Solar Radio Observations with High Spatial Resolution

Cláudio Faria [1, 3], Stephan Stephany [2], Hanuman S. Sawant [1]

[1] *Computing and Applied Mathematics Laboratory - LAC/INPE.*
[2] *Astrophysics Division – DAS/INPE*
[3] *Computer Science Dept. – PUCMINAS.*
faria@pucpcaldas.br, stephan@lac.inpe.br, sawant@das.inpe.br

Abstract

The Brazilian Decimetric Array (BDA), under development at National Space Research Institute (INPE), is a radio interferometer for solar/non-solar observations at radio-protected bands of 1.2-1.7, 2.8 and 5.6 GHz. The BDA will have high spatial resolution of ~9 arc seconds at 2.8 GHz and time resolution of 100 ms respectively when completed. The maximum baselines will be ~2.5 and ~1.2 km in east-west and north-south directions respectively. Estimated rms sensitivity is 3 mJy at 21 cm for a system temperature of 50 K. The final version of the BDA will consist of T shaped array composed of 37 parabolic mesh type antennas of 4 and 5 meters of diameter. The array is being developed at Cachoeira Paulista (CP), São Paulo (Longitude 45º 0' 20" W, Latitude 22º 41' 19" S) by various institutes as national and international collaborative program. The BDA will have a Central T with dimensions of ~400x200 m that is most suitable from point of view of available land and resources. This Central T will have expected spatial resolution of ~1x1.5 arc minutes, field of view of ~40 arc minutes and synthesized beam with side lobes minimized below 20 percent of the main lobe. Here are reported investigations of some antennas positions within this central T, e.g. linear increased spacing and geometric increased spacing among these antennas. In addition, results of one optimized non-regular spacing distribution of antennas have been investigated. Design aspects of these configurations, uv-coverage and synthesized array beam pattern will be presented. Also will be presented simulations of imaging capability of the BDA array using Nobeyama data at 17 GHz.

Key words: radio interferometers, solar imaging, array configuration

1. The Brazilian Decimetric Array - BDA

The Brazilian Decimetric Array (BDA) is a radio interferometer operating in the frequency range of 1.2-1.7, 2.8 and 5.6 GHz with high spatial and temporal resolutions of 4.5" at 5.6 GHz and 100 ms respectively to produce images of radio sources with high dynamic range [1][2][3]. The BDA is being developed at National Institute for Space Research (INPE, Brazil) as an international collaborative program. The images of active regions provided by BDA will be analyzed by using spectral tomography technique being developed for application to space weather forecasting [4]. Also analysis of the flare component will lead to better understanding of the fundamental problems in solar physics. BDA also will be useful for galactic and extra-galactic investigations of the southern sky that is not accessible to Very Large Array (VLA) [5].

The BDA is been constructed at INPE in Cachoeira Paulista (Longitude 45º 0' 20" W, Latitude 22º 41' 19" S), located approximately 110 km northeast of the main campus of INPE at São José dos Campos, São Paulo. This site has a valley with dimensions ~ 400m x 300m where will be constructed a central compact Tee array and a control room with facilities to have on line data processing.

The BDA project is been developed in three phases:

1. BDA Phase I: five antennas will be totally operated by the end of 2004 at INPE–CP. This prototype is composed of five antennas of 4-meter diameter parabolic dish with alt-azimuth mount and complete tracking capability to operate in the frequency range of 1.2–1.7 GHz [6]. The five antennas had been laid out over a distance of 216 meters in the west-east direction getting a spatial resolution about ~3 minutes of arc at 1.5 GHz. The aim of the prototype is to test engineering aspect of the BDA system so as define entire BDA project and to estimate the cost of the total project Also will make the first solar observations providing one dimensional profiles of the Sun with spatial and time resolutions of 3 min of arc and ~100 ms respectively. The figure 1 presents the configuration of BDA Phase I and expected resolution of all base lines.

2. BDA Phase II: in the second phase is planned that 21 antennas will be laid out over the distance of ~400 meters in the east-west direction and 10 antennas will be laid out over a distance of ~200 meters in the southern direction forming a "T" shape array. The frequency range will be increased from 1.2-1.7, 2.8 and 5.6 GHz.

3. BDA phase III: finally, in the third phase, 4 more antennas will be added in the east-west direction

and two antennas will be added in the south direction. The baselines will be increased in both directions to 2.5 km and 1.25 km, respectively, to increase the spatial resolution of the array up to approximately ~4.5 arc seconds at 5.6 GHz.

