Prototype for pulsar observations at low radio frequencies using log-periodic dipole antennas

Kshitij S. Bane, Indrajit V. Barve, G. V. S. Gireesh, C. Kathiravan, and R. Ramesh

Abstract. A prototype for dedicated observations of pulsars and other astrophysical transients in the frequency range of 50 to 80 MHz has been recently commissioned in the Gauribidanur Radio Observatory near Bangalore in India. The antenna setup, the analog and digital receiver systems, and the initial observations are presented.

Keywords: pulsars; radio observations; low frequencies; instrumentation.

1 Introduction

A pulsar is a neutron star, i.e., the ultradense core that remains after a massive star undergoes a supernova explosion. It spins at very rapid rates ranging from once in a few seconds to as much as \( \sim 700 \times \) per second. The strong magnetic fields (~10\(^8\) to \(10^{14}\) G) created when a neutron star is formed and the star’s rapid rotation result in a magnetosphere. Due to misalignment of the magnetic and rotation axes of the pulsar, the radio emission comes out in two beams, one from each pole of the magnetosphere. The observed emission is coherent, but the mechanism behind the coherence is still being debated. These rotating beams of radiation can be noticed whenever they intersect our line of sight to the pulsar, similar to a lighthouse on the sea-shore. Each rotation of the pulsar thus produces a narrow pulse of radiation. The first pulsar was observed at a low frequency of \( \approx 81.5 \text{ MHz} \).\(^1\) However, much of our present knowledge about pulsars has come primarily from radio observations at frequencies >300 MHz. The primary reason for this is that the emission from pulsars at low frequencies are more affected by dispersion and scattering during their propagation through the interstellar medium (ISM) as compared with higher frequencies. The delay in the arrival time of the pulses due to the dispersive properties of the ISM varies as \( \nu^{-2} \) (where \( \nu \) is the frequency of observation), whereas the interstellar scattering changes as \( \sim \nu^{-4} \) (see Ref. 2). The latter leads to broadening of the pulses, resulting in them overlapping.\(^3,4\) It then becomes difficult to distinguish the maxima and minima in a pulse. The periodic nature of the signal is either subdued or nearly lost when the pulse broadening time becomes nearly comparable to the spin period of the pulsar (see Ref. 5). The other reasons for the limited observations of pulsars at frequencies \( \leq 100 \text{ MHz} \) are the comparatively intense synchrotron emission from the Galactic background and the radio frequency interference (RFI).

Pulsar observations at frequencies \( \leq 100 \text{ MHz} \) are necessary for understanding the emission mechanism and characteristics of the pulse profile as a function of frequency, which are still being examined. For example, the radius-to-frequency mapping effect in pulsars is most prominent at lower frequencies.\(^5,7\) Many pulsars exhibit a turn-over in the spectrum close to \( \approx 100 \text{ MHz} \).\(^8,9\) Therefore the extension of their spectra toward lower radio frequencies is naturally of great interest. This is especially so for pulsars with an intensity that is increasing with decreasing frequency in the known part of their spectra. An understanding of the propagation of the low frequency radio waves in the ISM is also important. The \( \nu^{-3} \) dependence of scattering in

\(^1\)Address all correspondence to Kshitij S. Bane, kshitij.sb@iiap.res.in

2329-4124/2022/$28.00 © 2022 SPIE
the ISM makes the dispersion effects stronger at lower frequencies and making it easier to carry out better measurements of the dispersion measure (DM). Observations of pulsars at frequencies $\lesssim 100$ MHz are currently carried out with LOw-Frequency ARray (LOFAR),\textsuperscript{10,11} UTR-2 telescope,\textsuperscript{12} Murchison Widefield Array (MWA),\textsuperscript{13} Long Wavelength Array (LWA),\textsuperscript{2} and Engineering Development Array (EDA)\textsuperscript{14,15} in the time-sharing mode. Exploration of transient phenomena in the universe is an exciting and rapidly growing area of radio astronomy. Considering this, we have set up a radio telescope in the Gauribidanur Observatory\textsuperscript{6,17} (longitude: 77.4°E; latitude: 13.6°N) for dedicated observations of pulsars in the frequency range of 50 to 80 MHz. RFI in Gauribidanur is also minimal.\textsuperscript{18–20} Its purpose is for observation and understanding of the characteristics of known pulsars and periodic fast radio bursts (FRBs)\textsuperscript{21–24} at low frequencies. The observing facility described in this work is a dedicated instrument with wide sky coverage, large bandwidth, and high time resolution (see Secs. 2 and 3), all of which are important for observations of fast transients (see Ref. 5). In the rapidly developing field of study of the transient sky, FRBs are perhaps the most exciting objects of scrutiny at present, so there is potential for new observations.\textsuperscript{25}

