

# Solar imaging capabilities of the Brazilian decimetric array

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Received: November 6, 1998; accepted: May 15, 1999.

## RESUMEN

En colaboración con la Universidad Federal de São Carlos, el Instituto Nacional de Pesquisas y la Universidad Federal de Santa María se hacen esfuerzos para desarrollar una tomografía solar utilizando imágenes solares obtenidas en varias longitudes de onda en distintos observatorios, en particular se utilizan imágenes de radio, con el objetivo de predecir la ocurrencia de perturbaciones solares y relacionarlas con efectos solar terrestres y de clima espacial. Se sugiere que la emisión decimétrica ocurre cerca de las regiones solares donde son aceleradas partículas o la energía de la ráfaga solar se libera. Sin embargo, aún no ha sido construido ningún radioheliógrafo con suficiente resolución espacial y temporal que opere en longitudes de onda decimétricas; debido a esto se hacen esfuerzos multi institucionales y multinacionales para desarrollar un radioheliógrafo solar decimétrico en forma de T. En este trabajo describimos las capacidades para formar imágenes de un heliógrafo solar de banda ancha en forma de T que opera entre 1.2 y 1.7 GHz que es capaz de obtener imágenes del disco solar con una resolución de 100 ms y una resolución angular de aproximadamente 4 minutos de arco. Con el desarrollo futuro del equipo se espera obtener una resolución angular de 18 x 24 segundos de arco que será comparable a las imágenes de rayos X que se obtuvieron con el satélite YOHKOH y las imágenes de radio del radioheliógrafo milimétrico de Nobeyama.

**PALABRAS CLAVE:** Sol, imaginación solar, ondas de radio.

## ABSTRACT

In collaboration with the Universidad Federal de São Carlos (UFSC), the Instituto Nacional de Pesquisas, and the Universidad Federal de Santa María (UFMSM) efforts are made to develop solar tomography using solar images obtained at various wavelengths from different observatories, in particular radio images, in order to predict occurrences of solar disturbances and related solar terrestrial and space weather effects. It is suggested that decimetric emission occurs near the solar regions where particles are accelerated or flare energy is released. However, no solar radioheliograph with sufficient time and spatial resolution at decimetric wavelengths has been built so far. In this paper, we describe the imaging capabilities of a T-shaped wideband solar heliograph operating at 1.2 - 1.7 GHz which is capable of obtaining solar disk images at 100 ms time resolution and angular resolution of ~4 arcminutes. With future hardware upgrades the final angular resolution will be 18 x 24 arcseconds which is comparable to X-ray images obtained with the YOHKOH satellite or radio images of the Nobeyama millimeter radioheliograph.

**KEY WORDS:** Sun, solar imaging, radio waves.

## INTRODUCTION

Computerized solar tomography employs images at several observing frequencies ranging from radio observations to X-ray images. The technique of tomography by pattern recognition is based on the use of images at various wavelengths obtained simultaneously with high spatial and time resolution (Rosa *et al.*, 1998). We apply spectral tomography for solar active regions using high spatial resolution images obtained in X-rays from YOHKOH (Kosugi *et al.*, 1991) and in UV from SOHO (Gabriel *et al.*, 1997). Also, we propose to use radio images with high spatial resolution at several frequencies in real time, obtained by a

radio heliograph operating in the frequency range of 1.2 - 1.7 GHz to be constructed in Brazil by INPE, for spectral tomography of solar active regions and real time space weather predictions. In particular, we are interested in the detailed investigations of dynamics of coronal holes observed in soft X-rays, related to the dynamics of active regions observed in radio frequencies. Such a study will permit us to understand the complex events known as CHARCS (Coronal Holes - Active Regions - Current Sheets) (Gonzalez *et al.*, 1996; Srivastava *et al.*, 1996), associated with the activity in coronal holes and active regions with occurrence of geomagnetic storms.

Where and how the energy of solar flares is stored in

the magnetic field of the active region, how this energy is transported to the flaring region and what rate and when this energy is released, are not well understood. This may be due to the lack of simultaneous multi-spectral time and spatial resolution. SKYLAB observations have suggested that soft X-rays and decimetric emission are generated from the same region. Simultaneous high spatial and time resolution solar radio and X-ray observations may will lead to a better understanding of these problems.

