Solar Phys (2007) 242: 213–220
DOI 10.1007/s11207-007-0350-3

Brazilian Decimetric Array (Phase-I)

H.S. Sawant · R. Ramesh · J.R. Cecatto · C. Faria · F.C.R. Fernandes · R.R. Rosa · M.C. Andrade · S. Stephany · L.B.T. Cividanes · C.A.I. Miranda · L.C.L. Botti · J.W.S.V. Boas · J.H. Saito · C.E. Moron · N.D. Mascarenhas · K.R. Subramanian · M.S. Sundararajan · E. Ebenezer · M.R. Sankararaman

Received: 3 November 2006 / Accepted: 17 April 2007 /
Published online: 2 June 2007

Abstract An East – West, one-dimensional radio interferometer array consisting of five parabolic dish antennas has been set up at Cachoeira Paulista (longitude 45°0′20″ W, latitude 22°41′19″ S) for observations of the Sun and some of the strong sidereal sources by the Instituto Nacional de Pesquisas Espaciais (INPE), Brazil. This is Phase-I of the proposed Brazilian Decimetric Array and can be operated at any frequency in the range 1.2 – 1.7 GHz. The instrument has been in operation since November 2004 onwards at 1.6 GHz. The an-

H.S. Sawant · J.R. Cecatto (✉) · M.C. Andrade · J.W.S.V. Boas
Astrophysics Division – DAS/INPE, Sao Jose dos Campos, Brazil
e-mail: jrc@das.inpe.br

R. Ramesh · K.R. Subramanian · M.S. Sundararajan · E. Ebenezer
Indian Institute of Astrophysics, Bangalore, India

C. Faria · R.R. Rosa · S. Stephany
Laboratory for Computing and Applied Mathematics – INPE, Sao Jose dos Campos, Brazil

C. Faria
Department of Computer Sciences, University of PUC Minas, DC/PUC, Minas, Brazil

F.C.R. Fernandes
Institute of Research and Development, IP&D/UNIVAP, Sao Jose dos Campos, SP, Brazil

L.B.T. Cividanes · C.A.I. Miranda
Division of Aerospace Electronics, DEA/INPE, Sao Jose dos Campos, SP, Brazil

L.C.L. Botti
Center of Radio Astronomy and Astrophysics, Mackenzie University, Sao Paulo, CRAAM/INPE, Brazil

J.H. Saito · C.E. Moron · N.D. Mascarenhas
Department of Engineering and Computer Sciences, Federal University of São Carlos, DC/UFSCar, Sao Carlos, SP, Brazil

M.R. Sankararaman
National Center of Radio Astronomy, NCRA-GMRT (TIFR), Pune, India

gular and temporal resolutions at this frequency are $\sim 3'$ and 100 ms, respectively. Details of the array, analog/digital receiver system, and a preliminary East – West one-dimensional solar image at the 1.6 GHz are presented in this paper.

1. Introduction

Observations of radio emission from the Sun have contributed significantly to the understanding of fundamental problems in solar physics over the past several decades (Pick, Klein, and Trottet, 1990; Bastian, Benz, and Gary, 1998, and the references therein). Emission from the Sun is observed over almost the entire radio window of the electromagnetic spectrum. Observations in the decimetre wavelength range, in particular, play an important role because solar radio emission observed in the decimetric band is considered to originate close to the region where particle acceleration and energy release during a solar flare takes place (Tanuma and Shibata, 2005; Bárta and Karlický, 2005). The flare-related radio emission in this range includes a wide variety of plasma emission processes and is a potential diagnostic tool for probing the associated energy release and electron acceleration (Bastian, Benz, and Gary, 1998, and references therein). Over the past several years, radio spectrograph observations in the decimetre band have provided a wealth of data on different solar transients (Aschwanden, 2004; Benz, 2004, and references therein). But their location in the solar atmosphere is yet to be clearly established. In view of this situation and because of the absence of a facility for dedicated imaging observations of solar radio emission to the West of Greenwich, the scientists and engineers of INPE, Brazil, are now in the process of constructing a radioheliograph that can operate in the frequency range 1.2 – 5.6 GHz (Sawant *et al.*, 2000a, 2000b, 2002).

