

## Speckle interferometric observations of the collision of comet Shoemaker-Levy 9 with Jupiter

S.K. Saha<sup>1</sup>, R. Rajamohan<sup>1</sup>, P. Vivekananda Rao<sup>2</sup>, G. Som Sunder<sup>2</sup>,  
R. Swaminathan<sup>2</sup> and B. Lokanadham<sup>2</sup>

<sup>1</sup>Indian Institute of Astrophysics, Bangalore 560 034, India

<sup>2</sup>Astronomy Department, Osmania University, Hyderabad 500 007, India

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**Abstract.** Speckle interferometric technique has been used to obtain a series of short exposure images of the collision of comet Shoemaker-Levy 9 with Jupiter during the period of July 17-24, 1994 using the nasmyth focus of 1.2 meter telescope of Japal-Rangapur Observatory, Hyderabad. The technique of Blind Iterative Deconvolution (BID) was used to remove the atmospherically induced point spread function (PSF) from these images to obtain diffraction limited information of the impact sites on Jupiter.

*Key words* : speckle imaging, image reconstruction, Jupiter, Shoemaker-Levy 9

### 1. Introduction

The impact of the collision of the comet Shoemaker-Levy 9 (1993e) with the gaseous planet Jupiter during the period 16-22 July 1994, has been observed extensively worldwide, as well as from the Hubble Space Telescope. Several observatories in India too had planned observations of the crash phenomena starting from the observations in the visible part of the electromagnetic spectrum to the radio frequencies (Cowsik, 1994). As a part of the programmes, we had developed an interferometer to record the images of the collision of the fragments of Comet Shoemaker-Levy 9 (SL 9) with Jupiter during the period 17-24 July 1994, with a goal of achieving features with a resolution of 0.3-0.5 arc sec., in the optical band, using 1.2 meter telescope at Japal-Rangapur Observatory (JRO), Osmania University, Hyderabad. Though, monsoon condition prevailed over large part of the country, we were able to record more than 600 images of the entire planetary disk of Jupiter during the said period. In this paper, we describe the observational technique using interferometer, as well as the image processing technique used to restore the degraded images of Jupiter.

## 2. Observations

The image scale at the nasmyth focus ( $f/13.7$ ) of 1.2 meter telescope of JRO, was enlarged by a Barlow lens arrangement (Saha *et al.*, 1987, Chinnappan *et al.*, 1991). The set up was modified to suit the requirement of sampling 0.11 arc sec/pixel of the CCD (at  $0.55 \mu$ ) which is essentially the diffraction limit of the said telescope. A set of 3 filters were used to image Jupiter, viz.,: (i) centered at  $5500 \text{ \AA}$ , with FWHM of  $300 \text{ \AA}$  (ii) centered at  $6110 \text{ \AA}$ , with FWHM of  $99 \text{ \AA}$  and (iii) RG9 with a lower wavelength cut-off at  $8000 \text{ \AA}$ .

A  $1024 \times 1024$  pixel water cooled CCD with a pixel size  $22 \mu$  was used as a detector. 50 speckle-grams were sequentially recorded (each of 100m sec exposure) in each of the 3 filters. The exposure time was chosen to obtain a good signal- to noise ratio. Since the smearing due to the equatorial rotation of Jupiter is about 0.15 arc sec/min., one can afford to accumulate speckle-grams for 2-3 minutes, if one expected to attain a resolution of 0.5 arc sec. In this experiment, we have recorded 10 speckle-grams/min. Therefore, 20-30 frames with good enough signal-to-noise ratio at the desired spatial frequencies are required to perform speckle reconstruction. 600 images were recorded on July 17, 1994 soon after the fragment E of the Comet SL-9 collided with Jupiter. On July 24, 1994, 80 more images were recorded. A liquid nitrogen cooled  $512 \times 512$  CCD was used to record 3 images of Jupiter in integrated light on July 22, 1994.