2 Antenna and Front-End Analog Receiver System

The basic signal reception element used in at the observatory is a log-periodic dipole antenna (LPDA). It is a broadband directional antenna with characteristics that are nearly constant over its entire operating frequency range.\textsuperscript{26} We set up an array of 16 LPDAs on a north–south baseline with a spacing of 5 m between the adjacent antennas. They are combined as two groups with eight LPDAs in each group (see Fig. 1). The LPDAs used in the array are designed according to the formulations reported in the literature.\textsuperscript{27} The characteristic impedance of the LPDA is $\approx 50$ $\Omega$. Its half-power beam widths (HPBW) as per calculations are $\approx 80$ deg (E-plane) and $\approx 110$ deg (H-plane). All of the 16 LPDAs were mounted with their H-plane in the east–west direction. The effective collecting area and gain of each LPDA is $\approx 0.4 \lambda^2$ (where $\lambda$ is the wavelength corresponding to the observing frequency) and $\approx 6.5$ dBi (with respect to an isotropic radiator), respectively. The voltage standing wave ratio is $< 2$ over the frequency range of 40 to 440 MHz.\textsuperscript{28} The aforementioned effective collecting area and the HPBW of the LPDA are

![Fig. 1 The array configuration and the front-end signal path.](image-url)
larger compared with that of the other similar frequency independent receiving elements such as the inverted V-shaped dipoles and bowtie antennas, respectively, used elsewhere. Since the LPDAs are arranged on a north–south baseline, the combined response pattern of the array (16 LPDAs) is \(\approx 110\) deg in the east–west (hour angle) direction and \(\approx 3\) deg in the north–south (declination) direction for observations near the zenith at a typical frequency such as 65 MHz. It is a fan beam with the above resolution in declination. The width of the east–west response pattern is nearly independent of frequency. Being very wide, a radio source should be observed continuously for \(\geq 7\) h. A RG58U coaxial cable connected to the feedpoint near the top of the LPDA is used to transmit the radio frequency (RF) signal incident on the LPDA to the input of a low-pass filter with 3 dB cutoff at \(\approx 85\) MHz, followed by a high-pass filter with 3 dB cutoff at \(\approx 35\) MHz and a wideband amplifier with a uniform gain of \(\approx 30\) dB in the frequency range of 35 to 85 MHz. The two filters and the amplifier are kept near the base of the LPDA to minimize the length of the RG58U cable and hence the transmission loss. The high- and low-pass filters help to attenuate the unwanted signal at frequencies \(\lesssim 30\) and \(\gtrsim 85\) MHz. The filtered and amplified signal from each LPDA is then passed via a cable delay unit (explained in the following paragraph). Subsequently, they are combined using two sets of an eight-way power combiner followed again by a high-pass filter, low-pass filter, and wideband amplifier as mentioned earlier.

