P.K. Manoharan
Radio Astronomy Centre
National Centre for Radio Astrophysics
Tata Institute of Fundamental Research
Ooty 643001, India

mano@ncra.tifr.res.in

IPS Workshop
STEL, Nagoya University
23 – 24 November 2013
National Centre for Radio Astrophysics
Tata Institute of Fundamental Research

Observing Facilities

Giant Metrewave Radio Telescope

Ooty Radio Telescope
Radio Astronomy Facilities

- **Giant Meter wavelength Radio Telescope (near Pune)**
  - Multi-frequency synthesis imaging system
  - 25-km baseline
  - 30 antennas of each 45 m diameter
  - In the NCRA campus, 15m antenna (various Radio Physics Lab. projects)

- **Ooty Radio Telescope (southern part of India)**
  - Observing frequency 327 MHz
  - Steerable antenna of size 530m x 30m parabolic cylindrical antenna
  - Various astronomical observations and solar wind studies
  - Callisto Solar Spectrograph (part of worldwide radio net)
    - Frequency range 45 – 890 MHz
    - 300 kHz – each channel bandwidth
    - solar radio spectrograph
  - Muthorai Radio Telescope – for dedicated solar observations
    - 290 – 350 MHz
    - Steerable antenna of size 92m x 9m
    - fixed-frequency solar observations (high temporal resolution ~1 ms)
Ooty Radio Telescope (ORT)

- Latitude: 11°23’ North Longitude: 76°40’ East
- Equatorially mounted, off-axis parabolic cylinder
- 530m (N-S) x 30m (E-W)
- Reflecting surface made of 1100 stainless steel wires
- Feed – 1056 λ/2 dipoles
- E-W Tracking and N-S Steering of ORT (~9.5 hours, ± 60°)

IPS measurements - advantages

- High sensitivity
- tracking
- good declination coverage
- less radio interference in this region

Operated by
Radio Astronomy Centre
National Centre for Radio Astrophysics
Tata Institute of Fundamental Research (NCRA-TIFR)
- 530m (N-S) x 30m (E-W) – east-west tracking of ~9.5 hours
- North-South beam steering (± 65 deg. declination)
- High sensitivity, S/N ~ 25 (1s integration, BW 4 MHz)

http://rac.ncra.tifr.res.in
Reflector is made of 1100 thin ss wires
Linear array of dipoles 1056
- LNA behind each dipole
- 4-bit phase shifter for a dipole

Operating frequency 326.5 MHz
- LO 296.5 MHz
- IF 30 MHz

22 Modules (N1-N11 and S1-S11)
- 48 dipoles in each module

Analog beams – 12-beam system
- 3 arcmin separation
- covers 2° x 36’ sky
- total-power mode
- correlated-beam mode

Block diagram of the ORT receiver system
One module of ORT

Block diagram of a module of the ORT
ORT Correlated Beam Shape

09072013 - 0240-002

Time 06:47:12
Beam No 11
S/N: 23.8
Lunar occultation (initial period of ORT)

Various Pulsar studies

VLBI (ground and space)

Radio recombination line works

Radio transients, etc.

Interplanetary Scintillation (IPS) Measurements

PSR B1642-03 Profile on 16 September 2012

Pulsar receiver system
BW ~16 MHz
samples ~64 ms

enables to study of details of profiles and emission away from main pulse
e-Callisto – Worldwide Radio Network
24-hour Solar Observing

measurements: type II radio bursts, CMEs, shock waves, type III bursts etc.

Data available at http://www.e-callisto.org/
Ooty e-Callisto

13 Jun 2010 Radio flux density (OOTY)

OOTY India

Frequency [MHz]

Intensity

05:36:16 05:38:21 05:40:26 05:42:31 05:44:36

Time [UT]
Upgrades for Ooty Radio Telescope

In collaboration with Raman Research Institute, Bangalore
ORT upgrade – Phase I

ORT as a 44-element programmable telescope

– Digitize RF from 44 half modules (11.5mx30m section of ORT)

– 44 numbers of Stage 1 and Stage 2 amplifiers, respectively, at the feed and at the bottom of the telescope

– Transporting signal via fiber optic link

– A distributed signal processing chain (12-ch A/D converts with Xilinx Spartan-6 FPGA-based pre-processing capability)

– RF digitization tested for all half modules, data transfer over optical fibre to central computers completed

– Software offline FX correlator developed and tested
Figure 3.1: ORT RF Frontend for an array of 24 dipoles (Half module). The RF tapping location for the RF digital receiver is shown. The RF frontend is implemented within the line feed of the telescope.
Figure 3.2: *Frontend IF conversion subsystem,* which generates a single IF output by combining the RF of 48 phased dipoles. The generated IF is then sent to the central receiver room for further processing.
Phase I – 44 half-module signals
ORT upgrade – Phase II

Major components

– ORT has been configured as a 264-element programmable telescope
  • To digitize RF for every 4-phased dipoles (2m x 30m section; 264 sections along the feed of ORT)

– 264 pre-amplifiers and a set of 264 low-loss cables bring RF outputs of pre-amplifiers to the fixed enclosures

– 264 Stage-II amplifiers plus filter (to provide ~80 dB gain)

– Fiber optic communication for distributing clock and data between central receiver and base of each module
Phase II