## 3. Data processing

Atmospherically induced phase fluctuations distort incoming plane wave-fronts from the distant objects which reach the entrance pupil of telescope with patches of random excursions in phase. Such phase distortions restrict the effective angular resolution of most telescopes to 1 second of arc or worse. Speckle interferometry (Labeyrie, 1970) recovers the diffraction limited spatial Fourier spectrum and image features of the object intensity distribution from a series of short-exposure ( $< 20$  m sec.) images. Schemes like Knox-Thompson algorithm (Knox-Thompson, 1974), triple correlation (Lohmann *et al.*, 1983) have been successfully employed to restore the Fourier phase of an extended object. All these schemes require statistical treatment of a large number of images within the time interval over which the statistics of the atmospheric turbulence remains stationary. There are a number of schemes, viz., Maximum Entropy Method (Jaynes, 1982), CLEAN algorithm (Hogbom, 1974) and Blind Iterative Deconvolution (BID) technique (Ayers and Dainty, 1988) being applied to restore the image using some prior information about the image. Here, we employed a version of BID developed by P. Nisenson (Nisenson, 1991), on degraded images of Jupiter.

In this technique (see Bates and McDonnell, 1986), the iterative loop is repeated enforcing image-domain and Fourier-domain constraints until two images are found that produce the input image when convolved together. The image-domain constraint of non-negativity is generally used in iterative algorithms associated with optical processing to find effective supports of the object and or point spread function (PSF) from a speckle-gram. Here, the Weiner filter was used to estimate one function from an initial guess of the PSF.

The algorithm has the degraded image  $c(x,y)$  as the operand. An initial estimate of the point spread function (PSF)  $p(x,y)$  has to be provided. The degraded image is deconvolved from the guess PSF by Wiener filtering, which is an operation of multiplying a suitable Wiener filter (constructed from the Fourier transform  $P(u,v)$  of the PSF with the Fourier transform  $C(u,v)$  of the degraded image as follows

$$O(u,v) = C(u,v) \frac{P^*(u,v)}{P(u,v)P^*(u,v) + N(u,v)N^*(u,v)}$$

where  $O$  is the Fourier transform of the Deconvolved image and  $N$  is the noise spectrum.

This result  $O$  is transformed to image space, the negatives in the image are set to zero, and the positives outside a prescribed domain (called object support) are set to zero. The average of negative intensities within the support are subtracted from all pixels. The process is repeated until the negative intensities decrease below the noise.

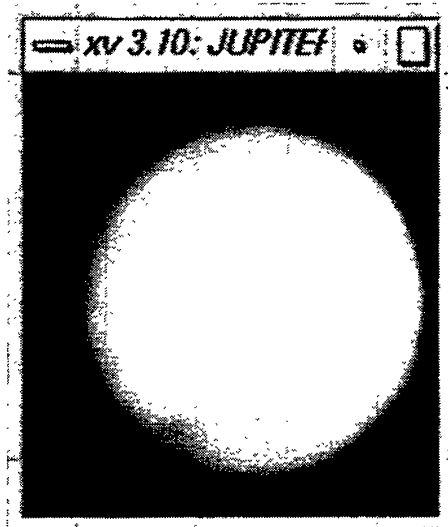
A new estimate of the PSF is next obtained by Wiener filtering the original image  $c(x,y)$  with a filter constructed from the constrained object  $o(x,y)$ . This completes one iteration. This entire process is repeated until the derived values of  $o(x,y)$  and  $p(x,y)$  converge to sensible solutions.

