An optimized implementation of the CLEAN method for the BDA

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Abstract
This work presents an optimized implementation of the CLEAN deconvolution method. This implementation is employed for the restoration of solar images acquired by the BDA (Brazilian Decimetric Array), a radio telescope under development at the National Institute for Space Research (INPE). The acquisition process causes degradation of the images that must be restored by some deconvolution process. Since the BDA is being implemented and is currently acquiring only one-dimensional images, the current work employs two-dimensional dirty images obtained from a similar radio telescope, the SSRT (Siberian Solar Radio telescope) at 5.7 GHz. Image restoration results are shown and discussed.

Keywords: (CLEAN, Fourier transform, radio astronomy, image processing)

1. Introduction

The First International Program of Space Weather Forecast [5], started in 1989, in Japan. Due to this program, several laboratories of space weather forecast had been established in institutes and universities around the world, in order to investigate the solar activity. The primary objective of this research is to forecast solar explosions that may cause serious perturbations in the terrestrial communication systems, damage to satellites and energy transportation systems, as well as the emission of extremely dangerous radiation for astronauts in space missions.

The Latin-American Space Weather Forecast Program is being conducted in Brazil by two departments of the National Institute for Space Research (INPE), the Astrophysics Division (DAS) and the Associated Laboratory for Computing and Applied Mathematics (LAC). The Sun emits energy at different wavelength of the electromagnetic spectrum, from radio waves up to higher energy emissions such as X-rays and gamma rays. The radio waves can be detected by radio telescopes on the Earth, but X-rays and gamma radiations do not penetrate the terrestrial atmosphere and thus only telescopes on board of satellites can detect them. This work is focused on a particular array of radio telescopes, the Brazilian Decimetric Array (BDA) of DAS/INPE. Recent studies and analysis of solar activity suggest that a large amount of energy is emitted during solar explosions/flares in the form of radio waves, specifically in the decimetric band. The BDA was designed to have high spatial and temporal resolutions in order to obtain high spatial resolution solar images for better understanding of the fundamental phenomena of Solar Physics, and consequently of space weather prediction.

The angular resolution of a single (parabolic) radio telescope depends on the diameter of the dish and also on the wavelength. In order to obtain telescopes with high resolution, it would be necessary to build antennas with bigger diameters. Alternatively, radio interferometry allows building radio telescopes with high resolution, by adding the acquired signals of a number of small antennas obtaining the same resolution as a radio telescope with a larger antenna. The resolution of an interferometer array is proportional to the length of its maximum baseline – the farthest distance between the extremities of the antennas.

In radio interferometry, an array of antennas acquires data that corresponds to the Fourier transform of the real image (or brightness distribution). The application of the inverse Fourier transform, implemented by means of hardware or software, yields a degraded image, the dirty image or dirty map. It contains distortions and artifacts caused by noise and by the image acquisition process.

The acquisition process can be modeled as the convolution of the real image and a transfer function, called dirty beam. In Optics, it is said that the image is the convolution of the object with a point-spread function (PSF), and these patterns are referred as diffraction patterns. Therefore, image-restoring processes use some deconvolution method. One that is commonly used in Radio
Astronomy is the CLEAN algorithm. This work presents an optimized implementation for this algorithm, designed for parallel processing in a distributed memory parallel machine. This implementation was formerly proposed in a previous work [13]. The master processor distributes data of the dirty image among the remaining processors. Image restoration is then performed in parallel by the processing nodes. The master node collects the output data from these nodes and assembles the reconstructed clean image.

A Prototype of the Brazilian Decimetric Array (PBDA) [11], composed by 5 antennas has been tested at INPE in São José dos Campos at the beginning of 2003. Currently this prototype is shifted to its definite location at INPE in Cachoeira Paulista/SP. However, the PBDA only acquires one-dimensional images, and the current work is proposed for two-dimensional dirty images. Image restoration tests were then performed using data from a similar radio telescope, the SSRT (Siberian Solar Radio telescope) at 5.7 GHz. Image restoration results are shown and discussed.