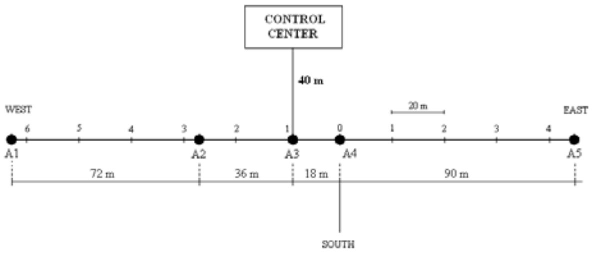

Figure 1 – BDA phase I - five antennas was installed at east-west baseline at locations 126W, 54W, 18W, 0 and 90E.

Here are presented investigations of BDA array configuration that is been conducted to BDA Phase II which involves to define 32 antennas locations in the central “T” at BDA site. We discuss aspects of the array configuration of the BDA and the imaging capabilities of three possible configuration investigated. The major characteristics of the BDA phase II are shown in table 1.

Table 1. Major Parameters of` the Brazilian Decimetric Array Phase II.

Location of the Array	*Longitude* *22°41’19” S* *Latitude* *45°00’22” W*
Observing frequency	1.2-1.7 and 2.8 GHz
Field of View	40’
Spatial Resolution	0.9’
Temporal Resolution	100 ms
Sensitivity	~ 5 Jy
Numbers of Antennas	31
Diameter of Antenna	4/5 m

2. BDA configuration aspects

Radio interferometers, like the BDA, measure the Fourier transform of the radio sources on a finite set of points in the Fourier plane. These points are determined by the cross-correlation of all possible pairs of antennas in the array [7][8]. The image of a radio source can be obtained by the inverse Fourier transform of the sampled data. Each pair measures a specific Fourier component given by the projected distance of the antenna in a plane that is normal to the incident angle of the radiation. Therefore, the sampling in the Fourier plane performed by the array is mainly dependent on the configuration. Therefore, the physical layout of the array is very important to optimize the performance of the overall system.

Several approaches have been proposed to optimize the response of the array [9][10][11]. It is clear that the best array configuration is dependent on the scientific goals intended for the array. In generic interferometers, best imaging performance is achieved when sampling in the Fourier domain is more uniform for a circular boundary defined by the spatial resolution of the array [10]. This kind of sampling in the Fourier plane provides images less affected by errors caused by non-measured Fourier components. However, the optimization of the antenna positioning involves several others aspects, that may be conflicting, such as cost or geographic constraints and requirements of the scientific goals.

The BDA is being designed to obtain optimized images of the radio sources at the decimetric band with high temporal and spatial resolutions. This precludes the use of earth rotation synthesis [7] requiring snapshot image acquisition.

The BDA “T” shape configuration is suitable since it yields a uniform sampling in a retangular region using a regular spacing between antennas, not requiring the use of a gridding technique [12]. Therefore, it requires less processing. In addition, this shape is good considering site constraints and also implementation and maintenance costs.

This work presents investigations of some array configurations, which that are very important for the BDA phase II. earth rotation synthesis. A specific software, developed in IDL, was used for these antennas positioning investigations. Three possible “T-shape” configurations are studied, according to the spacing between antennas: (i) a linear increased spacing, (ii) an geometric increased spacing and (iii) a non-regular optimized spacing.

The expected resolution for the central “T” array of BDA phase II is about 0.9 arc minutes at 2.8 GHz. This will provide approximately 32 sampled points in the radio solar disk. This resolution can be achieve with a maximum baseline of the 400 m. A minimum spacing between antennas was imposed to yield a Field of View of 40 arc minutes at 2.8 GHz, which is enough to cover the entire Sun diameter.

2.1 Linear-increased spacing

In order to achieve a spatial resolution of ~1 arc minutes at 2.8 GHz, an equally spaced “T” array with a minimum spacing between antennas $b = 9\ m$, requires 66 antennas in the East-West baseline. Such number of antennas would be very costly. Hence, it was adopted a linear increased spacing based on multiples of b, i. e. b, $2b$, $3b$, $4b$ and $5b$, shown in Figure 2. The obtained configuration presents a dense array near the intersection of the “T”, with distances of 9 meters between each pair of antennas. In Figure 3, it is presented the Fourier plane coverage for this configuration and the corresponding synthesized beam pattern. The maximum baseline is 396 m in East-West direction and 198 m in the North-South direction.