2. Array Configuration

Phase-I of the Brazilian Decimetric Array (BDA) consists of five mesh-type parabolic antennas (A1, A2, A3, A4, and A5) with an f/d ratio of 0.42 (Figures 1 and 2). They are mounted in alt – azimuth mount with a tracking capability of 340° in azimuth and 0 – 180° in elevation. The pointing accuracy is $<3'$ (Sawant *et al.*, 2003). We propose to add 20 more antennas to the array by the end of 2009. This will be Phase-II of the BDA and the array configuration will be a "T" with arms in east, west, and south directions. The frequency range of operation will be 1.2 – 1.7, 2.8, and 5.6 GHz. Another 12 antennas will be added to the array by 2010 and the maximum baseline length in each arm will be extended to 1.25 km. This will be Phase-III.

3. Receiver System

Dual polarized log-periodic feeds operating in the frequency range 1.2 – 1.7 GHz with a gain of $\sim$8 dB are mounted at the prime focus of each dish. A low-noise amplifier with a noise figure of $\sim$1.5 (about 150 K), a gain of $\sim$25 dB, a VSWR $\sim$ 1.2, and an intermodulation ~ -30 dB in this frequency range is connected to one of the output ports of the log-periodic feed. Note that observations are presently carried out in single polarization mode and hence only one output from the feed is taken. The output of the amplifier is passed first through a

Figure 1 Phase-I of the BDA at the INPE campus in Cachoeira Paulista (longitude 45°0′20″ W, latitude 22°41′19″ S). The array is in the E – W direction and the longest baseline length is 216 m. The antenna (A5) in the foreground is the East end of the array.

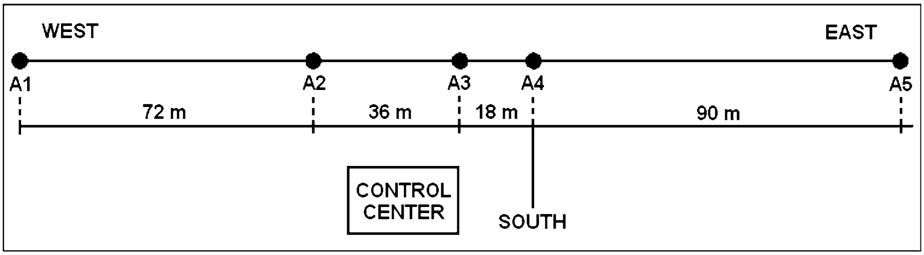


Figure 2 Antenna locations and corresponding interferometer baselines in Phase-I of the BDA. Note that a sixth antenna is presently being installed at a distance of nine meters from A4 in the east direction to improve the low spatial frequency coverage of the array.

high-pass filter (>1200 MHz) and then a band-pass (1.2 – 1.7 GHz) filter, thereby attenuating interference from the carrier frequency (900 MHz) of mobile communications.

There are three down conversions in the analog receiver (see Figure 3) system and two of them are performed at the antenna end. The first local oscillator (LO_1) is tunable and can be programmed to any particular spot frequency in the range 2 050 – 2 500 MHz. We select the desired frequency of operation by adjusting the above LO. To begin with, the filtered RF signal is mixed with LO_1 and the output is passed through a band-pass filter with center frequency $f_c = 836.5$ MHz (IF_1) and bandwidth $\Delta f = 25$ MHz. In the present case, the frequency of LO_1 is 2 436 MHz and this corresponds to an observing frequency