As the array is oriented in the north–south direction, the RF signal coming from an astronomical source with a declination that is different from the local zenith (\(\approx 14^\circ\) N) will be incident on each LPDA in the array at different instances of time. So, to coherently combine the signal from the different LPDAs, there is provision to include a cable of appropriate length in the signal path from each LPDA in the array to compensate for the time delay. This allows the response pattern (“beam”) of each group of eight LPDAs to be “phased” toward any desired declination in the range of \(\approx -26^\circ\) S to \(\approx +54^\circ\) N. The limits are due to the HPBW of the LPDA along its E-plane and the local latitude mentioned earlier. The step interval in the cable delay unit corresponds to an angle of \(\approx 3\) deg, and the maximum angle to which the “beam” of the group of eight LPDAs could be “phased” in the north-south direction is \(\approx 45\) deg. Note that the aforementioned minimum step interval in the delay unit results in a phasing error of \(\pm 1.5\) deg (the same as that for the “beam” of the array in declination mentioned in the previous paragraph). It corresponds to a delay error of \(\pm 3\) ns for the total length of 35 m for the group of eight LPDAs (see Fig. 1). We neglect this since it is small in general and less than the minimum delay of \(\approx 11\) ns that could be applied digitally in the present case (see Sec. 3). The combined output from each group of antennas is then transmitted to the receiver building (located \(\approx 300\) m away) via low-loss coaxial cables buried \(\approx 1\) m below the ground level to minimize possible diurnal variations in the characteristics of the cable. To compensate for the transmission losses during propagation, the RF signal from the two antenna groups are amplified in the receiver building. The output of the amplifiers is passed through 50 to 80 MHz bandpass filters to attenuate any spurious pickup outside the band. Then the signal is fed to the input of the digital receiver.

3 Back-End Digital Receiver System

We used a field-programmable gate array (FPGA)
-based digital spectrometer, which converts the input voltage signal to its power spectrum using the fast Fourier transformation (FFT) technique. The spectrometer is implemented on Reconfigurable Open Architecture Computing Hardware (ROACH) from the Collaboration for Astronomy Signal Processing and Electronics Research. The ROACH board hardware has the Xilinx Virtex-5 FPGA. Figure 2 shows the schematic of the digital receiver system.

The RF signals corresponding to the two antenna groups in Fig. 1 are connected to the input of an analog-to-digital converter (ADC). It is a quad-ADC containing four AD9480 ICs. We use two channels of the ADC for this work. The ADC converts the input voltage to an 8-bit Fixed point number (Fix 8.7) between \(-1\) and \(+1\). Note that a linear relation between the input and output of the ADC for a large range of the input signal is important for any digital system. To check this, a broadband noise signal with provision to vary the input power level was connected to the input of the ADC. The output from the ADC was recorded for different levels of the input signal and then processed offline to get the power spectrum using FFT. Figure 3 shows the results...
The spectral power is linear for the input signal amplitude in the range $\approx -42$ to $\approx -4$ dBm. This implies that the measured dynamic range (MDR) of the ADC is $\approx 38$ dB. The effective number of bits (ENOB) = $\frac{MDR}{6.02} = 6.3$ bits. Note that, for an 8-bit ADC, the expected dynamic range and ENOB are $\approx 6.02 \times 848$ dB and $\approx 7.3$ bits, respectively. But these numbers are valid primarily for continuous wave (CW) signals at specific spot frequencies only.

