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Techniques for Achieving Higher Spatial Resolution

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Abstract. The application of speckle and interferometric techniques for imaging small scale solar features is studied in detail. A computer program(speckle code) was developed to analyze the speckle data. The capability of the code to obtain a 'good' reconstruction from a few selected best frames has been demonstrated. It is found that the interferometric imaging technique can probably be used for imaging bright isolated point-like objects that ride on a bright or locally depressed background.

Keywords : Speckle Imaging – Interferometric imaging

1. Introduction

The aim of this work was to develop both the hardware and the software required for obtaining high angular resolution images on a regular basis from ground based telescopes using speckle and interferometric imaging techniques. A program (speckle code) has been developed and used to analyze the speckle data obtained from a few solar telescopes. Another program has been developed to generate phase screens and simulate interferograms from them. The possibility of using interferometric imaging as a viable tool for imaging small solar features has been explored with the help of the simulated interferograms and those recorded in real time.

2. Data

analyzed in this paper were obtained from four different solar telescopes. The first set of data was obtained using the 38 cm tunnel telescope of the Kodaikanal Ob-

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servatory (hereafter KO data). A portion of the Sun's image was re-imaged using a combination of two lenses. Speckle images of a few sunspots and pores were recorded with a filter of 160 Å bandwidth (BW) centered at 6520 Å with an exposure time of 1 milli-second (ms) per frame. Interferograms of the same region were recorded with an exposure time of 9 ms after inserting a non-redundant mask at the re-imaged pupil plane. The second set of data consisted of speckle images of a few sunspots recorded with a filter of 0.5 Å BW centered at 6563 Å with an exposure time of 7 ms per frame using the 15 cm Coude telescope of the State Observatory, Nainital (hereafter UPSO data). The third set of data consisted of speckle images of the sub-flare region NOAA AR 8898, recorded with a filter of 1 Å BW centered at 6563 Å with an exposure time of 20 ms per frame using the 13.5 cm Coude telescope of the Udaipur Solar Observatory (hereafter USO data). The fourth set of data consisted of speckle images of a plage region, a quiet Sun region and the NOAA AR 8923, recorded near-simultaneously with filters of 10 Å BW centered at 4305 Å and 3 Å BW centered at 3933 Å using the 76 cm Dunn Solar Telescope of the Sacramento Peak Observatory, New Mexico (hereafter SP data). In addition to these, another set of data was obtained by performing a laboratory experiment on interferometric imaging technique. A lens collimated He-Ne laser light falling on a pinhole of 30 micron diameter. Another lens focused the image of the pinhole on to a CCD. Interferograms were recorded by inserting a non-redundant mask between the two lenses. A glass plate sprayed with silicon oil was kept close to the imaging lens to introduce phase errors.

3. Analysis

We estimated the Fried's parameter (r_0) from each sequence of data after preprocessing the images. We explored three different ways of estimating r_0, viz. from the angle of arrival fluctuations (Roddier, 1981), power spectrum equalisation method (Castleman, 1979; Stockham et al, 1975; Huang et al, 1971; Andrews and Hunt, 1977) and the spectral ratio method (Von der Lühe, 1984). We developed a computer code to analyze speckle images. In our speckle code, we used speckle interferometry (Labeyrie, 1970) to estimate the Fourier amplitudes of the object and speckle masking (Weigelt, 1977) to estimate the Fourier phases. We use the noise filter developed by Pehlemann and von der Lühe (1989) and de Boer (1996). We estimate the mean squared gradient in the image as a measure of its contrast and use it for selecting the best frames. When the field of view is larger than the typical size of the isoplanatic patch ($\sim$ 5 arc sec), we 'de-stretch' (November, 1986) the images. We reconstruct the image as a mosaic of several reconstructed images, similar to the procedure followed by von der Lühe (1993). We use the 'optimum apodisation window' (Keller, 1999) to apodise the sub-images so that the effect of the usual cosine -bell function on the phases of the bispectrum is minimized. Our speckle code takes about 10 minutes to reconstruct an image from a sequence of 90 images of size 128 by 128 pixels and requires a RAM size of 100 MB. This does not include the time required to estimate r_o for all the sub-images.