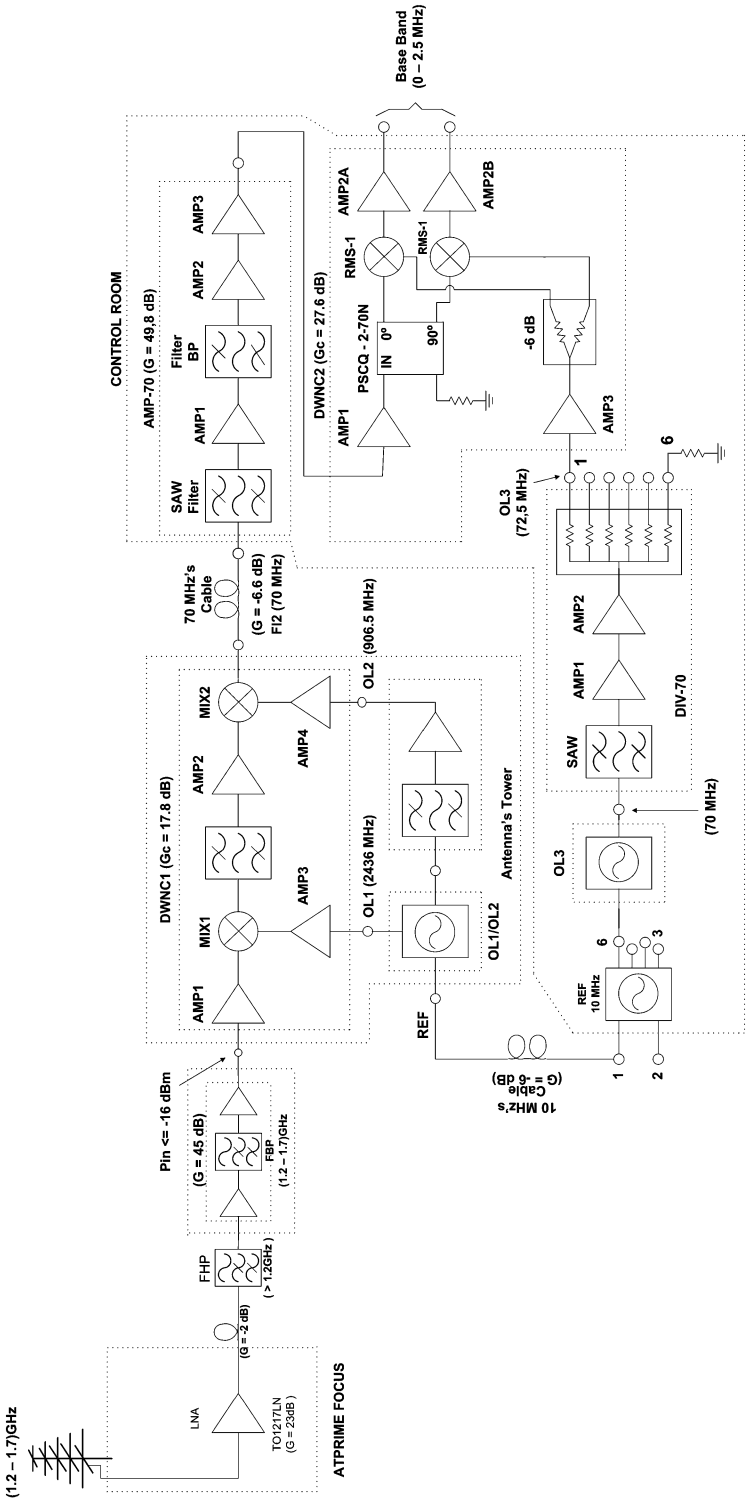


Figure 3 Schematics of the analog receiver operating in the frequency range 1.2 – 1.7 GHz showing its various functions used in BDA Phase-I.

of ∼1.6 GHz. After amplification and filtering, the IF signal is again down converted to 70 MHz (IF_2) by mixing with another local oscillator signal (LO_2) of frequency 906.5 MHz. Note that both LO_1 and LO_2 are generated by using a dual-band frequency synthesizer kept at the base of each antenna. The two LO signals derived from a 10-MHz rubidium clock signal are sent from the control room. The 70-MHz second IF signal is then sent to the control room located at distance of ∼125 meters via shielded coaxial cables buried underground. There it is passed through a phase inversion switch (Walsh switching) and then split into 0° (cosine) and 90° (sine) signals using a quadrature splitter. The latter are then independently down converted to the base band (0 – 2.5 MHz, IF_3) using a third local oscillator LO_3 (72.5 MHz) generated by using the same aforementioned 10-MHz rubidium clock signal. The generation of all the three LO signals from the same 10-MHz rubidium source ensures that they are phase synchronized. This operation is performed for the 70-MHz IF signal from each antenna, yielding ten baseband IF outputs. These are then fed to the digital back-end receiver.

The array has five antennas, and the signal from each is correlated with that from the remaining antennas. We get ten complex visibilities from the ten different pairs of antennas (interferometers) in the array. There is also provision for independently measuring the total power output from any two antennas in the array.