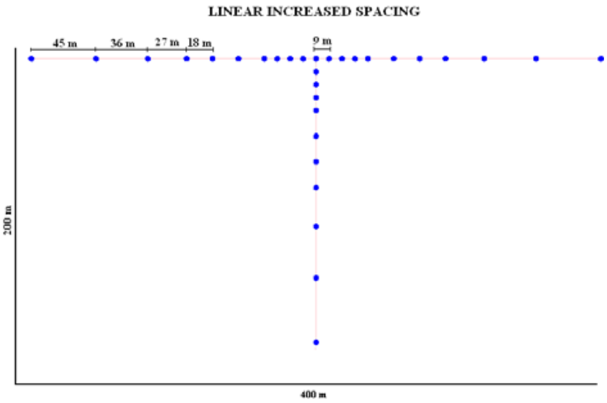

Figure 2 – BDA configuration with 31 antennas for a linear-increased spacing (*b*, 2*b*, 3*b*, *4b* and 5*b*).

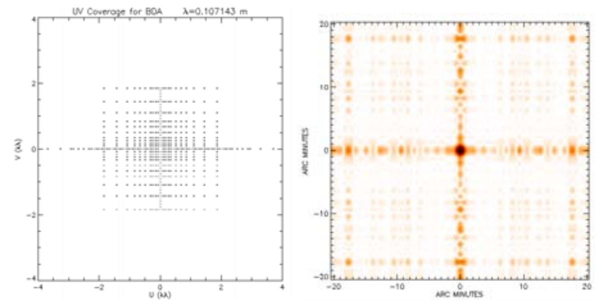

Figure 3 – Resulting uv coverage and synthesized beam for a linear increased spacing. FOV is ~40' at 2.8 GHz.

2.2 Geometric-increased spacing

The use of a geometric-increased spacing, with *b*, *2b* and *4b*, as shown in Figure 4, yields a configuration with a more dense array near the intersection of the "T" (with 13 antennas). This would provide more information about large structures in the Sun. The resulting uv-coverage and synthetized beam are presented at Figure 5. The maximum baseline will be 410 m in East-West direction and 205 m in North-South direction.

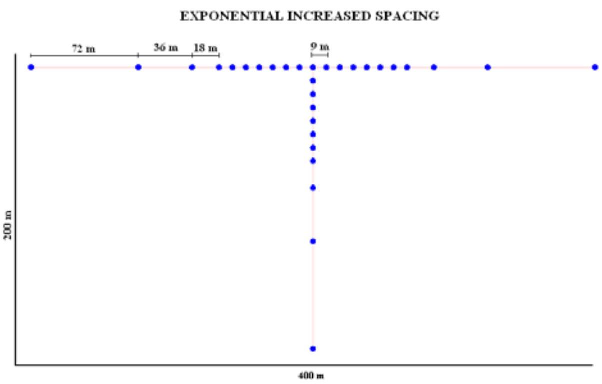

Figure 4 – BDA configuration with 31 antennas for a geometric-increased spacing (*b*, 2*b* and 4*b*).

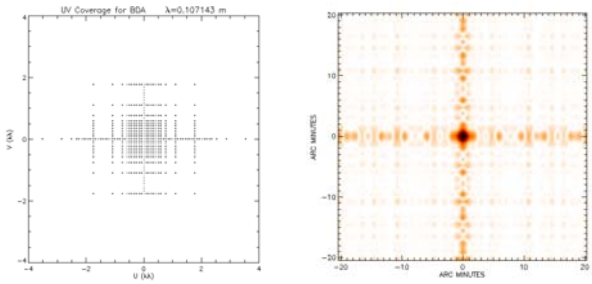

Figure 5 – Resulting uv coverage and synthesized beam for a geometric-increased spacing. FOV is ~40' at 2.8 GHz.

2.3 Optimized spacing

The optimized antenna spacing for the "T-shape" array configuration is shown in the following section.

3. The proposed optimization strategy for the array configuration

The optimization problem associated to the design of correlation arrays, like the BDA, consists to find antennas locations constrained by the available area in order to obtain better image fidelity. Here, it is proposed a new optimization strategy that is based on the entropy of the response function of the array in both the Fourier and spatial domains. An Ant Colony based algorithm [13] is employed to optimize the response function.

A radio interferometer composed by N antennas measures N(N-1)/2 Fourier components that are defined by the projected vector separation of the antennas [9]. This projection is onto a plane perpendicular to direction of the source.

Assuming that the source is located at the zenith, an instantaneous sampling of the Fourier plane can be determined by the correlations between each pair of antennas. For a pair of antennas A_i and A_j located at coordinates (x_i, y_i) and (x_j, y_j) respectively, the set of all *uv* points measured by the array is given by:

$$(u_{ij}, v_{ij}) = (x_i - x_j, y_i - y_j) \qquad (1)$$

where $i \neq j$ and $i, j = 1,2,..., N_{antennas}$.