Since decimeter emission is correlated with soft X-rays, high sensitivity decimeter images will indicate active regions as well as coronal holes. In the absence of X-ray images by satellites, decimetric images will fill this gap of obtaining images of coronal holes. In Coronal Mass Ejections (CME) there is a earlier decrease in soft X-ray intensities suggesting depletion of the particles. If the soft X-ray and decimeter emission come from almost the same region the reduction of the radio flux in the decimeter emission will be clearly seen in the radio images. Thus we should be able to obtain a prior signature of the CME in the decimeter band.

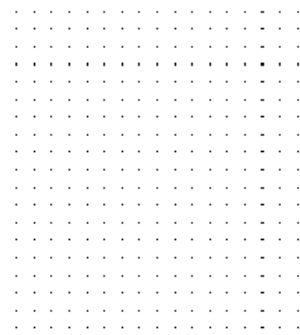
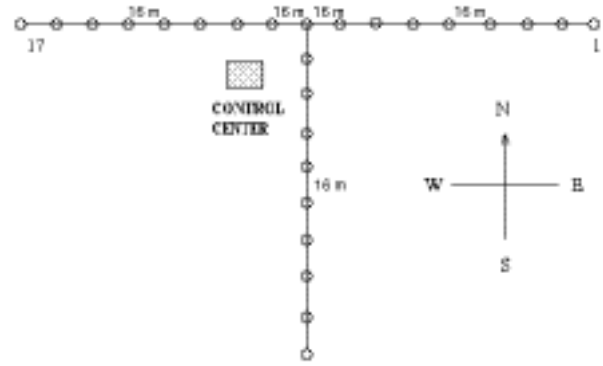
Using state-of-art electronics and radio interferometry techniques (Thomson, Moran & Swenson, 1986) it is possible to design high-frequency radio heliographs which can obtain instantaneous images of solar regions at arcsecond angular resolutions with time resolutions of the order of tenths of milliseconds (Nakajima *et al.*, 1984).

We discuss the design of the Brazilian Decimetric Array (BDA) and we simulate radio observations at 1500 MHz to compare them with images obtained by Nobeyama Radio Heliograph and the YOHKOH satellite. This instrument will be a unique radioheliograph in Latin America, for obtaining images of active regions and coronal holes in the decimeter frequency range.

### BRAZILIAN DECIMETER ARRAY IMAGING CAPABILITIES

The antenna positions follow the so-called supersynthesis antenna array (Chow, 1972) from which the Nobeyama Radioheliograph (Nishio *et al.*, 1994), the Gauribidanur Radioheliograph (Ramesh *et al.*, 1998) and the Very Large Array (Napier *et al.*, 1983) antenna distributions have been derived. The receivers and the signal processing has been described elsewhere (Sawant *et al.*, 1998a; Sawant *et al.*, 1998b).

The antenna position and  $uv$ -coverage for an array of 26 elements is shown in Figure 1, and an improved short-spacing coverage by adding six more antennas is shown in



320  $\lambda$

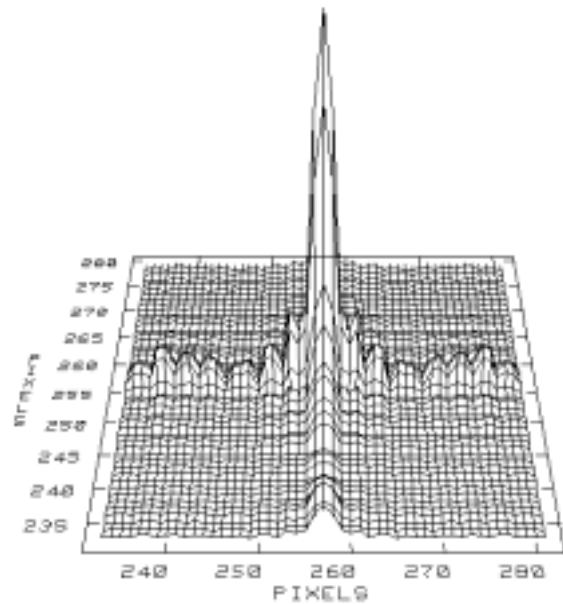
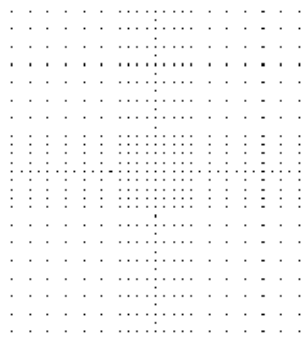
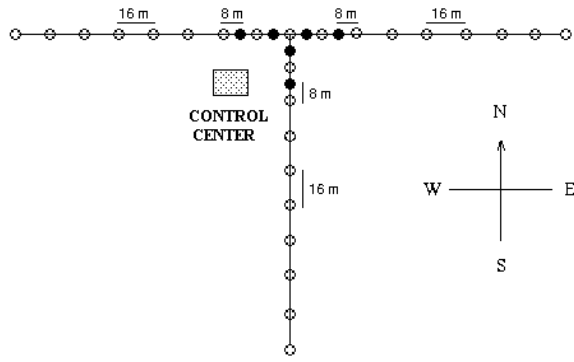