The following sequence of operations is performed in the digital receiver system: The base-band signal from the analog receiver is quantized to two levels (either “1” or “0”) in a zero-crossing detector. The basic element used here is a high-speed comparator. Its output is a “TTL” signal corresponding to whether the input of the final IF signal is above or below the “ground” level. The quantized signal is sampled in a D-type flip-flop at a rate of 5 MHz. An EX-OR gate is used to demodulate the sampled signal for Walsh switching. Note that the latter is useful for minimizing spurious correlation from **i**) crosstalk among the different analog signal paths and **ii**) the DC offset in the digital receiver (see Ramesh, Sundararajan, and Sastry, 2006, for details). After the removal of phase inversion, the signal flows through delay lines constructed by using a combination of shift registers and multiplexers. The necessary delay is implemented under the control of a computer up to a maximum value of 3 μs in steps. The step interval is 0.2 μs. Finally, the signal enters the correlator unit, which is a one-bit, two-level system similar to that used in the Gauribidanur radioheliograph (Ramesh *et al.*, 1998; Ramesh, Sundararajan, and Sastry, 2006). The integration used is 0.1 seconds and the expected point source sensitivity (1σ) is about 80 Jy ($1\ \text{Jy} = 10^{-26}\ \text{W}\,\text{m}^{-2}\ \text{Hz}^{-1}$). Table 1 summarizes the characteristics of the BDA (Phase-I).

4. Calibration

There are many sources of errors that affect the visibility data obtained with an interferometer and may lead to an incorrect determination of the sky brightness distribution. Presently, we rely on the gain stability of antennas and receiver system, and we carry out calibration using strong sidereal sources. We routinely check the intraday as well as interday phase stability of the array by comparing the observed phases on different radio sources, and make necessary corrections. The gain-corrected visibilities are Fourier inverted and CLEANed (Hogbom, 1974) to obtain the one-dimensional brightness distribution. Our intention is to use the Astronomical Image Processing System (AIPS) for data reduction to obtain radio images and calibration in the future. We are developing software for converting the observed data into AIPS-readable FITS format.

Table 1 Characteristics of BDA (Phase-I).

Location	Longitude: 45°0′20″ W Latitude: 22°41′19″ S
Frequency range	1.2 – 1.7 GHz (log- periodic dipole feed)
Number of antennas	five parabolic dishes (four meters diameter)
Pointing accuracy	$<3'$
Tracking capability	Azimuth = 340° Elevation = 0 – 180°
Number of baselines	10
Baseline length	Minimum = 18 m Maximum = 216 m
Spatial resolution	$3'$
Temporal resolution	100 ms
Back-end receiver	1-bit, 2-level digital correlator, 32 channels
Point source sensitivity	80 Jy (1σ)
Observing period	∼11 – 19 UT

5. Preliminary Observations

Figure 4 shows the one-dimensional brightness distribution of the Sun obtained with Phase-I of the BDA on 11 December 2004, at 15:00 UT. The observing frequency was 1.6 GHz. The image was synthesized by using the visibilities observed on different baselines in the array when the Sun drifted across the corresponding interferometer pattern in the sky. The anten-

