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1D SUN BRIGHTNESS PROFILE USING BDA DATA

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ABSTRACT

The process to generate images from the raw data involves several steps: editing, calibration, deconvolution and cleaning. In order to generate one-dimensional brightness temperature map of the Sun in a snapshot mode, we have developed an alpha version of a computational code, making use of the ten baselines available for the Prototype of the Brazilian Decimetric Array (PBDA) five element array operating in transit mode. The code based on simple assumptions and a standard method was developed in the Matlab environment. Description of the method, assumptions and parameters applied on the code development are described. One-dimensional brightness temperature map of the Sun will be presented using raw data of five element array and that of the calibrator sources.

Key-words: 1D imaging, BDA, brightness

INTRODUCTION

It is well known since the beginnings of radio interferometry that the brightness distribution of a target source in principle can be obtained applying a Fourier Transform to the measured visibility data. However, it is not so simple and both the element primary beam pattern and sampling in the uv-plane, due to the array configuration, must be taken into account during the process of reducing data as purpose to produce an acceptable quality image. Generally, the primary beam pattern is not known analytically and then must be determined empirically. Also, geometry of the array configuration together the source position in the sky permit us to know in detail the sampling in the uv-plane as well as geometric delay. In addition, noise must be taken into account for the recorded data. The basic equation, Eq. (1), is given by (Thompson et al., 1994):

$$I^{D}(l,m) \equiv \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(u,v) V^{'}(u,v) e^{2\pi i(ul+vm)} dl dm \tag{1}$$

S is the (u,v) sampling function, V' the observed visibility data which has intrinsic noise, and $I^{D}(l,m)$ is known as "dirty image" due to the artifacts which are generated by the limited discrete sampling and gaps in the uv-plane of the array. As the Fourier Transform cannot be analytically represented it must be numerically approximated. This can be done either by "Direct Fourier Transform - DFT" or by interpolating the data onto a rectangular grid and after that apply the "Fast Fourier Transform - FFT" algorithm (Taylor et al., 2003). In this work we choose the FFT method. Also, due to the array design at regular spacings a natural weighting is assumed.

To recover *I(l,m)*, i.e. the recovered "clean image" from $I^D(l,m)$ either a model with determined parameters, or a non-parametric approach must be used. By a practical point of view two algorithms have been applied during last four decades. CLEAN and Maximum Entropy (MEM) methods are the most traditional and widely used to produce a "clean image" since the "dirty image". Each one has its own advantages and drawbacks (Taylor et al., 2003) discussed below. We know that recently improved versions of the traditional algorithms and hybrid ones have been applied to the interferometric data showing better results in comparison to the algorithms used before (Wakker and Schwarz, 1998). However, several additional aspects must be considered to implement any other method than CLEAN which we used on the code. CLEAN is basically an empirical method which produces a brightness distribution image of a source from raw data and calibration, although its criterious noise analysis is not available yet (Högbom, 1974; Taylor et al., 2003).

Also, the five antenna array (PBDA) is a prototype put into operation to engineering and operational tests in actual conditions of severe weather in open field. Details of PBDA are given in Sawant et al. (2007).

In this work, we present a computational code development and generation as a purpose to produce 1D Sun brightness profiles using the BDA prototype East-West 5-element array data. It is the alpha version based on the pure CLEAN algorithm (Högbom, 1974). Preliminary results of its application to PBDA data are also presented. Also, a discussion about these first results to guide either future developments or alternatives is described.

TRADITIONAL ALGORITMS APPLIED TO GENERATION OF INTERFEROMETRIC IMAGES

We know the brightness distribution of a target source can in principle be obtained by the inverse Fourier transform of the measured visibility function. By this method a "dirty" image is produced which requires further processing. The additional processing must take into account for the primary beam pattern of each antenna (assuming all antennas are identical), sampling function in the uv-plane, and the calibration of interferometric data using calibrator sources, e.g. Cygnus-A.