Fig. 1. (top) The original BDA antenna distribution with 26 antennas. (middle)  $uv$ -coverage, for a 100 ms integration time with the sun in transit. (bottom) The interferometer response to point sources (beam) which will give a expected angular resolution of  $4 \times 3$  arcminutes for the original design.



320  $\lambda$

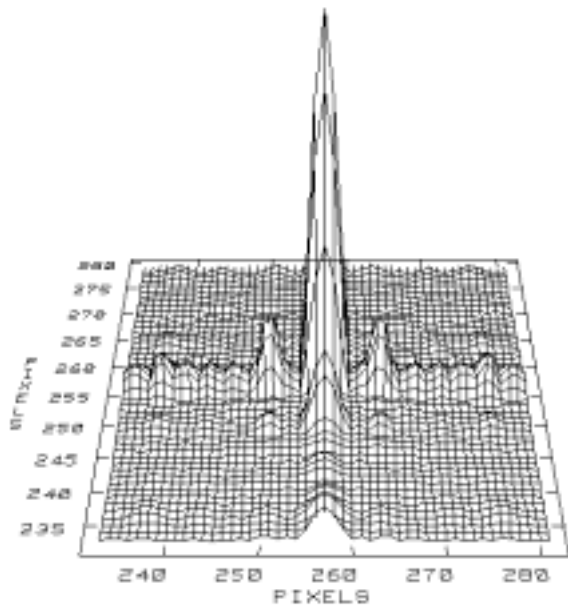


Fig. 2. (top) The improved BDA antenna distribution with 6 more antennas identified by black circles. (middle) Better short-spacing coverage, for a 100 ms integration time. (bottom) The interferometer response to point sources (beam) which will give an expected angular resolution of 4 x 3 arcminutes for improved short spacing.

Figure 2. These antennas are placed at about  $40 \lambda$  from the antenna which is common to the east-west and north-south interferometer branches.

The PSF shapes, which can be computed from the array current distribution in the radio source plane (< biblio >), are the antenna beams, shown at the bottom of Figures 1 and 2. Figure 2 shows (a) image fidelity enhancements apart of the increase in instrumental sensitivity; (b) the nearest grating image beams will be at about twice the distance to the main lobe for the original design, and will ensure that these grating responses will be well off the radio solar disk, (c) the nearest sidelobes to the main beam will be about one beam size away from the nominal beam position, allowing deconvolution algorithms such as CLEAN to be more effective in removing sidelobe spurious responses when the solar active regions are less than 8 arcminutes away from each other. The efficiency of the CLEAN algorithm is important for the subtraction of a model thermal disk contribution to the solar emission which is independent of the solar activity, and obtain high dynamic range images from the flares and coronal holes. This can be improved by adding short-spacing elements to the interferometer transfer function.

We have tested the “battery-powered” CLEAN algorithm (Clark, 1980; Cornwell, 1995) available in the NRAO Astronomical Imaging Processing System (AIPS) using simulated data (Figure 3). This software is remarkably easy and quick in removing grating and incomplete  $uv$ -coverage spurious responses or contamination of multiple

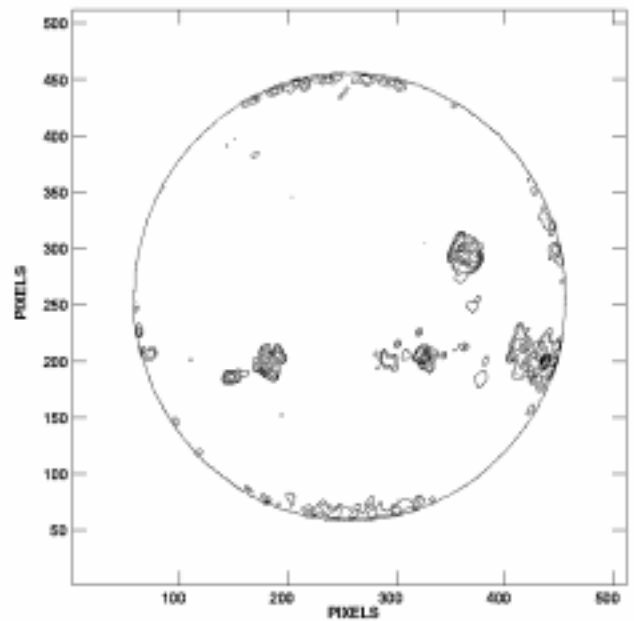


Fig. 3 Radio image obtained with the Nobeyama Radioheliograph at 17 GHz which is used as model for the solar disk.