We use a 90 MHz clock to sample the bandlimited RF signal of 50 to 80 MHz since the latter is in the second Nyquist zone (45 to 90 MHz) of the aforementioned sampling frequency. Depending on the declination of the source, appropriate delays are applied to the RF signal from either of the two groups in steps of 11.11 ns to coherently combine the signals later. The corresponding delay error (i.e., $\pm 5.5$ ns) limits the phasing of the north–south “beam” of the array to $\pm 2.3$ deg with respect to the source declination. To obtain the power spectra of the RF voltage signals, the outputs from the delay units are processed using a combination of a finite impulse response (FIR) filter and FFT, together called a “Polyphase filterbank” (PFB). Since the FFT is computed over a finite number of samples, its response suffers from spectral leakage. But when an FIR filter with windowing function is used before the FFT, leakage into the adjacent spectral channels is considerably reduced. In our design, a 4-tap FIR filter with Hamming window of 18-bit coefficients followed by 2048-points FFT is used. The latter has 1024 “positive” frequency bins. The total bandwidth sampled is 45 MHz, as mentioned earlier. So, the frequency resolution is 43.945 kHz. To test the spectral leakage, the CW signal at different frequencies (64.9 to 65.1 MHz in steps of 1 kHz) was fed to the input of the digital receiver in succession. An inspection of the test results (Fig. 4) indicates that the isolation between adjacent frequency bins is $\approx -49$ dB. The full width at half maximum (FWHM) of each frequency bin is $\approx 36$ kHz. Note that the latter should have been $\approx 43.945$ kHz, as mentioned earlier. But due to the frequency response of the 4-tap PFB, the FWHM of each bin is reduced to $\approx 36$ kHz. The isolation
offered by a 4-tap PFB (≈50 dB, see Fig. 5) is sufficient for isolating spectral leakage. Note that increasing the number of taps in the PFB improves the isolation. The main lobe response will be flatter (see Fig. 5 for a comparison between 4-tap and 8-tap PFBs). These are useful for carrying out high precision timing studies of pulsars. But the possibilities of timing studies at low frequencies are restricted since the pulse profiles are scattered more broadly. Further, folded/average pulse profiles are generated on most occasions. So a 4-tap PFB with a Hamming window is used.

Note that the pulsar signal gets dispersed during its propagation through the ISM. The higher frequency components in the signal reach the observer earlier compared with the lower frequency components. Therefore the received signal needs to be de-dispersed to reconstruct the pulse. There are two types of de-dispersion methods: coherent and incoherent. \(^{36}\) We use the incoherent de-dispersion technique as it is computationally easier. \(^{37}\) The frequency resolution mentioned earlier allows for finer correction for the dispersion and limits the possible leakage of the narrowband RFI to adjacent spectral channels. The PFB block output is 36 bits wide with 18 bits each for the real and imaginary parts. The outputs corresponding to the two antenna groups are combined and squared to get the power spectrum (see Fig. 6). The spectral data are then integrated for the desired duration. The output at this stage is 39 bits wide. The 10 Gb Ethernet interface (see Fig. 2) allows for 64-bit data to be transmitted. \(^{38}\) To facilitate the transfer, the aforementioned output is truncated to 32 bits by leaving 7 bits from the least significant bit (LSB) and thereby making it easier to packetize the data in such a way that two data points are mixed together. Any degradation of the signal due to this truncation is expected to be minimal since the information content in the LSBs corresponds primarily to noise fluctuations in the data only. The integrated output, which is now quantized to a 32-bit unsigned number, is packetized.
with headers and sent to the data acquisition computer over 10 Gb Ethernet (see Fig. 2). Each packet contains a user datagram protocol (UDP) header and a custom header. The latter has observation details, 1 pulse per second (PPS) count, and a packet count. The 1 PPS signal is derived from a GPS clock (Trimble Thunderbolt E-GPS Disciplined clock) and given to the FPGA via the ADC card to generate the 1 PPS count. The packet count is a unique packet number assigned to each packet.

4 Data Processing Pipeline

The data acquired are first processed through a MATLAB-based quick-look code for a quality check of the observation. The spectral response (see Fig. 6) is plotted and inspected to ensure that the system performance was in order during the observation. The aforesaid code checks for any “packet loss” that might have happened while writing the data to the hard disk of the acquisition computer. The “packet loss” would give rise to gaps in the data stream, which in turn affect the arrival times of the pulses leading to a lower signal-to-noise (S/N) for the observed pulsar. In extreme cases, it may not be possible to detect the pulsar when the data are folded. A unique number is assigned to each packet and mentioned in the file header while writing the data. The packet number is used to assess “packet loss.” If there are any, a new file is created by inserting zeros in the place of the lost packets to maintain continuity in the data stream. After the above processes, the data are converted to SIGPROC “filterbank” format for further analysis using the Pulsar Search and Exploration Toolkit. The file is read using the “readfile” tool, and the metadata are examined. RFI mitigation is performed using the “rfifind” tool, which searches for prominent RFI in the time series as well as in the frequency domain and creates “mask” files. It also generates diagnostic files containing data statistics, identifies the time-domain statistical issues, and marks them as RFI. The RFI “masks” are used in the subsequent stages of data processing. Subsequently, the “prepfold” tool is used to carry out folding and de-dispersion. It searches over a range of pulse periods and DM values to obtain the best fit for the corresponding parameters, i.e., the period and DM of the pulsar present in the observed data. Finally, the integrated pulse profile with the highest S/N is generated.