1- CLEAN – The CLEAN method was first noticed by 1974 (Högbom, 1974). Roughly, it is an empirical method that represents emission components by δ-functions. Initially, maximum intensity is identified in the image as the strongest compact emission component. About 10% of that component with a Gaussian fit is removed from the image. After this the strongest component is compared with the rms noise level in the image. In case both are about at the same level the "cleaning" process is stopped and the "clean" image is restored. This constitutes the first cycle of "CLEAN". In case, the emission components present in the image are stronger than noise a new cycle of "cleaning" runs iteratively. This process keep running until the last component in the image is at the rms noise level. Then, all components removed are restored and the final image is produced. As "CLEAN" is modeling compact sources is dedicated to image either point or compact sources. Despite of that three conditions are required as to provide good quality images. First, the beam must be symmetric; second, the beam must be positive definite or semi-positive definite; and the last, there must be no spatial frequencies present in the dirty image which are not also present in the dirty beam.

2- MEM – Maximum Entropy Method is an analytic method (Frieden, 1972; Frieden and Burke, 1972). In this case, the image selected is that which fits the data, to within the noise level, and also has maximum entropy. Here, entropy can be defined by the expression (Taylor et al., 2003) given in Eq. (2):

$$\mathrm{H} = -\sum_k I_k \ln \frac{I_k}{M_k e} \tag{2}$$

where M_k is the “default” image to allow a priori information to be used. A “default” image is assumed as model. Then, a priori information is used based on data constrained to the fact that the fit, χ^2, of the predicted visibility to that observed, be close to the expected value given by Eq. (3):

$$\chi^2 = \sum_k \frac{\left|V(u_k, v_k) - V'(u_k, v_k)\right|}{\sigma^2_{V(u_k, v_k)}} \tag{3}$$

Maximizing H with the constraint that χ^2 be equal to expected value leads to an image which fits the long spacings extremely well (better than 1σ) since that a predicted value for the zero-spacing flux density is provided by the user (Cornwell and Evans, 1985).

COMPUTATIONAL CODE DEVELOPMENT

The computational code development was based on simplified hypothesis and assumptions as a purpose the alpha version be available in a relatively short time. Actual version is a crude code which requires several additional improvements. However, first and preliminary results could be obtained and give us information about the interferometer functioning, quality of data, and subside to plan either a further code improvement or necessity of new code development.

The hypothesis on which the computational code is based are the following:

1- Application of the closure phase method provides the best phase calibration;

2- Observations of the Sun on transit mode are able to generate a sufficiently high S/N ratio on the data recorded;

3- Snapshot mode permits us to produce an image of a strong source like the Sun;

4- The phase gains do not change during a sample of data;

5- No solar activity is noticed during the acquisition of sample data used to generate the image;

6- Any interference signal which could deprove the data quality is completely mitigated by the Walsh switching put at the back-end before the correlator inputs;

7- Last significant digit on data bring no useful information about measured visibilities and is excluded from raw data through the edition data process;

8- Instrumental phase components keep constant during the data recording and cause no disturbance relevant to a deproval of data quality;

9- Pure CLEAN method gives us good results;

10- Amplitude is normalized to the maximum measured value on the smaller baselines and scaled with the daily solar flux measured by solar patrols. No absolute amplitude calibration is done because the absence of a strong source with a comparative flux level as the Sun.