The set of spatial frequencies *u* and *v* measured by the array defines its spectral response function, known as the Fourier plane coverage $S(u,v)$, given by:

$$S(u,v) = \sum_{q=1}^{N(N-1)/2} \delta(u - u_q, v - v_q) \qquad (2)$$

where $\delta(u-u_q, v-v_q)$ is the bi-dimensional Dirac-delta function at the u_q, v_q point of the Fourier domain. The Fourier Transform of the sampling function S is the Point Spread Function (PSF) or array beam pattern (B).

In the current work, the Ant Colony System (ACS) [13] uses information about the entropy of the beam for iteratively refines the candidate solutions. The criteria adopted for image quality is to obtain a beam with a narrow main lobe and minimum intensity side lobes. Thus, the objective function to be minimized is given by an entropic function of the array beam pattern:

$$J(B) = \sum_{q=1}^{NPOINTS} B_q \log\left(B_q\right) \qquad (3)$$

where *NPOINTS* is the total points of a rectangular grid associated to *B*. This entropic function has a minimum when *B* is a Dirac-delta function.

In order to provide more flexibility for the choice of the array configuration, the "T-shaped" array is spatially expanded in a sense that antennas can be placed within a width of 10% of the total baseline in each direction.

In the ACS, several generations/iterations of ants are produced. At each generation, an user defined amount of ants is randomly generated and evaluated. Each ant is associated to a candidate solution, an array configuration.

A recent strategy is employed to improve the performance of the ACS [14]. At each generation, a pre-selection is performed to select the ants that present the most uniform sampling in the Fourier space, i.e. only a fraction of the generated ants is actually evaluated.

A discrete probability density function of distribution points in Fourier plane is calculated for each candidate solution. only the candidates with best uniform distribution is selected to evaluate by the equation (3). In the end of all generations, the best solution is assumed to be achieved.

An optimized configuration, obtained by the above strategy, is shown at Figure 7. The resulting uv coverage and the synthetized beam corresponding to a point source (point spread function) are shown in Figure 8.

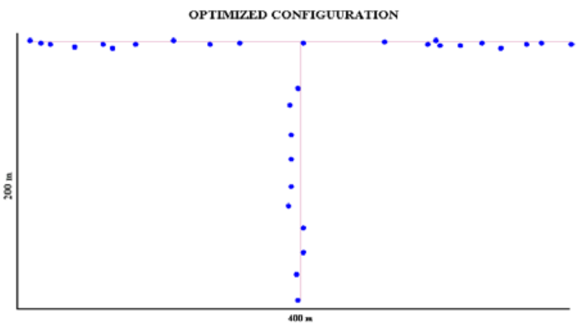

Figure 6 – BDA configuration with 31 antennas using optimized spacing strategy.

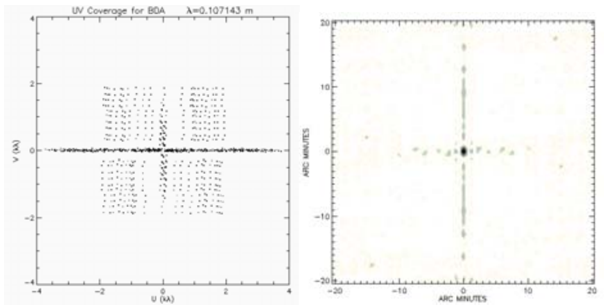

Figure 7 – Resulting uv coverage and synthesized beam obtained for the optimized configuration. FOV is ~40' at 2.8 GHz.

5. Radio imaging simulations

With purpose to compare the performance of the three configurations on radio imaging of the SUN, we evaluate the imaging capability of these arrays using images obtained by Nobeyama Radio Heliograph at 17 GHz as model of the source (see figure 8). In all simulations, the position of the source is assumed located at the zenith and observation frequency is 2.8 GHz. The images were obtained performing the following steps:

1. Performing the Fourier Transform of the Source Model using the FFT algorithm obtaining the discrete visibility function;
2. For each configuration computing the sampling function of Fourier plane (S);
3. Samples the Fourier Tranform of the source model at points defined by sampling function *S*.
4. Invert the sampled visibilites obtaining a dirty image of source.

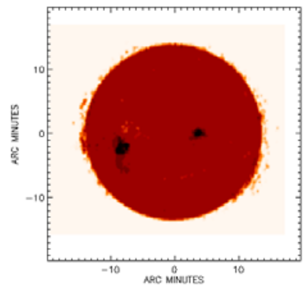

Figure 8. Image of Solar disc from Nobeyama Radio Heliograph at 17 GHz that was employed as a model of the Sun.

The dirty images obtained using the threes configurations proposals is shown at figure 9.