This paper is organized as follows: in section II, the BDA project is presented. Section III presents the new implementation of the CLEAN deconvolution method, and Section IV presents the results and comments.

2. The Brazilian Decimetric Array - BDA

The BDA is a modern interferometric array [12], being the unique radio interferometer in Latin America. BDA is being developed by DAS/INPE and other Brazilian and international institutes are collaborating in the associated project.

Figure A: Prototype of the Brazilian Decimetric Array with 5 antennas, located at INPE, São José dos Campos.

The final version of the BDA will be a “T” shaped array composed of 38 parabolic antennas of 5 m diameter, located at Cachoeira Paulista, Brazil. The BDA will acquire solar images with high (~5 x 8 sec of arc at 5.0 GHz) spatial resolution [10], in the frequency range of 1.2 to 5.0 GHz, at the rate of 10 images per second.

Once in full operation, in 2006, the BDA will be able to obtain, in a regular basis, radio images of the solar disc and of isolated active regions. The observation of solar phenomena will allow a better understanding of the mechanisms of CME (Coronal Mass Ejection). Further investigation of solar phenomena will contribute to improve space weather forecast, which is one of the objectives of the BDA project.

3. The proposed implementation of the CLEAN deconvolution method

One of the most successful algorithms used in radio astronomy for image restoration is the ‘CLEAN’ algorithm (Schwartz, 1978, Högbom, 1974). The CLEAN method assumes that the object (the real image) is only composed of point sources. It tries to decompose the dirty image/map into a set of Dirac Delta functions. This is done iteratively by finding the point with the largest absolute brightness and subtracting the PSF (dirty beam) scaled with the product of the loop gain and the intensity at that point. In order to find that point, a two-dimensional scan of the image is performed. The resulting residual image/map is then used to repeat the process, starting a new iteration. The process is stopped when some pre-specified intensity limit is reached. The convolution of the set of Dirac Delta functions with an ideal PSF (clean beam) plus the residual image is equivalent to the restored image (clean map).

The new implementation of the CLEAN deconvolution method can be parallelized in order to attain near real time visualization of restored BDA images. At each iteration, the standard CLEAN algorithm searches on the entire two-dimensional data set and decomposes the dirty map into Dirac Delta components. In the proposed method, the original CLEAN procedure is performed in two one-dimensional steps, i.e. instead of scanning the entire two-dimensional image, a row-wise one-dimensional scan is performed, to clean in one dimension (i.e. rows of the dirty map) and then another column-wise one-dimensional scan is done using the transposed data of the resulted row-wise clean output, to clean on the other dimension (i.e. columns of the dirty map). Since these operations are done by rows or columns, parallelization is easily achieved, by distributing sets of rows or columns among processors.

The image restoration process begins, as in the standard process, with the selection of an input file (dirty image) by the user, a normalization method is applied on input data, since the intensities may present typically vary different
orders of magnitude (from 0 to $7 \times 10^7$ W). The normalized data is then taken as input for the row-wise cleaning. The resulting output image is transposed and then given as the input for the column-wise cleaning. The final output image is stored in a separate text file format. MatLab is used for the visualization of the final restored images from these output files.

Assuming that the true image $I$, the dirty image $D$, the cleaned image $C$, the dirty beam $B$, and the accumulated point source matrix $t$ have dimension $n \times n$, the image acquisition/degradation process can be expressed by:

$$D = I \times B$$

The step-by-step description of the ‘CLEAN’ procedure is shown below, for either row or column wise cleaning:

1) Initialize all elements of the $t$ with zero.

2) For a generic row $i$ of the dirty image, find the absolute intensity $\text{max}(i)$ and its position $j_{\text{MAX}}$.

3) At the position $j_{\text{MAX}}$ of that row, perform the following subtraction to update it:

$$\text{residual max}(i) = \text{max}(i) \times [1 - B(i, j_{\text{MAX}}) \times g]$$

Where $g$ is the loop gain (or damping factor, $0 < g < 1$). Record the subtracted flux value $[\text{max}(i), B(i, j_{\text{MAX}})]$ at the corresponding element of matrix $t$, that is, $t(i, j_{\text{MAX}})$

4) Go to step (1) unless any remaining peak in that row is below some user specified intensity level. What are left are residuals (residual value of row $i$).

