High Resolution Image Recovery by Speckle Interference Method in Huairou's 60 cm Telescope

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Abstract

On the basis of the speckle interference method and by a series of short exposure images (< 10 ms), high resolution granulation near the center of the solar disc has been recovered in Huairou's Multi–Channel Solar Telescope.

1. Introduction

How about is the fine structure of the Sun? This is a very important and far from solved problem in solar physics. High resolution observation data is the key to answer this question. But because of the turbulence of the atmosphere, the ground-based telescope can hardly obtain high resolution data better than 1 arcsec (especially for the fine magnetic field structure). So what we are interested in is how to remove the effect of the atmosphere in order to study the solar fine structure. There exist three ways to remove or avoid the effect of the atmosphere. The first is placing the telescope outside the atmosphere (space telescope); the second is adaptive optical technology. Although these two means are perfect and a few such systems have been achieved, many difficuties still exist under today's technical condition. The last way, an effective and relatively easy way for us, is the image restoration method.

In this paper, we will introduce the use of speckle interference method — one of the image restoration technology in Huairou's 60 cm Multi–Channel Solar Telescope. Some reconstruction images of the granulation near the center of the sun will be given.

2. Basic method of speckle interference image restoration.

Speckle interference method was introduced into astronomy by A. Labeyrie, a French astronomer, in 1970. From then on, it has been developed by many astronomers (Knox and Thompson 1974; Weigelt 1977; von der Luhe 1984; Keller and von der Luhe 1992; etc), and now it has become an important tool to study the fine structure of the Sun (von der Luhe 1984; Keller and von der Luhe 1992).

As for an image obtained by a ground-based telescope, the imaging equation is:

$$I_{(\vec{x})} = O_{(\vec{x})} * P_{(\vec{x})}$$

or in frequency domain it is:

$$\tilde{I}_{(\vec{q})} = \tilde{O}_{(\vec{q})} \tilde{P}_{(\vec{q})} \quad (1)$$

where, $\vec{x},\vec{q}$ are the 2–D space and frequency vector, I, O are the 2–D intensity distribution of the speckle sample and the object, "$\sim$" denotes the Fourier transform and " $*$ " denotes convolution. $\tilde{P}$ is called the optical transfer function of the atmosphere and telescope system.

If I is recorded by long exposure as we usually do ("long exposure" means the exposure time is longer than the characteristic time scale of atmosphere turbulence), the resolution of the image will be determined by the atmosphere Fried Parameter r_0. Because the value of "r_0" is usually smaller than 10 cm in optical region for the solar observation, the resolution of the image can hardly be better than 1 arcsec. But if I is recorded by short exposure (<10 ms), high resolution information up to the diffraction limit resolution of the telescope can be retained. So it is the base of the speckle image recovery that a series of short exposure image replace the long exposure image. From these data the modulus and the phase of the object can be found separately by Korff' s log-normal model of the atmosphere (Korff 1973).

(1) Modulus recovery by spectrum ratio

Start from equation (1)

$$|\tilde{O}_{(\vec{q})}|^2 = <|\tilde{I}_{i(\vec{q})}|^2> / <|\tilde{P}_{i(\vec{q})}|^2> \quad (2)$$

$$i = 1,2,\cdots,N$$

in this equation, "$|\quad|$" denotes the modulus of the function, "$<\quad>$" denotes the sequence average of the samples and "N" is the sample number. The "$<|\tilde{P}_{i(\vec{q})}|^2>$" is called the atmosphere modulation transfer function (MTF) and it can be determined only by the atmosphere Fried parameter r_0. The r_0 can be estimated by spectrum ratio method (von der Luhe 1984):

$$\varepsilon_{(\vec{q})} = |<\tilde{I}_{i(\vec{q})}>|^2 / <|\tilde{I}_{i(\vec{q})}|^2> \quad (3)$$

The log-normal model points out: the spectrum ratio drops to zero very rapidly when the frequency increases and approaches the r_0, and its value is zero when the frequency is larger than r_0 in the case of ideality. In fact we can only find a drop-off point (figure 2) in the curve of spectrum ratio because of noise. So the object modulus can be recovered as soon as the drop-off point of the spectrum ratio is found.