5 Trial Observations

We carried out observations of the sky background in the meridian transit mode to understand the characteristics of the antenna array and the receiver system. Figure 7 shows the observations...
carried out on June 30, 2021, at a typical frequency such as 65 MHz. The bandwidth and integration time used were \( \approx 30 \text{ MHz} \) and \( \approx 1 \text{ s} \), respectively. The maximum in the observed emission was around \( \approx 18 \text{ h} \) local sidereal time (LST) as expected (see Refs. 42 and 43). The duration of the observed profile (at the half maximum level) derived from the least squares fit was \( \approx 9 \text{ h} \). This corresponds to an angular extent of \( \approx 135 \text{ deg} \). In comparison, the HPBW of the array pattern (in the east-west direction) was \( \approx 110 \text{ deg} \) (see Sec. 2). Note that the observed deflection in Fig. 7 is primarily due to the intense patch of emission extending over the LST range of \( \approx 16 \) to 21 h in any low frequency all-sky map (see Refs. 42 and 44). A convolution of the aforementioned region (angular extent \( \approx 75 \text{ deg} \)) with the array pattern (HPBW \( \approx 110 \text{ deg} \)) could give rise to a \( \approx 135 \text{ deg} \) width for the observed profile (see Refs. 45 and 46).

Moving on to pulsar observations, we targeted the historical B1919 + 21 (J1921 + 2153) for our trial run. It is also located closer to the local zenith (\( \approx 14^\circ \text{N} \)) in Gauribidanur. Some of the characteristics of this pulsar are as follows:

- Mean flux at 65 MHz \( \approx 1.6 \text{ Jy} \). Period = 1.337 s, pulse width \( \approx 0.140 \text{ s} \), and DM \( \approx 12.437 \text{ pc cm}^{-3} \). Note that the dispersive nature of the ISM causes smearing of the pulsar signal over a time \( t_{\text{smear}} \), which depends on the DM of the pulsar, frequency and bandwidth of observation. For the FWHM of the frequency bins mentioned earlier (\( \approx 36 \text{ kHz} \)) and the frequency band of observation in the present case (i.e., 80 to 50 MHz), \( t_{\text{smear}} \) for B1919 + 21 will be in the range \( \approx 5 \) to 34 ms. These values are well within the pulse period of B1919 + 21 (i.e., 1.337 s). We observed the pulsar for a total duration of \( \approx 2 \text{ h} \) with an integration time of \( \approx 4 \text{ ms} \). The north–south “beam” of the array was “phased” to the declination of the pulsar (21° N) for the observations (see Sec. 2).

Figure 7 shows the results of our observations. The pulsar was detected with S/N \( \approx 23 \). Comparing this with the mean flux of the pulsar, we find that the noise fluctuations should be \( \approx 0.07 \text{ Jy} \). This is reasonably consistent with the estimated \( \Delta S_{\text{min}} \) (\( \approx 0.12 \text{ Jy} \)) taking into consideration that the above S/N and duty cycle (i.e., ratio of the width W of the pulse profile to its period \( P \)) of the pulsar is \( \approx 0.078 \). The other parameters used in the calculations are as follows: total observing period \( \approx 2 \text{ h} \), \( T_{\text{sys}} \approx 8500 \text{ K} \) at 65 MHz, bandwidth \( \approx 30 \text{ MHz} \), and number of polarizations = 1. The above observational results from Figs. 7 and 8 indicate that our observing system is well characterized. Note that, for a total effective collecting area of \( \approx 136 \text{ m}^2 \) and an observing/integration period of \( \approx 1 \text{ ms} \), the minimum detectable flux density of the system is \( \approx 1 \text{ kJy} \). This is lower than the peak flux density (\( \sim 100 \text{ kJy} \)) of the FRBs reported recently in the frequency range of 400 to 800 MHz. Assumming that the flux densities of the FRBs are expected to increase toward the lower frequencies, similar detections as well as observations of giant pulses from the Crab Nebula pulsar are possible with our system. In addition, subsequent to the detection of B1919 + 21, the pulsars
B0950 + 08, B0834 + 06, and B1133 + 16 were also successfully observed with our system. The related results will be reported separately.