By the other side, taking into account for all the limitations relative to available time, experience and practice on interferomety and computer code development for interferometry, as starting point we based on the following assumptions:

I. The most important is phase calibration. Absolute amplitude calibration is not applied to this version of the code;

II. A modular architecture of the code is the best approach. Each module executes a determined task or run a specific function. The assembling of all modules integrate the computational code generated;

III. Correction for the slope and shift of the fringes from zero mean are required and applied to the data (mean of the first and last 200 points and straight line fit). This is part of the editing data processing;
IV. Due to array design the final antennas configuration is approximately at regular spacings. This permitted us to develop a code whose sampling is based on a natural weighting;
V. Time evolution of baseline amplitudes can well be fitted by Gaussian profiles. The maximum of each Gaussian gives us amplitude maxima for all baselines;
VI. Corrupted fringe patterns, amplitude profiles, and unstable phases are criteria used to edit data and exclude baselines which have compromised data.
VII. The Single Value Decomposition function available in the MatLab environment is able to apply the “closure phase” method (Jennison, 1958; Rogstad, 1968; Readhead and Wilkinson, 1978; Pearson and Readhead, 1984) and find a good and valid solution for the calibrated phases.

With those hypothesis and assumptions on mind we start the code development on a relatively flexible and available computational environment (MatLab) which had the most of functions necessary for the code generation. The software was planned on a main code and several modules with pieces of code which correspond each one to a specific function or task. The only usage of the main code is to establish a hierarchy and organize all the modules required. Then, the code is composed of one main code and eleven modules. Some few modules execute more complex tasks. For instance, those modules which perform the “closure phase” as well as the one executing the deconvolution and “cleaning” make use of fundamental functions and correspond to relatively complex tasks required. Despite the code be responsible for the execution of functions and tasks, it is interactive with the user. In this sense, the user is totally responsible for the inputs of parameters as well as to define the choices requested by the code based on all available information about the instrument, observational process, and target source.

It has to be mentioned that some of the most widely used software packages to perform the tasks of edition, calibration, deconvolution and imaging of interferometric data are AIPS, MIRIAD, CLIC and CASA. There are some packages of restricted usage, for instance, NEWSTAR and FESTIVAL. For details on these refer to the internet.

APPLICATION TO THE BDA PROTOTYPE DATA AND PRELIMINARY RESULTS

To test the functionality and validate the code developed and generated we selected a small sample of PBDA data. Besides, the application of the code to actual data recorded by the prototype permit us to check the interferometer is working properly or not. Doing this way, we could verify the best results are obtained for three of the five shortest baselines of the array (1×2, 2×3, and 1×3), and therefore these are used systematically to obtain any 1D brightness profiles using PBDA data. Particularly, we selected one sample of relatively old data as well as one sample of more recent and good quality data. The results of the code application to PBDA data are shown on Figures 1 and 2 jointly to EUV and X-ray data for comparison. Figure 1 (top) shows the 1400 MHz 1D brightness distribution of the Sun on 10th Sept., 2007 at 17UT. EUV, 175 Å (EIT-SOHO) solar map for same day is also shown (bottom). Figure 2 exhibits the 1600 MHz 1D brightness distribution of the Sun for 11th Dec. 2004 at 15UT (bottom). Also, is exhibited (top) East-West one-dimensional soft X-ray image of the solar corona for the same day and time. The original 2D image was integrated along latitude to allow us a comparison.

It has to be taken into consideration that these are results of the alpha version code applied to data of three baselines of the array. Then, the excessively smooth profiles obtained are mainly due to these reasons. However, as mentioned above, the array is limited to five antennas and the processing of any sample of data using additional baselines resulted in unreasonable 1D profiles in comparison to data on other spectral bands, e.g., EUV and X-ray.