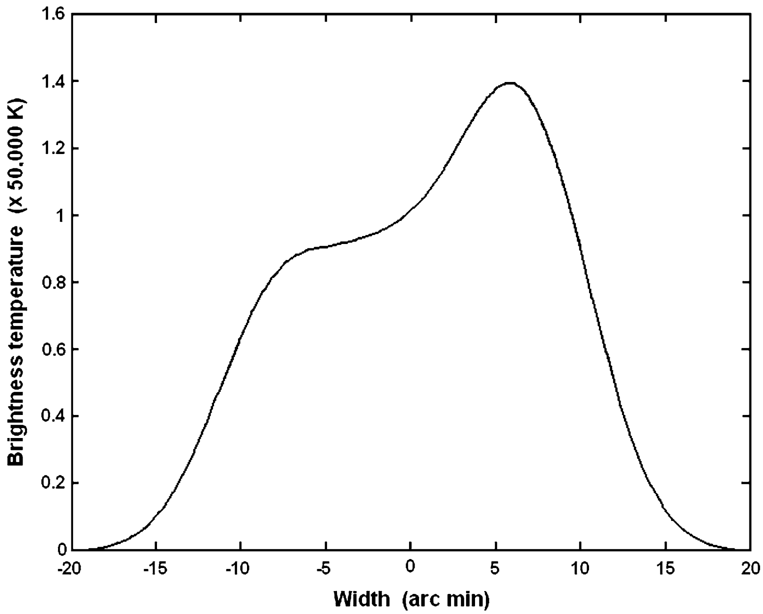


Figure 4 East – West one-dimensional brightness distribution of the Sun at 1.6 GHz obtained with Phase-I of the BDA on 11 December 2004, around 15:00 UT. The offline integration time used was 1.6 seconds. Solar East is to the left.

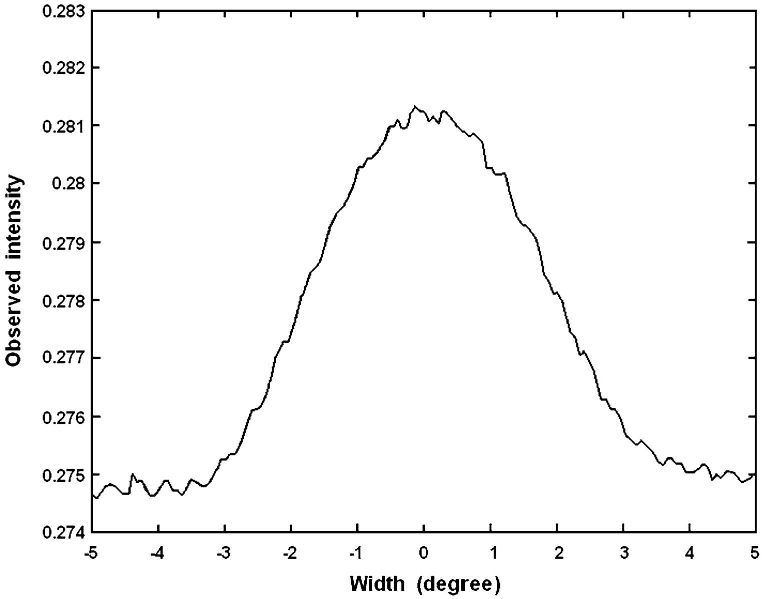
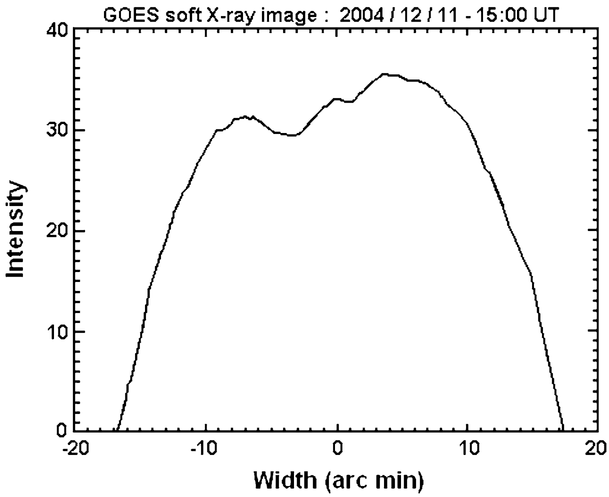


Figure 5 Total power from the Sun at 1.6 GHz measured with antenna A2 on 11 December 2004, around 15:00 UT. The offline integration time used was 1.6 seconds.

Figure 6 East – West one-dimensional soft X-ray image of the solar corona on 11 December 2004, at 15:00 UT. The original two-dimensional image was integrated along the latitude (North – South direction) to facilitate comparison with the radio brightness distribution in Figure 4.



nas were in the nontracking mode and their pointing was kept fixed. Only the visibilities obtained around the expected transit of the Sun over the corresponding position in the sky were used. The total power received by antenna A2 during the same period is shown in Figure 5. We compared our one-dimensional observations with the corresponding soft X-ray image of the Sun obtained with GOES-12 around the same time (Figure 6). There is a good similarity between the two images.