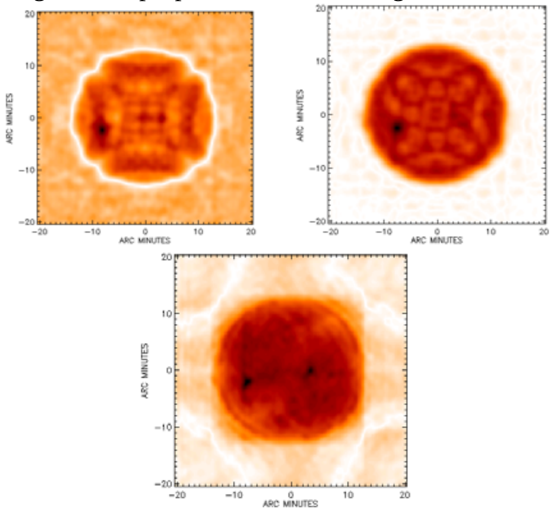

Figure 9. Dirty images simulated for BDA phase II using linear-increased spacing (upper left), geometric-increased spacing (upper right) and the optimized configuration (bottom) obtained with the ACS.

6. Final considerations

The present investigations propose 3 strategies for choosing the antenna location, according to the spacing between antennas: a linear increased spacing, an geometric increased spacing and a non-regular optimized spacing with antennas placed along a T shaped array with a width about 10% of the mximum baseline.

The linear and geometric increased spacing yielded side lobes with intensities below 30% and 20% of the main lobe, respectively. Small structures were not detected with these configurations.

The best imaging of the solar disc was obtained using the proposed optimized configuration. This configuration presents a more uniform uv coverage with less redundancy. Therefore, small structures in the Sun can be visualized. The side lobes are minimized below ~20% of the intensity if the main lobe.

In the presented simulations, a uniform weighting was chosen for the uv coverage, in reality due to the tapering effect weighting will not be uniform and hence the level of side lobes in reality will be further reduced.

7. References

[1] Sawant, H. S et al. A low cost steerable radio-telescope Advances in Space Research, 32(12), 2715-2720, 2003.

[2] Sawant, H. S et al. 10th European Solar Physics Meeting, 2002. Proc. The 10th European Solar Physics Meeting - ESA SP 506. , v.2, p.971 - 974, 2002

[3] Sawant, H. S, et al. A High Resolution Decimetric Solar. Radioheliograph. Astronomical Society of the Pacific Conference Series, 206, 341-346, 2000.

[4] Sawant, H.S et al. Brazilian Decimetric Array. Advances in Space Research. v.25, n.9, p.1809 - 1812, 2000.

[4] Marubashi, K The space weather forecast program, Space Science Reviews. 51 (197), 1989

[5] Thompson, A. R.; Clark, B. G.; Wade, C. M., and Napier, P. J. The Very Large Array. *Astron. J. Supp.* 44, 151-167, 1980.

[6] Cecatto, J. R. et al. Protótipo do primeiro interferômetro brasileiro (Projeto Brazilian Decimetric Array – BDA), Boletim da SAB, vol. 23, no. 3, 25-38, 2004.

[7] Thompson, A. R., Moran, J. M., Swenson Jr., G. W. Interferometry and Synthesis in Radio Astronomy. Wiley, New York, 2001, 1990.

[8] Wohlenben, R., Mattes, H. e Krichbaum, Interferometry in Radioastronomy and Radar Techniques. Dordrecht, Netherlands: Kluwer, 1991, 210 p.

[9] Cornwell, T. J. A novel principle for optimization of the instantaneous fourier plane coverage of correlation arrays," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 1165–1167, Aug. 1988.

[10] Keto, E. The Shapes of Cross-Correlation Interferometers, ApJ, 475, 843-852, 1997

[11] L. Kogan, Optimizing a Large Array Configuration to Minimize the Sidelobe. IEEE Trans. Antennas Propagat., vol. 48, p. 1075-1078, July 2000.

[12] Nakajima et al. The Nobeyama Radioheliograph. Proc. of the IEEE, 82, 705, (1994)

[13] Dorigo M., Maniezzo V. and Colorni A. The ant system: optimization by a colony of cooperating agents. IEEE Transactions on Systems, Man, and Cybernetics–Part B, Vol. 26, No. 2, 29–41, 1996.

[14] Preto, A. J. A new regularization technique for an ant-colony based inverse solver applied to a crystal growth problem. Proceedings of the 13th Inverse Problems in Engineering Seminar (IPES-2004). Cincinnati - EUA: University of Cincinnati, 2004. v. 1, p. 147-153.