6 Ongoing Work

Further development is in progress to (i) digitize the RF signal from individual antennas in the array. By applying different sets of delays while combining the signals, multiple beams can be formed to simultaneously observe different regions of the sky in declination. The array beam is already wide along right ascension (RA) (≈110 deg). By having several beams in declination (each ≈ 3 deg wide), a larger area of the sky can be monitored at the same time. This can be useful for observations of FRBs; (ii) use cross-polarized log-periodic dipoles52 and carry out polarization observations (see Ref.53); (iii) use a phase-coherent de-dispersion scheme with the Digital Signal Processing SoftwaRe (DSPSR) software package54; (iv) increase the sampling frequency and thereby minimize the delay error relative to the source position (see Sec.3); and (v) use calibrated noise sources that can be switched into the signal path and/or routine observations of B1919 + 21 for calibration purposes. For polarization data, it is planned to use observations of radio transients from the Sun since some of them such as type I bursts exhibit 100% circular polarization.55

7 Summary

We have presented the characteristics of the low frequency (50 to 80 MHz) observing system set up recently at the Gauribidanur Observatory near Bangalore in India, as well as the initial observations that were carried out. With its large bandwidth (≈30 MHz), wide sky coverage (≈110 x 80 deg), high spectral and temporal resolutions (≈36 kHz and 1 ms, respectively), geographical location (≈14° N), and the fact that the array is dedicated for time domain astronomy, it

Fig. 8 Observations of B1919 + 21 at 65 MHz with the pulsar array in the Gauribidanur Observatory. The data were analyzed using PRESTO. RFI was very minimal during the observing period was mitigated using the “rfifind” tool in PRESTO (see Sec. 4).
is expected to be very useful for observing pulsars, radio bursts from the Sun, \textsuperscript{56,57} and other high time resolution astrophysical phenomena such as the FRBs.

**Acknowledgments**

We express our gratitude to the staff of the Gauribidanur Observatory for their help in installation of the antenna/receiver systems and carrying out the observations. We thank A. A. Deshpande for his encouragement and suggestions. We acknowledge the referees for their kind comments, which helped us to present the results more clearly. The authors declare that there are no conflicts of interest.

**Data, Materials, and Code Availability**

Data used in the study are available at Ref. \textsuperscript{58}.