We reconstructed speckle images for each sequence of data using our code. As the

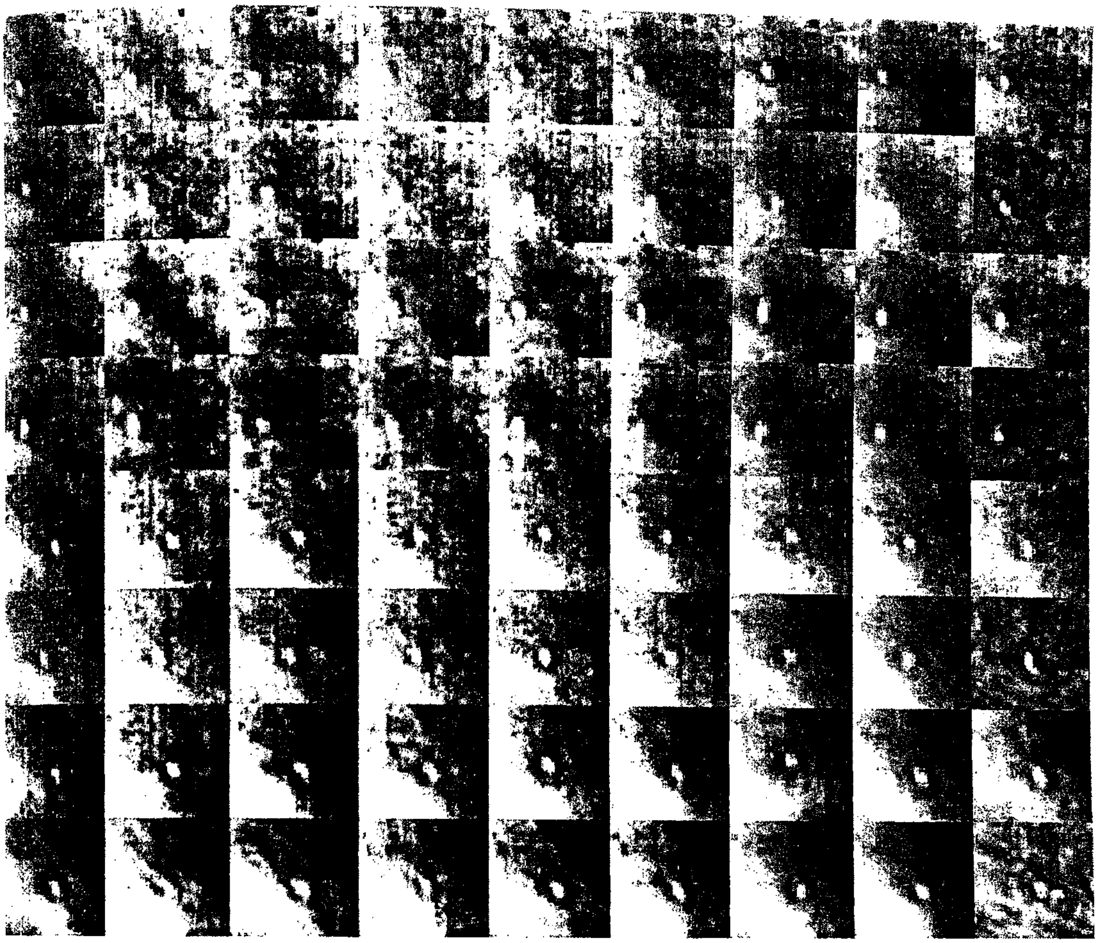

Figure 1. Two sequences of 36 images of a pore region, separated by 17 seconds. In each sequence, the 17th image is the average of the preceding 16 images. The 18th image is the reconstruction. The next 18 images represent the same images after 'de-stretching'. Each image is of size 4.3 arc sec by 4.3 arc sec. The size of the isolated bright point is 0.43 arc sec.