6. Conclusions

Phase-I of the Brazilian Decimetric Array consisting of five antennas and operating at 1.6 GHz has been commissioned at Cachoeira Paulista near São Paulo. The system has been in operation from December 2004 onwards. Observations with this array are expected to complement solar data obtained with the various existing facilities such as the Nançay radioheliograph, the Owens Valley Solar Array, and the Very Large Array around the same observing period.

Acknowledgements We thank the FAPESP authorities for funding Phase-I of the BDA project through their Grant No. 01/00056-9. We express our gratitude to Profs. G. Swarup, S. Ananthakrishnan, and R. Nityananda of the National Centre for Radio Astronomy – Tata Institute of Fundamental Research, Pune, for supporting the development of PBDA project; the digital part of the PBDA is designed and developed at the IIAP. We would like to thank Professors R. Cowsik and J.H. Sastri of the Indian Institute of Astrophysics, Bangalore, for supporting development of the digital part of the BDA project at the IIAP and donating the same for the BDA.

References

Aschwanden, M.J.: 2004, *Physics of the Solar Corona – An Introduction*. Springer-Praxis Publishing, Chichester.

Bárta, M., Karlický, M.: 2005, *Astrophys. J.* **631**, 612.

Bastian, T.S., Benz, A.O., Gary, D.E.: 1998, *Annu. Rev. Astron. Astrophys.* **36**, 131.

Benz, A.O.: 2004, In: Gary, D.E., Keller, C.U. (eds.) *Solar and Space Weather Radio Physics – Current Status and Future Developments*, *Astrophysics and Space Science Library* **314**, Dordrecht, Netherlands, 203.

Hogbom, J.A.: 1974, *Astron. Astrophys. Suppl.* **15**, 417.

Pick, M., Klein, K.L., Trottet, G.: 1990, *Astrophys. J. Suppl.* **73**, 165.

Ramesh, R., Sundararajan, M.S., Sastry, C.V.: 2006, *Exp. Astron.* **21**, 31.

Ramesh, R., Subramanian, K.R., Sundararajan, M.S., Sastry, C.V.: 1998, *Solar Phys.* **181**, 439.

Sawant, H.S., Subramanian, K.R., Ludke, E., Sobral, J.H.A., Swarup, G., Fernandes, F.C.R., Rosa, R.R., Gonzalez, W.D., Cecatto, J.R.: 2000a, *Adv. Space Res.* **25**(9), 1809.

Sawant, H.S., Ludke, E., Subramanian, K.R., Cecatto, J.R., Fernandes, F.C.R., Rosa, R.R., Sobral, J.H.A., Swarup, G., Scalise, E. Jr., Boas, J.W.V., Botti, L.C.L., Saito, J.H., Moron, C.E., Mucheroni, M.L.: 2000b, In: Ramaty, R., Mandzhavidze, N. (eds.) *High Energy Solar Physics Workshop–Anticipating HESSI*, *ASP Conf. Ser.* **206**, Astron. Soc. Pac., San Francisco, 341.

Sawant, H.S., Fernandes, F.C.R., Neri, J.A.C.F., Cecatto, J.R., Faria, C., Stephany, S., Rosa, R.R., Andrade, M.C., Ludke, E., Subramanian, K.R., Ramesh, R., Sundrarajan, M.S., Sankararaman, M.R., Ananthakrishnan, S., Swarup, G., Boas, J.W.V., Botti, L.C.L., Moron, C.E., Saito, J.H., Karlický, M.: 2002, In: Wilson, A. (ed.) *Proc. 10th European Solar Physics Meeting*, *SP **506*** **2**, ESA, Noordwijk, 971.

Sawant, H.S., Neri, J.A.C.F., Fernandes, F.C.R., Cecatto, J.R., Sankararaman, M.R., Faria, C., Stephany, S., Rosa, R.R., Andrade, M.C., Alonso, E.M.B., Lüdke, E., Subramanian, K.R., Ramesh, R., Sundararajan, M.S., Ananthakrishnan, S., Swarup, G., Boas, J.W.V., Botti, L.C.L., Moron, C.E., Saito, J.H.: 2003, *Adv. Space Res.* **32**(12), 2715.

Tanuma, S., Shibata, K.: 2005, *Astrophys. J.* **628**, L77.