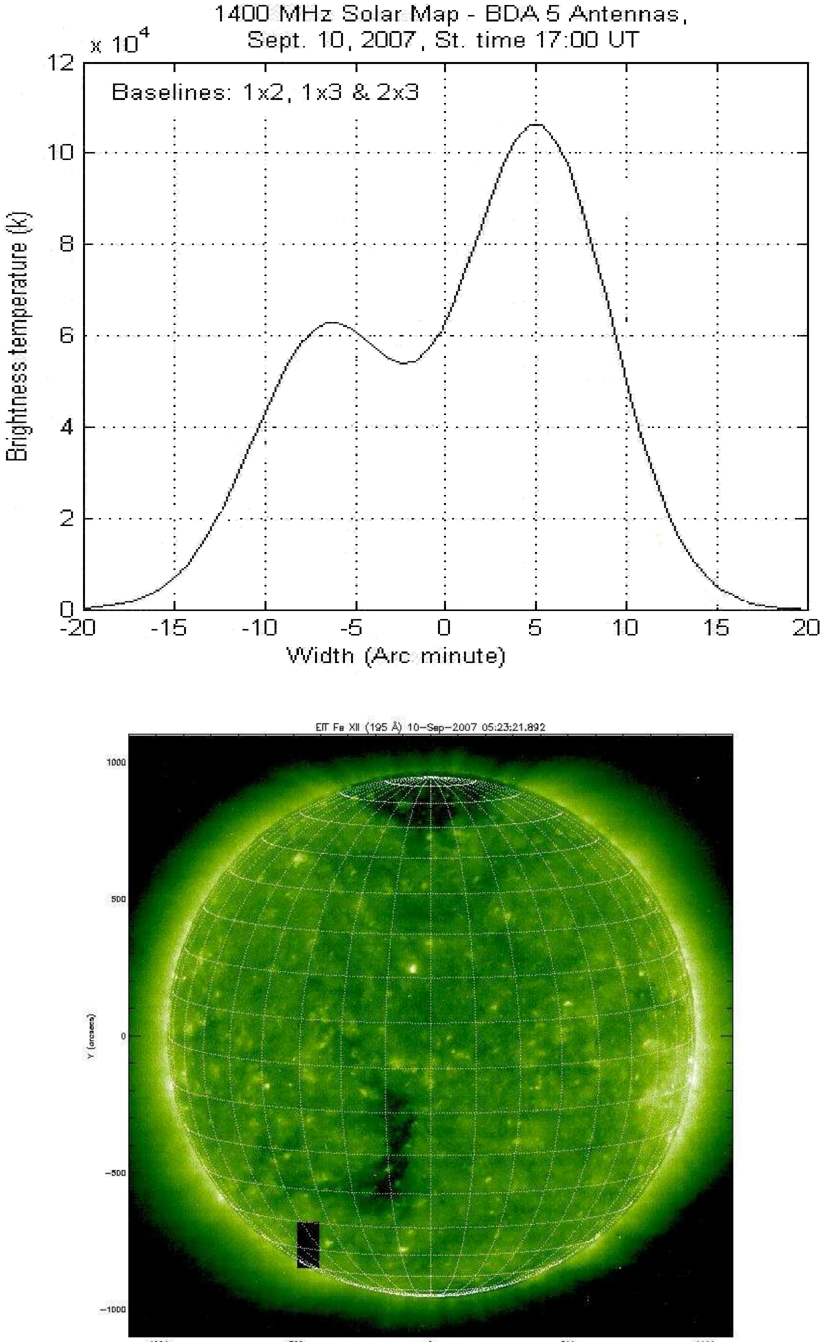

Fig. 1 – (Top) One-dimensional 1400 MHz brightness distribution of the Sun obtained on 10th Sept. 2007 at 17 UT, using 5-antennas BDA Prototype. (Bottom) EUV (175 Å) image of the solar corona on 10th Sept. 2007 at ~ 5:30 UT, obtained from EIT experiment on board SOHO satellite.