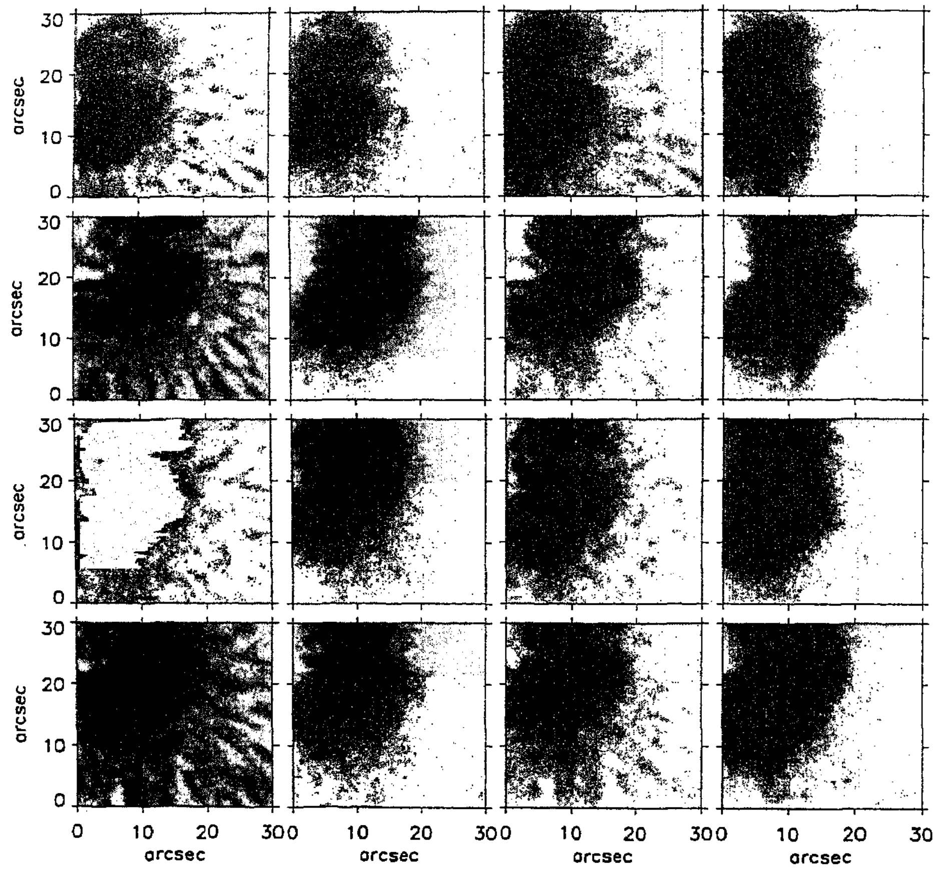

Figure 2. Four sequences of reconstructed images of a portion of NOAA AR 8898. The first column is the reconstruction from 5 best frames. The second column is the reconstruction from 5 worst frames. The third column is the reconstruction from all the frames (~90). The fourth column is the collage of best segments, each corrected for the transfer function of the telescope. The best frames were identified as those having higher mean square gradient in x and y directions.