#### 4. Results

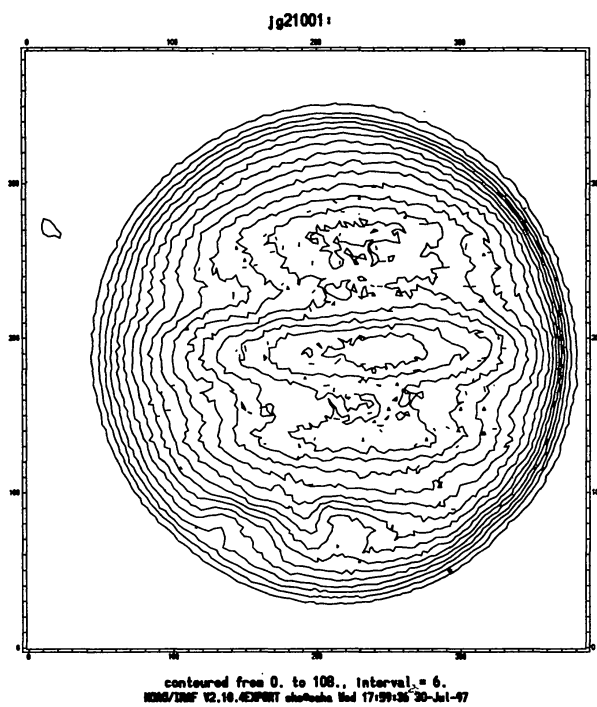
The flat field corrections, as well as bias subtractions were made for all the Jupiter images acquired on 17 and 24 July 1994, using IRAF image processing package and analyzed on SPARC ultra workstation. The images were converted to specific formats to make them IRAF compatible. The results for the Jupiter images obtained on 17 July 1994 and on 24 July 1994 were arrived at after 150 iterations. Since the combined PSF of the atmosphere and the telescope varies as a function of time, the value of support radius of the PSF had been chosen accordingly. The value of the Weiner filter parameters also had chosen according to the intensity of each of the images differently. Figure 1 shows the speckle-gram of Jupiter obtained on 24 July 1994, through the green filter centered at  $5500 \text{ \AA}$ , with FWHM of  $300 \text{ \AA}$ . The satellite Io can be seen on top left. Care has been taken to avoid the satellite while reconstructing the images. Figure 2 shows the deconvolved image of the same. The complex structure of the spots were identified and compared with Hubble space telescope observation. The chief result of this reconstruction is the enhancement in the contrast of spots. The complex spot at the East is due to impacts by fragments Q, R, S, D and G. The spot close to the centre is due to K and L impacts. Figure 3 depicts the reconstructed PSF.

#### 5. Discussion and conclusions

The uniqueness and convergence properties of the deconvolution algorithm are uncertain for the evaluation of the reconstructed images if one uses BID directly. The support radius of the PSF was estimated from the observations around the same time. The present scheme of BID has been tested by reconstructing the Fourier phase of the computer simulated convolved

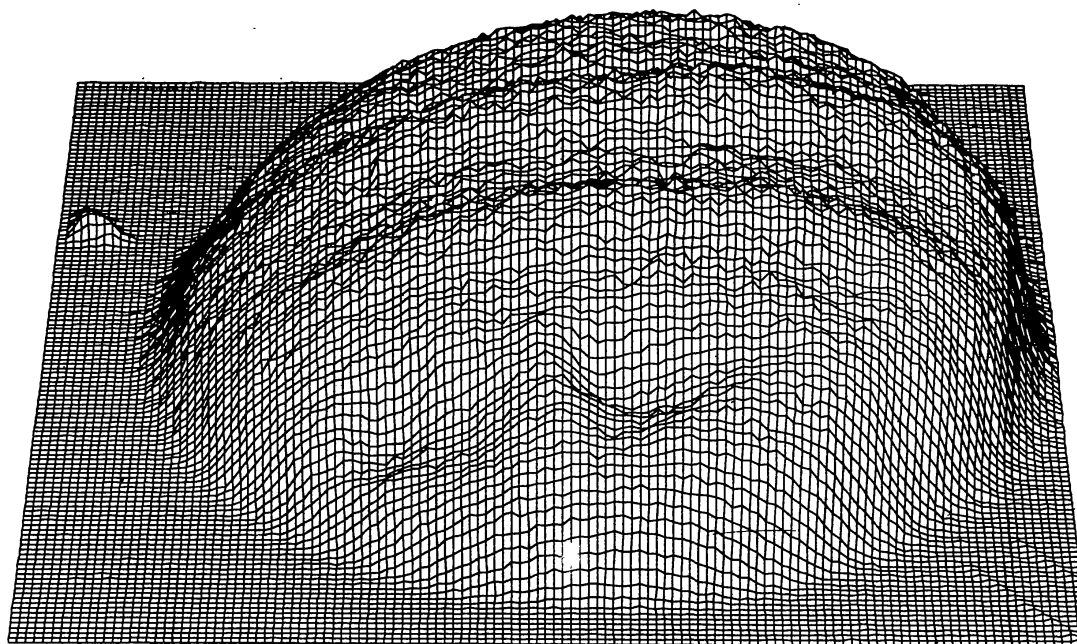


Figures 1(a-c) show the greyscale, 2-D contour and 3-D speckle-gram of Jupiter obtained on 24th. July'94 respectively. The numbers on the axes of the 2-D contour map denote pixel numbers with each pixel being to 0.1 arc sec. The satellite Io can be seen on top left.