**References**

1. A. Hewish et al., “Observation of a rapidly pulsating radio source,” *Nature* \textbf{217}, 709–713 (1968).
2. K. Stovall et al., “Pulsar observations using the first station of the Long Wavelength Array and the LWA pulsar data archive,” *Astrophys. J.* \textbf{808}, 156 (2015).
3. N. D. R. Bhat et al., “Multifrequency observations of radio pulse broadening and constraints on interstellar electron density microstructure,” *Astrophys. J.* \textbf{605}, 759 (2004).
4. M. Geyer et al., “Scattering analysis of LOFAR pulsar observations,” *Mon. Not. Roy. Astron. Soc.* \textbf{470}, 2659 (2017).
5. Y. Gupta et al., “Fast transients with the Square Kilometre Array and its pathfinders: an Indian perspective,” *J. Astrophys. Astron.* \textbf{37}, 37 (2016).
6. J. M. Cordes, “Observational limits on the location of pulsar emission regions,” *Astrophys. J.* \textbf{J. 222}, 1006 (1978).
7. S. E. Thorsett, “Frequency dependence of pulsar integrated profiles,” *Astrophys. J.* \textbf{377}, 263 (1991).
8. V. M. Malofeev et al., “Spectra of 45 pulsars,” *Astron. Astrophys.* \textbf{285}, 201 (1994).
9. A. V. Bilous et al., “A LOFAR census of non-recycled pulsars: average profiles, dispersion measures, flux densities, and spectra,” *Astron. Astrophys.* \textbf{591}, A134 (2016).
10. B. W. Stappers et al., “Observing pulsars and fast transients with LOFAR,” *Astron. Astrophys.* \textbf{530}, A80 (2011).
11. A. V. Bilous et al., “A LOFAR census of non-recycled pulsars: extending to frequencies below 80 MHz,” *Astron. Astrophys.* \textbf{635}, A75 (2020).
12. V. V. Zakharenko et al., “Detection of decameter-wavelength pulsed radio emission of 40 known pulsars,” *Mon. Not. Roy. Astron. Soc.* \textbf{431}, 3624–3641 (2013).
13. S. J. Tingay et al., “The Murchison widefield array: the Square Kilometre Array precursor at low radio frequencies,” *Publ. Astron. Soc. Aust.* \textbf{30}, e007 (2013).
14. R. Wayth et al., “The engineering development array: a low frequency radio telescope utilising SKA precursor technology,” *Publ. Astron. Soc. Aust.* \textbf{34}, e034 (2017).
15. M. Sokolowski et al., “A Southern-Hemisphere all-sky radio transient monitor for SKA-low prototype stations,” *Publ. Astron. Soc. Aust.* \textbf{38}, e023 (2021).
16. C. V. Sastry, “The decameter and meterwave radiotelescopes in India and Mauritius,” *Space Sci. Rev.* \textbf{72}, 629–654 (1995).
17. R. Ramesh, “Low frequency solar radio astronomy at the Indian Institute of Astrophysics,” *ASI Conf. Ser.* \textbf{2}, 55–61 (2011).
18. C. Monstein, R. Ramesh, and C. Kathiravan, “Radio spectrum measurements at the Gauribidanur observatory,” *Bull. Astron. Soc. India* \textbf{35}, 473 (2007).
19. K. Hariharan et al., “High dynamic range observations of solar coronal transients at low radio frequencies with a spectro-correlator,” *Astrophys. J. Suppl. Ser.* \textbf{222}, 21 (2016).
20. V. Mugundhan et al., “Spectropolarimetric observations of solar noise storms at low frequencies,” *Solar Phys.* 293, 41 (2018).
21. D. Thornton et al., “A population of fast radio bursts at cosmological distances,” *Science* 341, 53 (2013).
22. V. A. Fedorova and A. E. Rodin, “Detection of fast radio bursts on the large scanning antenna of the Lebedev Physical Institute,” *Astron. Rep.* 63, 39–48 (2019).
23. Z. Pleunis et al., “LOFAR detection of 110-188 MHz emission and frequency-dependent activity from FRB 20180916B,” *Astrophys. J. Lett.* 911, L3 (2021).
24. I. Pastor-Marazuela et al., “Chromatic periodic activity down to 120 megahertz in a fast radio burst,” *Nature* 596, 505 (2021).
25. Y. Maan, “Discovery of low DM fast radio transients: Geminga pulsar caught in the act,” *Astrophys. J.* 815, 126 (2015).
26. V. H. Rumsey, “Frequency independent antennas,” *IRE Nat. Conven. Rec.* 5, 114–118 (1957).