bright active regions. The maximum entropy deconvolution technique can also be employed to image the continuum emission underlying the unresolved active regions (Narayan & Nityananda, 1986). This will be particularly important when the BDA is to be upgraded to maximum resolution.

The CLEANed radio image at 20 cm is seen in Figure

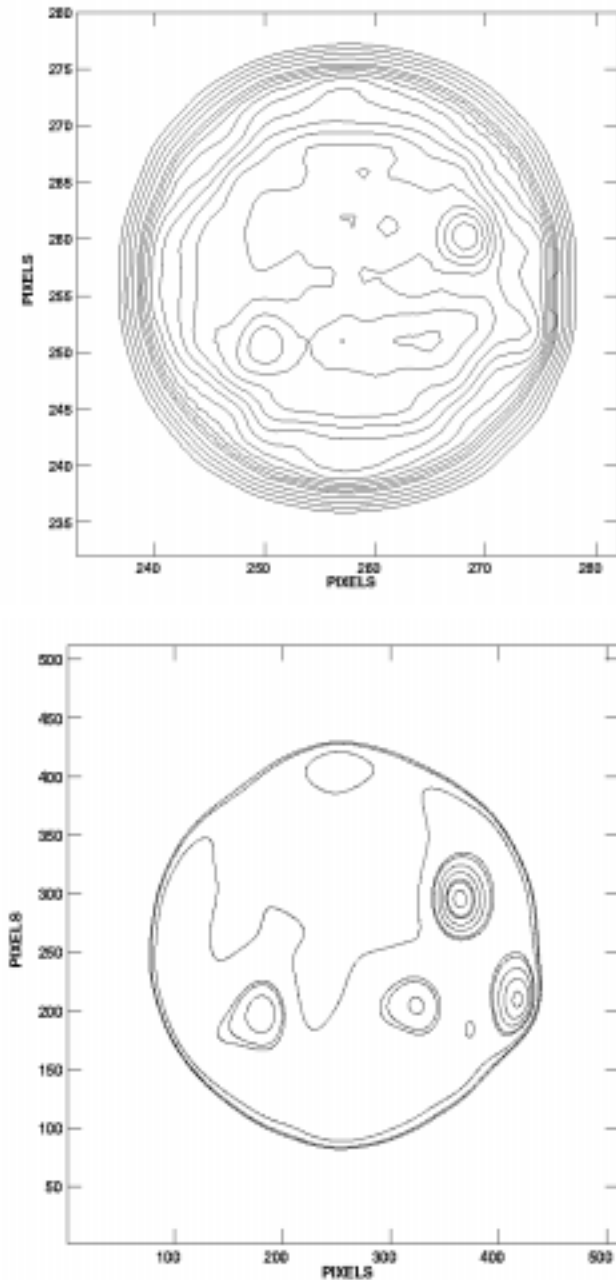


Fig. 4. Solar “Dirty image” and “CLEAN image” using a loop gain of 0.08 and 2500 clean components. The radio fluxes at observing wavelength of  $\lambda=20$  cm and positions can be measured and compared with the YOHKOH and Nobeyama images at shorter observing wavelengths.

4. This image can be obtained using a procedure similar to that employed by the Nobeyama data reduction procedure proposed by Hanaoka (1994). Similarity between the data processing for both arrays is important in order to enable astronomers interested in observations from both arrays to study images at millimeter and decimeter wavebands. A second option is to retrieve the “dirty image”, the “dirty beam” and the “cleaned image” obtained on-line by parallel processing from the data acquisition system.