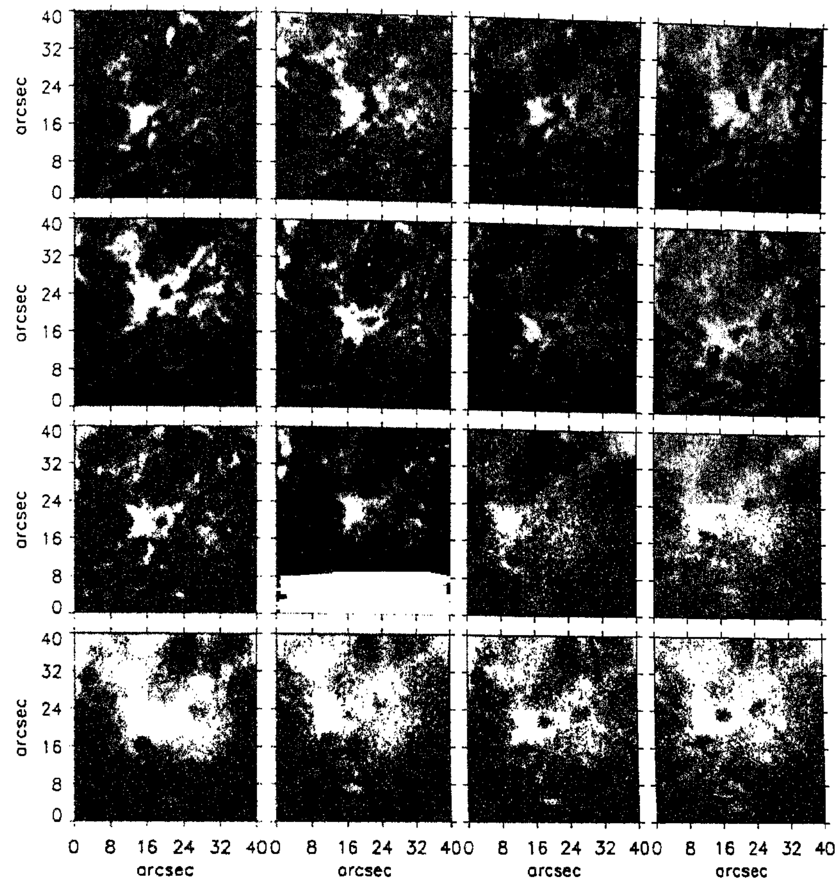

Figure 3. 16 consecutive reconstructed images of a sequence of a sub-flare region. The filament break-up is clearly seen. A sub-flare erupted at this region a few minutes later

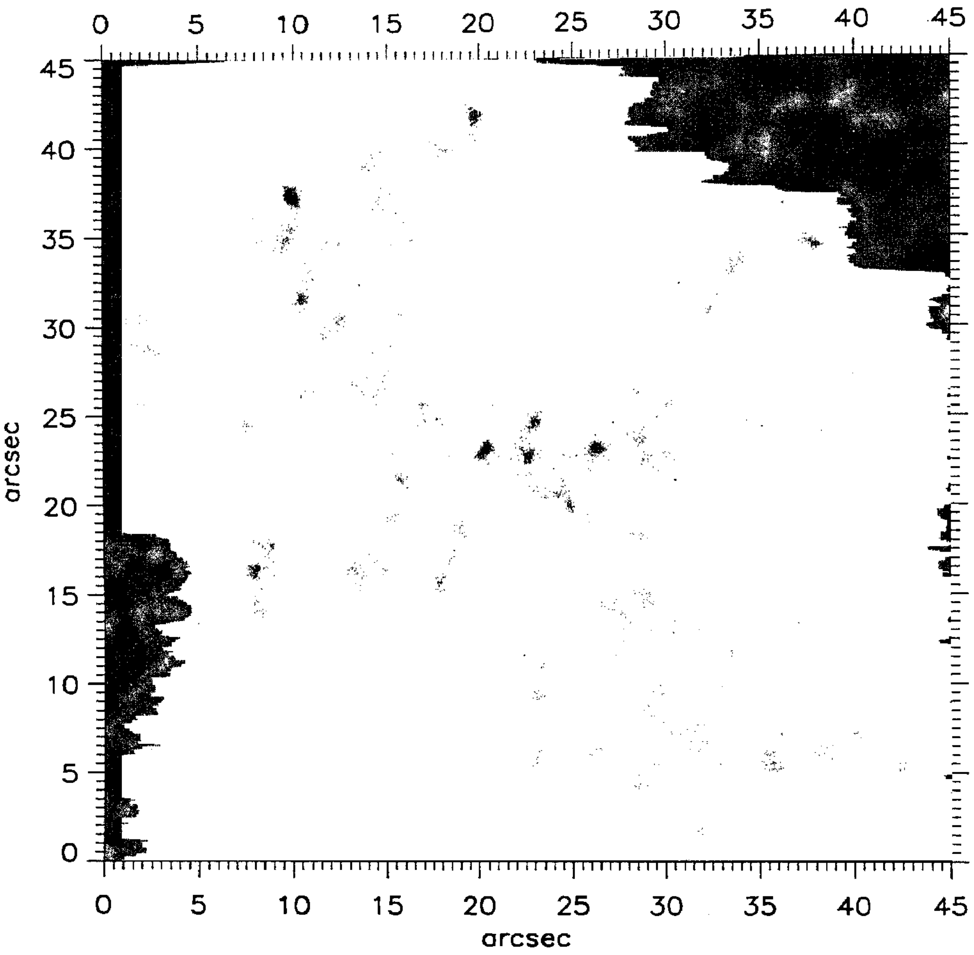

Figure 4. Image reconstructed from three best frames of a plage region in Ca II K line