27. R. L. Carrell, “The design of log-periodic dipole antennas,” *IRE Nat. Conven. Rec.* 1, 61–75 (1961).
28. P. Kishore et al., “Gauribidanur low-frequency solar spectrograph,” *Solar Phys.* 289, 3995–4005 (2014).
29. https://www.xilinx.com/products/silicon-devices/fpga/what-is-an-fpga.html
30. https://casper.astro.berkeley.edu/wiki/ROACH
31. https://www.analog.com/en/products/ad9480.html
32. https://www.allaboutcircuits.com/technical-articles/understanding-the-dynamic-range-specification-of-an-ADC/
33. https://www.analog.com/media/en/technical-documentation/data-sheets/AD9480.pdf
34. https://www.mikrocontroller.net/attachment/341426/Understanding_digital_signal_processing.pdf
35. D. C. Price, “Spectrometers and polyphase filterbanks in radio astronomy,” arXiv:1607.03579v2 [astro-ph.IM], 1–21 (2018).
36. D. R. Lorimer and M. Kramer, *Handbook of Pulsar Astronomy*, Vol. 4, Cambridge University Press, Cambridge, UK (2004).
37. http://www.ncra.tifr.res.in/ncra/gmrt/gmrt-users/low-frequency-radio-astronomy/ch17.pdf
38. https://casper-toolflow.readthedocs.io/projects/tutorials/en/latest/tutorials/roach/tut_ten_gbe.html
39. https://timing.trimble.com/wp-content/uploads/thunderbolt-e-gps-disciplined-clock-datasheet.pdf
40. http://sigproc.sourceforge.net/sigproc.pdf
41. S. Ransom, “PRESTO: pulsar exploration and search toolkit,” Astrophysics Source Code Library, record ascl:1107.017 (2011).
42. J. D. Kraus, *Radio Astronomy*, McGraw-Hill, New York (1966).
43. P. Kishore et al., “A low-frequency radio spectropolarimeter for observations of the solar Corona,” *Solar Phys.* 290, 2409–2422 (2015).
44. K. S. Dwarakanath and N. UdayaShankar, “A synthesis map of the sky at 34.5 MHz,” *J. Astrophys. Astron.* 11, 323 (1990).
45. R. Ramesh et al., “The equatorial background solar corona during solar minimum,” *Astrophys. J.* 648, 707 (2006).
46. R. Ramesh et al., “Low-frequency radio observations of the ‘quiet’ corona during the descending phase of sunspot cycle 24,” *Geophys. Res. Lett.* 47, e90426 (2020).
47. L. Bondonneau et al., “A census of the pulsar population observed with the international LOFAR station FR606 at low frequencies (25-80 MHz),” *Astron. Astrophys.* 635, A76 (2020).
48. N. H. Issur, “The pulsar observing system and data analysis procedure used at MRT,” *Astrophys. Space Sci.* 282, 77 (2002).
49. The CHIME/FRB Collaboration, “A bright millisecond-duration radio burst from a Galactic magnetar,” *Nature* 587, 54 (2020).
50. E. F. Keane et al., “The host galaxy of a fast radio burst,” *Nature* 530, 453 (2016).
51. T. Eftekhar et al., “A low frequency survey of giant pulses from the crab pulsar,” *Astrophys. J.* 829, 62 (2016).
52. K. S. Raja et al., “Design and performance of a low-frequency cross-polarized log-periodic dipole antenna,” *Astrophys. J. Suppl. Ser.* **207**, 2 (2013).
53. A. Noutsos et al., “Pulsar polarisation below 200 MHz: average profiles and propagation effects,” *Astron. Astrophys.* **576**, A62 (2015).
54. N. D. R. Bhat et al., “Observations of low-frequency radio emission from millisecond pulsars and multipath propagation in the interstellar medium,” *Astrophys. J. Suppl. Ser.* **238**, 1 (2018).
55. D. J. McLean and N. R. Labrum, *Solar Radiophysics—Studies of Emission from the Sun at Metre Wavelengths*, Cambridge University Press, Cambridge, UK (1985).
56. R. Ramesh et al., “Metric observations of transient, quasi-periodic radio emission from the solar corona in association with a ‘halo’ CME and an ‘EIT wave’ event,” *Astron. Astrophys.* **400**, 753–758 (2003).
57. V. Mugundhan, K. Hariharan, and R. Ramesh, “Solar Type IIIb radio bursts as tracers for electron density fluctuations in the Corona,” *Solar Phys.* **292**, 155 (2017).
58. [https://www.iiap.res.in/gauribidanur/home.html](https://www.iiap.res.in/gauribidanur/home.html)

Biographies of the authors are not available.