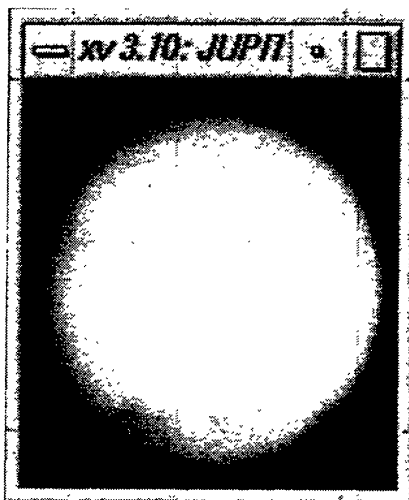


1 (b)

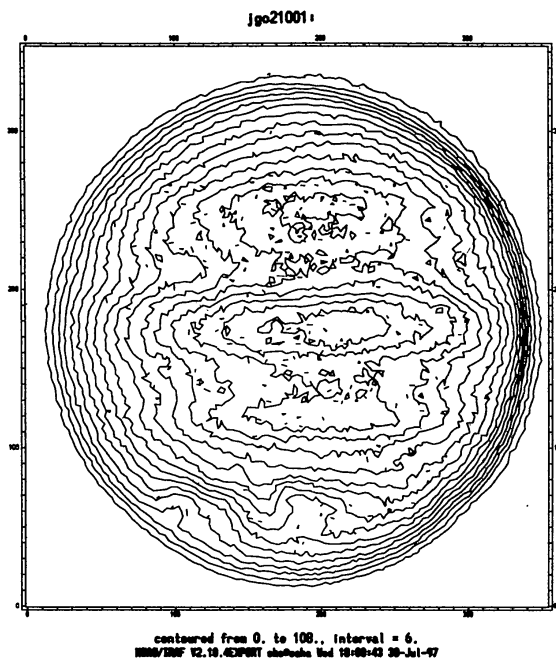
Fig 21001:



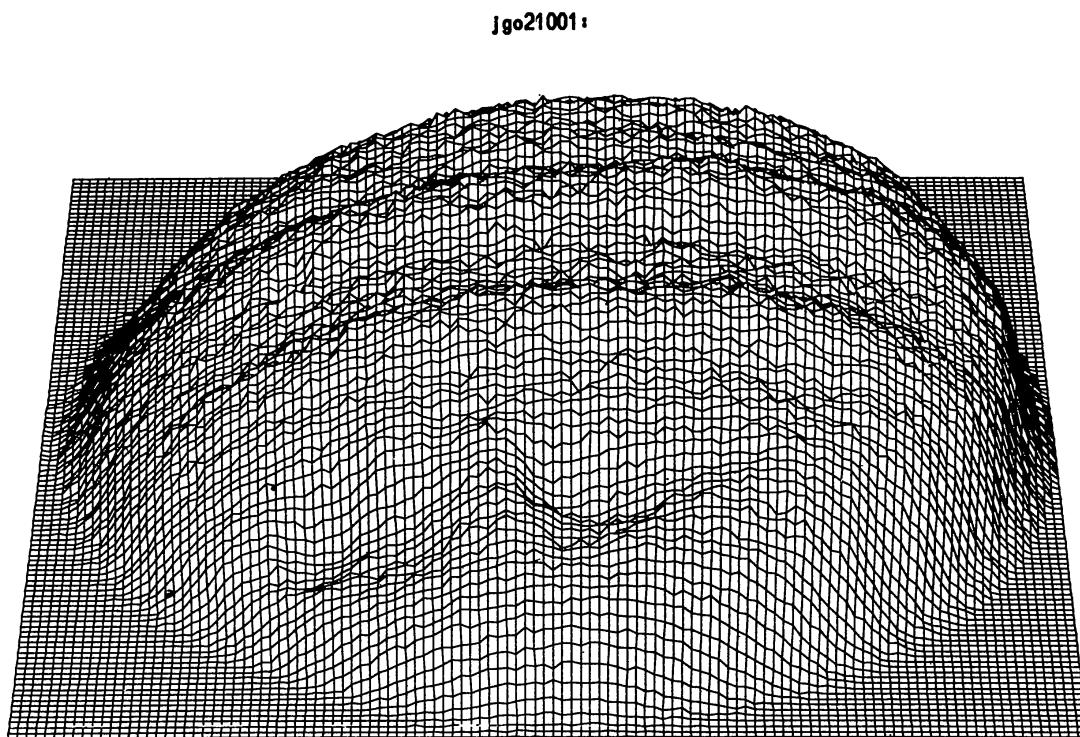
1 (c)