Figure 3.20: Proposed NSPS implementation for configuring ORT as a 264 element programmable telescope.
ORT – Recent upgrades – sensitivity and field of view

• 2 Phases
  • Digitize RF from every 24 phased dipoles (~12-m section)
  • Digitization of 4-phased dipoles (~2-m section)
    • Field view 27 deg.
    • Full 264-element programmable system
  • Software-based FX correlator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current</th>
<th>Phase-1</th>
<th>Phase-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>4 MHz</td>
<td>18 MHz</td>
<td>40 MHz</td>
</tr>
<tr>
<td>FoV</td>
<td>2.3° x 2.2°</td>
<td>2.3° x 4.6°</td>
<td>2.3° x 27°</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>40 mJy</td>
<td>12 mJy</td>
<td>8 mJy</td>
</tr>
</tbody>
</table>

(τ = 1 s)
Science with new Programmable Digital Receiver

ORT – a new versatile system for many astrophysical studies

IPS with ORT

- wide field of view (2° x 27°) – within the field of view, number of beams can be formed (or beam can be formed at any given direction of the scintillating source)
- at a given time (~2-3 min of observing time) several scintillating sources can be observed
- provides increased spatial resolution of the sky coverage
- Improved tool for space weather Studies (physics of propagation of solar eruptions)
Interplanetary Scintillation

High sensitivity of ORT allows day-to-day IPS monitoring of large number of compact radio sources

Ooty IPS at 327 MHz

• Sensitive to solar wind irregularities scale size of ~10 – 500 km
• Heliospheric coverage
  • 10 – 250 Rsun
  • at all helio latitudes

For each source- estimation of
  • power spectrum
  • scintillation index

Suitable calibration provides
  • solar wind velocity
  • density turbulence level

Scintillation Record (3C273, 220CT2009)

Intensity

Samples (each 20 ms)
Lines of sight typically observed in a day
(2-AU cube)
85% of Sources ≤200 mas
Spectral Power (dB)

Temporal Frequency (Hz)
IPS – Power Spectrum

\[ \rho(r, t) = \langle \Delta I(r_o, t_o) \Delta I(r_o + r, t_o + t) \rangle \]

\[ P_I = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \rho(0, t) \exp(-i2\pi ft) dt \]

\[ m^2 = \frac{1}{\langle I \rangle^2} \left[ \int_{-\infty}^{+\infty} P_I(f) df \right] \]
Density Turbulence

* Scintillation index, m, is a measure of level of turbulence
* Normalized Scintillation index, $g = \frac{m(R)}{<m(R)>}$
* Quasi-stationary and transient/disturbed solar wind

- $g > 1 \rightarrow$ enhancement in $\delta Ne$
- $g \approx 1 \rightarrow$ ambient level of $\delta Ne$
- $g < 1 \rightarrow$ rarefaction in $\delta Ne$

Scintillation enhancement w.r.t. the ambient wind identifies the presence of the solar wind transient (CME/CIR) along the line-of-sight to the radio source.
IPS temporal power spectrum

IPS – intensity fluctuations are caused by the solar wind density turbulence - time series transformation provides the temporal power spectrum

\[
P(f) = (2\pi r_e \lambda)^2 \int dq \frac{dz}{V_p(z)} \int_{-\infty}^{\infty} dq_y 4\sin^2 \left( \frac{q^2 z}{2k} \right) \left| V(q, z, \theta) \right|^2 R^{-\beta} q^{-\alpha}
\]
Density Turbulence Spectrum

“Interplanetary Scintillations” (IPS)

intensity fluctuations caused by the solar wind density turbulence

This time series transformation provides the temporal power spectrum

\[
P(f) = \frac{(2\pi r_e \lambda)^2}{d\eta} C_{Ne}^2 \Phi_{Ne}(q) F_{\text{diff}}(q) F_{\text{source}}(q)
\]

\(\lambda\) is wavelength of observation; \(r_e\) is classical electron radius.

\(F_{\text{diff}}(q)\) = Fresnel diffraction filter (attenuates low-frequency part of the spectrum)

\(F_{\text{Source}}(q)\) = Brightness distribution of the source (attenuates high frequency part)
Axial Ratio of Irregularity

When the density irregularities are field aligned and approximated with an ellipsoidal symmetry, the spatial spectrum of density fluctuations, $\Phi_{Ne}(q)$, for a radio source with the finite size, $\theta$, will be

$$\Phi_{Ne}(q, 0) | B(\theta) |^2 = (q_x^2 + \frac{q_y^2}{AR^2})^{-\frac{\alpha}{2}} \exp\left(-\frac{q^2}{q_i^2}\right)$$

AR is the ratio of major to minor axes (axial ratio), which is the measure of degree of anisotropy of irregularities ($\alpha$ power-law index. $q_i$ cut-off scale i.e., inner-scale size).
Interplanetary scintillation spectra

Power law $q^{-(\alpha+1)}$

Fresnel filter knee

Logarithmic temporal Frequency (Hz)

Source size and Inner-scale filters
Solar Wind Density Turbulence and Speed (3 days)

Solar Wind Density Turbulence Maps Observed at Ooty

Solar Wind Velocity Maps Observed at Ooty
The left movie shows an ecliptic cut through the 3D Ooty IPS density reconstruction and the right movie show a meridional cut (from East of the Sun-Earth line) of the same; both with the Earth on the right-hand side and it’s orbit shown in each case.
Thank You