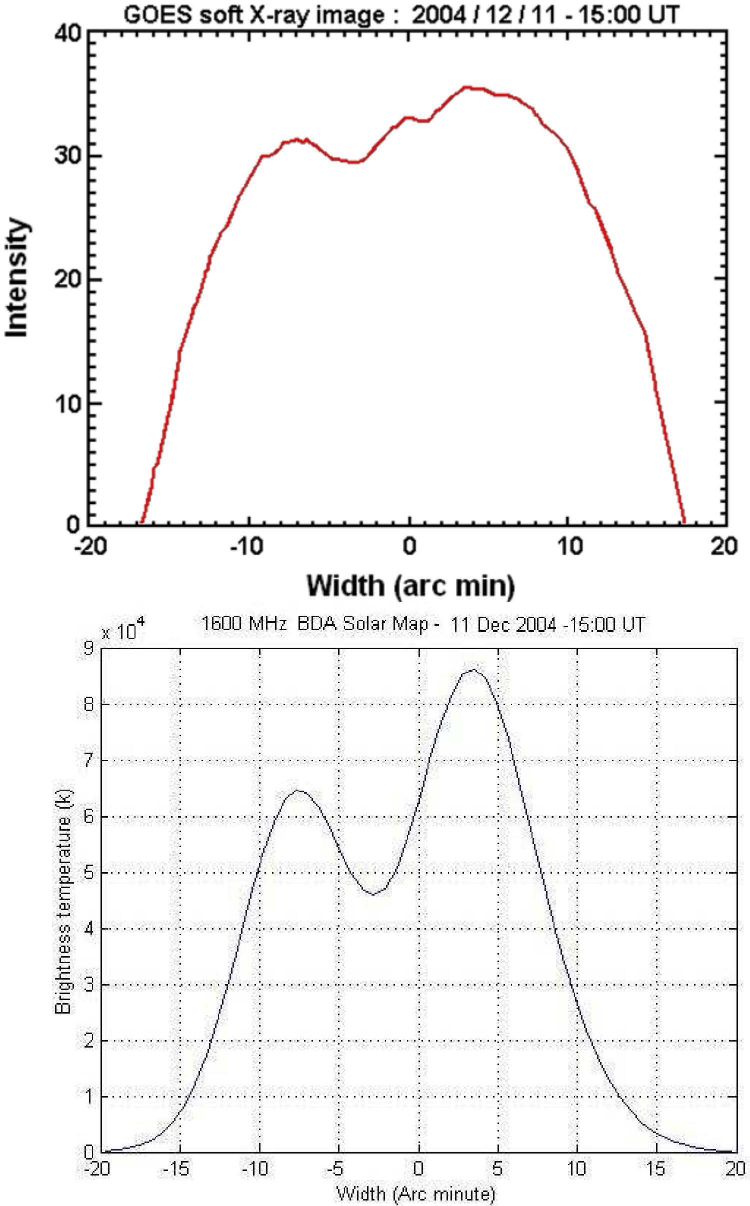

Fig. 2 – (Top) East-West one-dimensional soft X-ray image of the solar corona on 11th Dec. 2004 at 15 UT. Original two-dimensional image was integrated along the latitude (North-South direction) to permits a comparison with the radio brightness distribution obtained from BDA 1600 MHz observations (Sawant et al., 2007). (Bottom) One-dimensional 1600 MHz brightness distribution of the Sun obtained on 11th Dec. 2004 at 15 UT, using 5-antennas BDA Prototype.

DISCUSSIONS

Based on the results obtained by the application of the computational code developed some considerations must be done. First, in the code was implemented the empirical and simple algorithm

CLEAN due to the limited experience of developers on computation for interferometry. Despite this, at least a preliminary and operational code could be generated even though based on the most simple and traditional algorithm.

Second, the five element array was designed exclusively to perform engineering and operational tests of the several systems and sub-systems in the actual operation conditions at open land subjected to weather conditions as well as eventual interference signals. Although some results showing the proper performance of the interferometer could be obtained, those are not for scientific purpose due to the limited number of useful baselines with good data, 3.

The last, generated code is the first version only – alpha – supported by various hypothesis and assumptions. From this point there are at least two choices. To go ahead with the code development upgranding to a modern algorithm in a more sophisticated and complete code which attends the requirements of the BDA. The other choice is to adapt the data acquisition and formatting as a purpose the freely available Packages, e.g. AIPS, can be used to perform the reducing data to generate the interferometric images.

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