The BDA visibilities will be calibrated on-line. Antenna-based phase and amplitude gains will be obtained with an interactive on-line self-calibration technique which is an important focussing algorithm for phase-unstable arrays (Schwab, 1980; Cornwell & Wilkinson, 1981; Pearson & Readhead, 1984). The relationship between the complex components of the interferometer visibilities  $V(u,v)$  and the solar image  $I(l,m)$  is given by the Van Cittert-Zernicke theorem, which is applied to correlator data prior to CLEANing:

$$I(l,m) = \iint_{-\infty-\infty}^{\infty\infty} V(u,v) \exp(-i \frac{2\pi}{\lambda}(ul + vm)) du dv \quad (1)$$

An instantaneous image in JPG format will be updated at the BDA World Wide Web home page during observations; the interferometer visibilities will be calibrated in phase and amplitude on-line. This will enable the user to obtain first-look radio images faster than any other astronomical interferometer, which will be most helpful to the external user for primary data selection and imaging quality analysis. The selected visibilities can be retrieved from archives in standard AIPS-FITS format.

After the second phase is completed with an East-West baseline of about 2400 km, BDA will have  $18 \times 24$  arcsec spatial resolution, Figure 5 shows the simulated solar image using AIPS for the BDA compared with the YOHKOH X-ray image.

In conclusion, the Brazilian Decimetric Array will be used to obtain (a) solar radio images of active regions and coronal holes in the decimetric band with time resolution of 100 ms; (b) a priori signature of coronal mass ejection in the decimeter emission.

## ACKNOWLEDGEMENTS

E. Lüdke would like to thank CNPq for a fellowship (301114/94-0), CAPES and FAPERGS. K. R. Subramanian thanks CNPq for grant 30358-97/0. H. S. Sawant’s participation in this meeting is supported by CAPES.

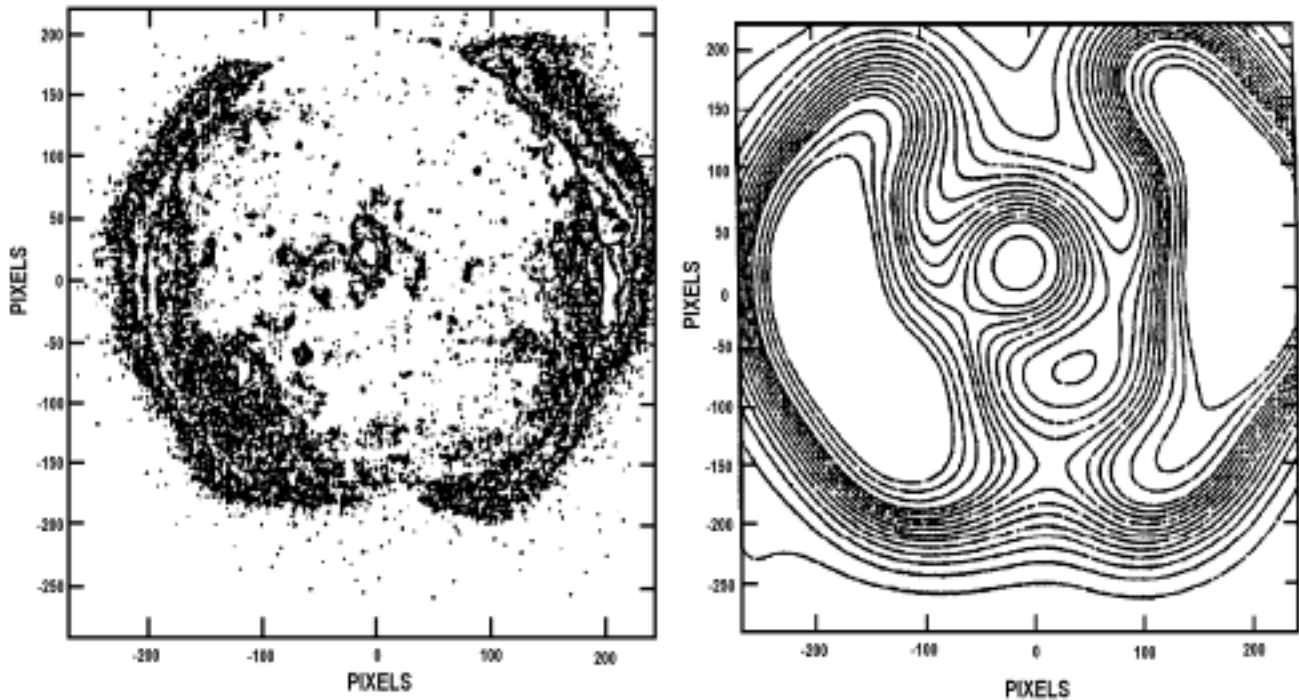


Fig. 5. Solar X-ray images obtained with YOHKOH on the left. To the right BDA radio image which would be seen with enough integration.

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