Figures 2 (a-c) are for the deconvolved image of Jupiter on 24 July 1994.



2 (b)



2 (c)

Jgp21001:

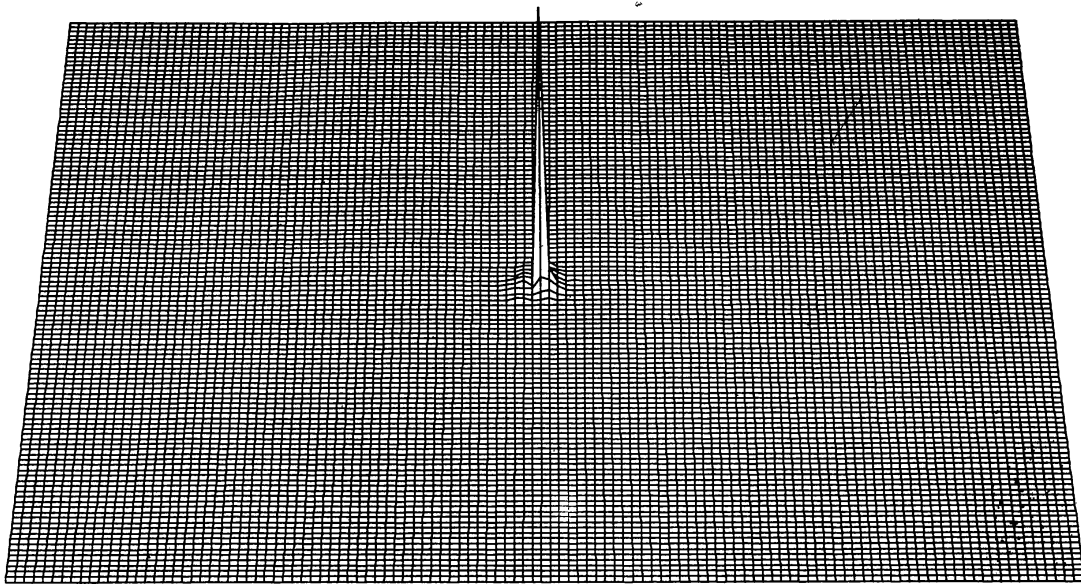


Figure 3. 3-D map of the reconstructed Point Spread Function (PSF).

functions of binary star and the PSF caused by the atmosphere and the telescope which was used as an input. It is found that this software preserves the photometric quality of the reconstructions. The same software was used to retrieve the Fourier phase of two binary stars obtained at the Cassegrain end of the 2.34 meter Vainu Bappu Telescope (VBT), at Vainu Bappu Observatory (VBO), Kavalur, India (Saha and Venkatakrisnan 1997). The authors have found the magnitude difference for the reconstructed objects compatible with the published values.

In the case of compact sources, it is essential and possible to put a support constraint on the object obtained from the auto-correlation. Whereas, in this case of an extended object of a complex structure, the auto-correlation is of not great help to constrain the individual features. Convergence could not be obtained in the absence of any constraints. The estimated support radius of the PSF was utilized in this case and a successful convergence was obtained. Thus in the case of complex objects, the prior knowledge of the PSF support radius seems to be vital for the reconstructions.

Though the chief problem of this software is that of convergence, it is indeed an art to decide when to stop the iterations. The results are also vulnerable to the choice of various parameters like the support radius, the level of high frequency suppression during the Wiener filtering, etc. The availability of prior knowledge on the PSF, in this case, of the degraded image was also found to be very useful. It is to be seen how the convergence could be improved (cf. Jefferies and Christou, 1993). For the present, it is noteworthy that such reconstructions are possible using single speckle frames.

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