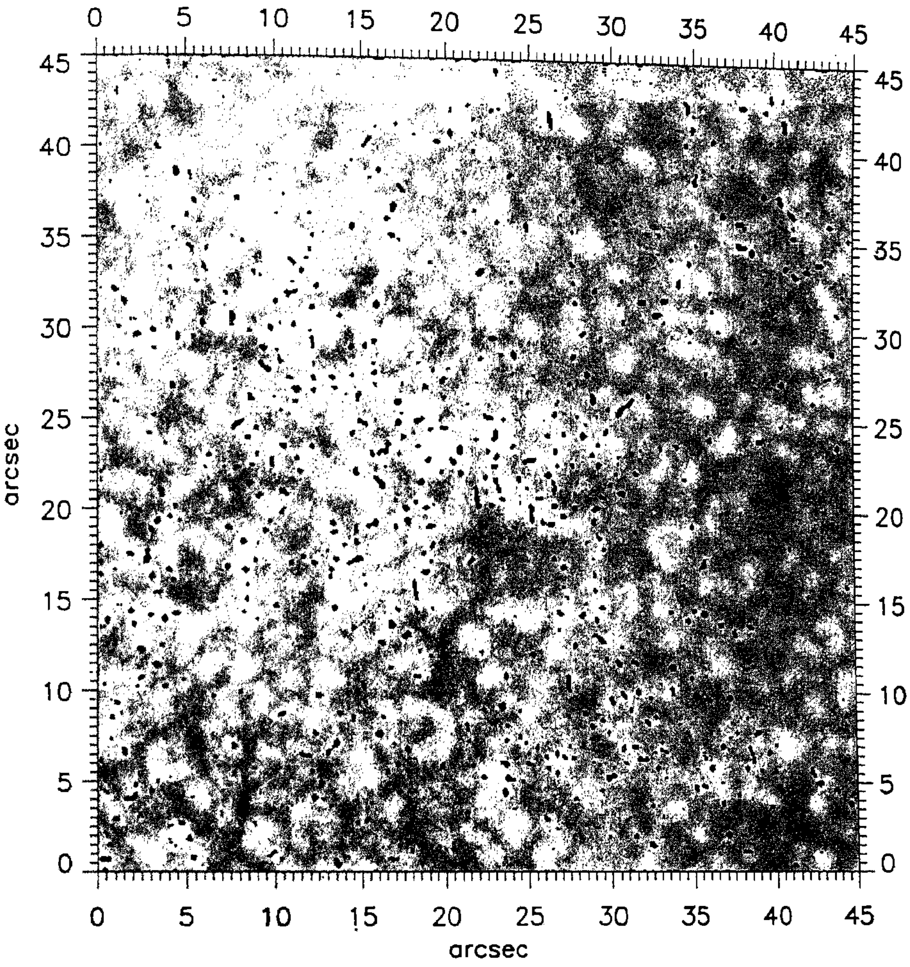

Figure 5. G band binary map of a plage region overlaid on the corresponding reconstructed G-band image

exposure time was more than 50 ms for the SP data and the seeing conditions were poor during the observations, we obtained a speckle reconstruction from three best frames without correcting for the attenuation of the Fourier amplitudes of the object for all the three (plage, quiet sun and NOAA AR 8923) regions in both G-band and Ca II K.

We reconstructed the image of the pinhole from the fringes recorded in the laboratory using the 'closure phase imaging' (Baldwin et al 1986, Nakajima et al, 1989) technique. We developed a software to generate phase screens and simulate interferograms from them for a given seeing condition. Then we simulated interferograms corresponding to the seeing conditions that prevailed during our observations at KO and convolved them with the speckle reconstructed image of a pore region that contained an isolated bright point. The resulting fringes were found to be similar to those recorded in real observations.

4. Results

The Fried's parameter was estimated to be 6±3 cm for the KO data, 3±0.5 cm for the UPSO/USO data and 8±3 cm for the SP data. The highest resolution that we could achieve was 0.43 arc sec (for KO data) (Figure 1). We could obtain a 'good' speckle reconstruction from a few selected best frames (Figure 2). Thus our speckle code is suitable for reconstructing images obtained from a large telescope. Even with moderate seeing conditions, we could reconstruct a sequence of images that depict the dis-appearance of a filament (Figure 3). We studied the morphological relationship between the G-band bright points (GBPs) and the Ca II K bright points (Figures 4 and 5). We speculate two varieties of GBPs, one that is continuously formed everywhere and hence observed at any given time and the other that is swept by the horizontal flow to the boundaries of the supergranular cells and hence cause heating. We found that the interferometric imaging technique could probably be used for finding sub-structure morphology of isolated bright point like sources. In future, we plan to parallelise our speckle code and continue the speckle imaging observations with the existing solar telescopes. We also plan to implement some of the speckle processing techniques through hardware.

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