare events such as radio transients. Interest in radio studies of transient events has been steadily increasing in the recent past, and forms one of the key science goals of many of the next generation telescopes including the SKA (Fender *et al.* 2015). In particular, the discovery of a new class of radio bursts with millisecond duration and dispersion measures consistent with an origin in cosmologically distant objects has led to renewed interest in blind searches for short duration bursts (Lorimer *et al.* 2007; Thornton *et al.* 2013). Although most of these so-called Fast Radio Bursts (FRBs) have been detected at frequencies ∼1.4 GHz, there has also been a detection at lower frequencies ($\sim 700 - 900$ MHz, Masui *et al.* 2015). While the DMs associated with FRBs are consistent with an extra-galactic origin, the exact source of these bursts is as of now yet unclear and there are models in which the sources are local (see e.g. Loeb *et al.* 2014). Detailed calculations of the expected FRB rate using the OWFA (assuming that the sources are at cosmological distances) show that the detection rate could be as high as several per day, depending on the assumed spectral index (Bera *et al.* 2016). Clearly transient searches with the OWFA would be of high scientific interest. More detailed calculations of the expected rate for different assumed scattering models and different observing strategies with the OWFA are presented in Bhattacharyya *et al.* (2017).

4. Summary

This paper describes an ongoing upgrade to the legacy Ooty Radio Telescope (ORT) to convert it into a wide field-of-view interferometer, called the Ooty Wide Field Array (OWFA). The key elements of this upgrade are briefly described, more details can be found in other papers in this issue. There are three main science drivers to this upgrade, viz. (1) observations of large scale distribution of HI in the post-reionization era, (2) studies of the propagation of plasma irregularities through the inner heliosphere and (3) blind surveys for transient sources. The key points of these three science cases have been discussed. Interested readers can find more details in the other papers in this issue.

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References

Ali, S. S., Bharadwaj, S. 2014, *J. Astrophys. Astr.*, **35**, 157–182, doi: 10.1007/s12036-014-9301-1.

Bagla, J. S., Khandai, N., Datta, K. K. 2010, *MNRAS*, **407**, 567–580, doi: 10.1111/j.1365-2966.2010.16933.x.

Bandura, K., Addison, G. E., Amiri, M., Bond, J. R., Campbell-Wilson, D., Connor, L., Cliche, J.-F., Davis, G., Deng, M., Denman, N., Dobbs, M., Fandino, M., Gibbs, K., Gilbert, A., Halpern, M., Hanna, D., Hincks, A. D., Hinshaw, G., Höfer, C., Klages, P., Landecker, T. L., Masui, K., Mena Parra, J., Newburgh, L. B., Pen, U.-l., Peterson, J. B., Recnik, A., Shaw, J. R., Sigurdson, K., Sitwell, M., Smecher, G., Smegal, R., Vanderlinde, K., Wiebe, D. 2014, Canadian Hydrogen Intensity Mapping Experiment (CHIME) pathfinder, in: *Ground-based and Airborne Telescopes V,* volume 9145 of Proc. SPIE, page 914522, doi: 10.1117/12.2054950.

Bera, A., Bhattacharyya, S., Bharadwaj, S., Bhat, N. D. R., Chengalur, J. N. 2016, *MNRAS*, **457**, 2530–2539, doi: 10.1093/mnras/stw177.

Bharadwaj, S., Sethi, S. K. 2001, *J. Astrophys. Astr.*, **22**, 293–307, doi: 10.1007/BF02702273.

Bharadwaj, S., Nath, B. B., Sethi, S. K. 2001, *J. Astrophys. Astr.*, **22**, 21, doi: 10.1007/BF02933588.

Bharadwaj, S., Sethi, S. K., Saini, T. D. 2009, *Phy. Rev. D*, **79(8)**, 083538, doi: 10.1103/PhysRevD.79.083538.

Bharadwaj, S., Sarkar, A. K., Ali, S. S. 2015, *J. Astrophys. Astr.*, **36**, 385–398, doi: 10.1007/s12036-015-9346-9.

Bhattacharyya, S., Bera, A., Bharadwaj, S., Bhat, N. D. R., Chengalur, J. N. 2017 , FRB event rate predictions for the Ooty Wide Field Array (OWFA), *J. Astrophys. Astr.*, this issue.

Chang, T.-C., Pen, U.-L., Bandura, K., Peterson, J. B. 2010, *Nature*, **466**, 463–465, doi: 10.1038/nature09187.

Chatterjee, S., Marthi, V. R., Bharadwaj, S. 2017, Simulating the $z = 3.35$ HI 21-cm visibility signal for the Ooty Wide Field Array (OWFA), *J. Astrophys. Astr.*, this issue.