5) After all rows are cleaned, perform the following convolution in order to get $C$, using an idealized beam $B_{\text{fit}}$ (for instance, a Gaussian fit of the dirty beam $B$ at its central lobe):

$$C = t \times B_{\text{fit}}$$

6) In the final step, add to the CLEAN image the residuals of the dirty image:

$$C = C + R.$$  

The purpose of steps 5 and 6 is to weight down the high frequency terms of the estimated visibility and to keep the significant features that may still be left in residuals. At every row, the iteration stops when all intensities of that row are below a user-defined intensity.

4. The Siberian Solar Radio Telescope - SSRT

In the introduction section, it was mentioned that we are expected to obtain two-dimensional images from BDA in the near future. Meanwhile this method is being developed and tested with the SSRT Dirty images. The Siberian Solar Radio Telescope (SSRT) (Smolkov et al. 1986) is a large astronomical instrument configured as a cross-shaped interferometer consisting of 128x128 parabolic 2.5-meter antennas, equally spaced with a separation of 4.9m. This radio telescope is devoted to the study of solar activity in the microwave range of 5.7GHz, where processes in the solar corona are visible across the entire solar disk.

Figure B: The Siberian Solar Radio Telescope (SSRT) layout.

Figure 1a illustrates a SSRT dirty image of the Sun, with size 1024x1024, obtained on 21st August 2002 at UT 04:26:25 with polarization ‘R+L’. Figure 1b shows the same data in log scale in order to have a better view of the compact bright sources, solar disc, sidelobes, etc. The dotted region in figure 1b is zoomed and focused in figure 1c since we are interested to show this particular region in
the dirty image where the sidelobes are mixed with compact sources. The figure 1d represents the contour version of figure 1c. Figure 1a and 1b show two bright sources surrounded by few other smaller compact bright sources. Also, the Figures show two structures aligned along vertical and horizontal lines inclined at certain angle passing through the observed bright sources. These structures are related to the sidelobes, an effect of deficient signal sampling in the Fourier plane [6]. Usually, these sidelobes are seen along the bright sources, their size depending on how strong the source is. This can be concluded from the SSRT dirty image, where the right side source is brighter than left one, hence the sidelobes on the right side seem to be larger in size than left ones. In any case, such dirty maps always cause difficulties during the interpretation of the solar activity. Restoration of such diffuse sources is always a complicated task, especially in case of solar observations. However, deconvolution methods such as CLEAN or MEM (Maximum Entropy Method) can lead to good results in the restoration process of solar images in radio astronomy.

Figure 1a: SSRT Dirty image of the Sun obtained on 21-Aug-2002, time: '04:26:26'.

Figure 1b: SSRT Dirty map, plotted on log scale showing compact bright sources and sidelobes.

Figure 1c: Zoomed region from the dirty image.

Figure 1d: Contour version of the zoomed region.
5. Test Results

Figure 2a illustrates the intermediate result obtained after row-wise cleaning. Comparing Figure 2a with figure 1a and 1b, it can be observed that the majority of the sidelobes along the vertical direction was removed completely. Nevertheless, a few sidelobes in the horizontal direction still remained. It can be observed that those sidelobes could be removed by column-wise cleaning. The end result of column-wise cleaning is shown in Figure 2b. The dotted region in Figure 2b is zoomed and illustrated in Figure 2c. Finally, Figure 2d illustrates that the cleaning process removed those sidelobes and still preserving the significant sources.

6. Final remarks

The new implementation of the CLEAN deconvolution method was applied to SSRT data. Test results have shown that complicated brightness structures could be restored using an automatic data processing routine. This implementation can be easily adapted for the BDA, requiring only a few modifications in the loop gain and user specified CLEAN level.

7. References