Chen, X. 2011, *Scientia Sinica Physica, Mechanica & Astronomica*, **41**, 1358, doi: 10.1360/132011-972.

Fender, R., Stewart, A., Macquart, J.-P., Donnarumma, I., Murphy, T., Deller, A., Paragi, Z., Chatterjee, S. 2015, *Transient Astrophysics with the Square Kilometre Array*, ArXiv e-prints, arXiv:150700729.

Ghelot, B., Bagla, J. S. 2017, Prospects of detecting HI using redshifted 21-cm radiation at $z \sim 3$, *J. Astrophys. Astr.*, this issue.

Kumar, P., Manoharan, P. K., Uddin, W. 2011, *Solar Phys.*, **271**, 149–167, doi: 10.1007/s11207-011-9805-7.

Loeb, A., Shvartzvald, Y., Maoz, D. 2014, *MNRAS*, **439**, L46–L50, doi: 10.1093/mnrasl/slt177.

Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., Crawford, F. 2007, *Science*, **318**, 777, doi: 10.1126/science.1147532.

Manoharan, P. K. 1993, *Solar Phys.*, **148**, 153–167, doi: 10.1007/BF00675541.

Manoharan, P. K. 2010, *Solar Phys.*, **265**, 137–157, doi: 10.1007/s11207-010-9593-5.

Manoharan, P. K., Agalya, G. 2011, *Advances in Geosciences: Solar Terrestrial (ST)*, **27**, 165.

Manoharan, P. K., Tokumaru, M., Pick, M., Subramanian, P., Ipavich, F. M., Schenk, K., Kaiser, M. L., Lepping, R. P., Vourlidas, A. 2001, *ApJ*, **559**, 1180–1189, doi: 10.1086/322332.

Manoharan, P. K., Subrahmanya, C. R., Chengalur, J. N. 2017, Space weather and solar wind studies with OWFA, *J. Astrophys. Astr.*, this issue.

Marthi, V. R. 2017, Prowess – a programmable ORT wide-field emulator system, *J. Astrophys. Astr.*, this issue.

Marthi, V. R., Chengalur, J. 2014, *MNRAS*, **437**, 524–531, doi: 10.1093/mnras/stt1902.

Masui, K., Lin, H.-H., Sievers, J., Anderson, C. J., Chang, T.-C., Chen, X., Ganguly, A., Jarvis, M., Kuo, C.-Y., Li, Y.-C., Liao, Y.-W., McLaughlin, M., Pen, U.-L., Peterson, J. B., Roman, A., Timbie, P. T., Voytek, T., Yadav, J. K. 2015, *Nature*, **528**, 523–525, doi: 10.1038/nature15769.

Pober, J. C., Parsons, A. R., DeBoer, D. R., McDonald, P., McQuinn, M., Aguirre, J. E., Ali, Z., Bradley, R. F., Chang, T.-C., Morales, M. F. 2013, *AJ*, **145**, 65, doi: 10.1088/0004-6256/145/3/65.

Prasad, P. 2011, *A high speed network centric receiver architecture for low frequency arrays*, Ph.D. thesis, Jawaharalal Nehru University.

Prasad, P., Subrahmanya, C. R. 2011, *Exp. Astron.*, **31**, 1–22, doi: 10.1007/s10686-011-9216-7.

Pritchard, J. R., Loeb, A. 2012, *Rep. Progress Phys.*, **75(8)**, 086901.

Sarkar, A. K., Bharadwaj, S., Ali, S. S. 2017, Fisher matrix based predictions for measuring the $z = 3.35$ binned 21-cm power spectrum using the Ooty Wide Field Array (OWFA), *J. Astrophys. Astr.*, this issue.

Selvanayagam, A. J., Praveenkumar, A., Nandagopal, D., Veluswamy, T. 1993, *IETE Tech. Rev.*, **10**, 333–339.

Subrahmanya, C. R., Prasad, P., Girish, B. S., Somasekhar, R., Manoharan, P. K., Mittal, A. K. 2017, *J. Astrophys. Astr.*, this issue.

Swarup, G., Sarma, N. V. G., Joshi, M. N., Kapahi, V. K., Bagri, D. S., Damle, S. H., Ananthakrishnan, S., Balasubramanian, V., Bhave, S. S., Sinha, R. P. 1971, *Nat. Phys. Sci.*, **230**, 185–188, doi: 10.1038/physci230185a0.

Thornton, D., Stappers, B., Bailes, M., Barsdell, B., Bates, S., Bhat, N. D. R., Burgay, M., Burke-Spolaor, S., Champion, D. J., Coster, P., D'Amico, N., Jameson, A., Johnston, S., Keith, M., Kramer, M., Levin, L., Milia, S., Ng, C., Possenti, A., van Straten, W. 2013, *Science*, **341**, 53–56, doi: 10.1126/science.1236789.