(2) Phase recovery by bispectrum

The bispectrum of a function is defined as:

$$\tilde{F}_{(\vec{q},\vec{p})} = \tilde{F}_{(\vec{q})}\tilde{F}_{(\vec{p})}\tilde{F}_{(-\vec{p}-\vec{q})} \tag{4}$$

Then we rewrite the imaging equation with bispectrum and average it:

$$< \tilde{I}_{i(\vec{p},\vec{q})} > = \tilde{O}_{(\vec{p},\vec{q})} < \tilde{P}_{i(\vec{p},\vec{q})} > \tag{5}$$

where, the last term of the right is called as Speckle–Masking transfer function and it can be proved to be a real function by the log-normal model. Then we will have a recursive equation:

$$\text{Phase of } \tilde{O}_{(\vec{p}+\vec{q})} = \text{phase of } \tilde{O}_{(\vec{q})} + \text{phase of } \tilde{O}_{(\vec{p})} - \text{phase of } < \tilde{I}_{i(\vec{p},\vec{q})} > \tag{6}$$

Because the object intensity distribution is real function in space domain, the phase of $\tilde{O}_{(\vec{0})}$ is zero, and so all of the phases can be found.

3. Some characteristic of the instrument

In section 2 we have mentioned that short exposure is the base of speckle image restoration. In this case the atmosphere can be "frozen" and high resolution information can be retained. So first of all, rapid exposure receiver must be needed. The CCD camera is used as the receiver and its exposure time can be changed from 0.1ms—20ms in our system.

On the other hand we have used atmosphere's log-normal model in our image recovery. In this case ergodic hypothesis must be satisfied. That is to say the number of the sample should be large enough and the time interval for sampling must be longer than the characteristic time scale of atmosphere's turbulence. The second condition can be satisfied easily because the CCD's sampling rate is 25 frames per second. For the first condition, large sample number means long sampling time. But this sampling time cannot be too long because we have assumed the object to be unchanged within this time. We choose 30 second sampling time and so 750 samples can be obtained (We do not think 30s is short enough but we have to do so by the limit of our instrument). We use TMT real-time hard disk as the storage. About 3000 MB data can be stored in it.

4. Results and discussion

In this section, some restoration examples and a brief discussion will be given. The observed object is granulation in quiet region and near the center of the Sun. The data were obtained in Huairou's 60 cm Multi–Channel Solar Telescope on June 4, 1993. The exposure time is 0.1 ms and the transmission band is 5250 ± 50 Å.

Figure 1b is a speckle sample. In this figure, you can find many fine structures even if a little distortion and blur exist. Figure 1a is the long exposure result and its resolution is obviously low. Figure 1c is also the long exposure result but before average, each image has been centered by correlation method in order to remove the image's shift caused by the atmosphere turbulence and the telescope instability. Figure 1d is the reconstruction image. We think its resolution is not worse than 0.5 arcsec (Our system can obtain about 0.25 arcsec recovery image in ideal case. But the CCD we are using causes some local fringes in the image. In order to remove them the resolution has to be lowered. We will use a better CCD in the future). The dark lanes between granules are sharper in 1d than in 1b, so we can say the resolution of the recovery image is higher than that of speckle sample. The r. m. s. of intensity fluctuation, which can be considered as the contrast of the image, has also proved this conclusion. Because the higher the resolution is, the larger the r. m. s. is. In 1b and 1d, the r. m. s. is about 10% and 14%.

Figure 3 consists of three segments and each segment is recovered separately. There is no new information, only for the effect of vision.

From these figures, we can say it is very successful to use the speckle interference method to recover high resolution image in our telescope. But it is only a good beginning. Our goal is to observed the fine magnetic structure of the Sun. We hope we can reach our end next summer.

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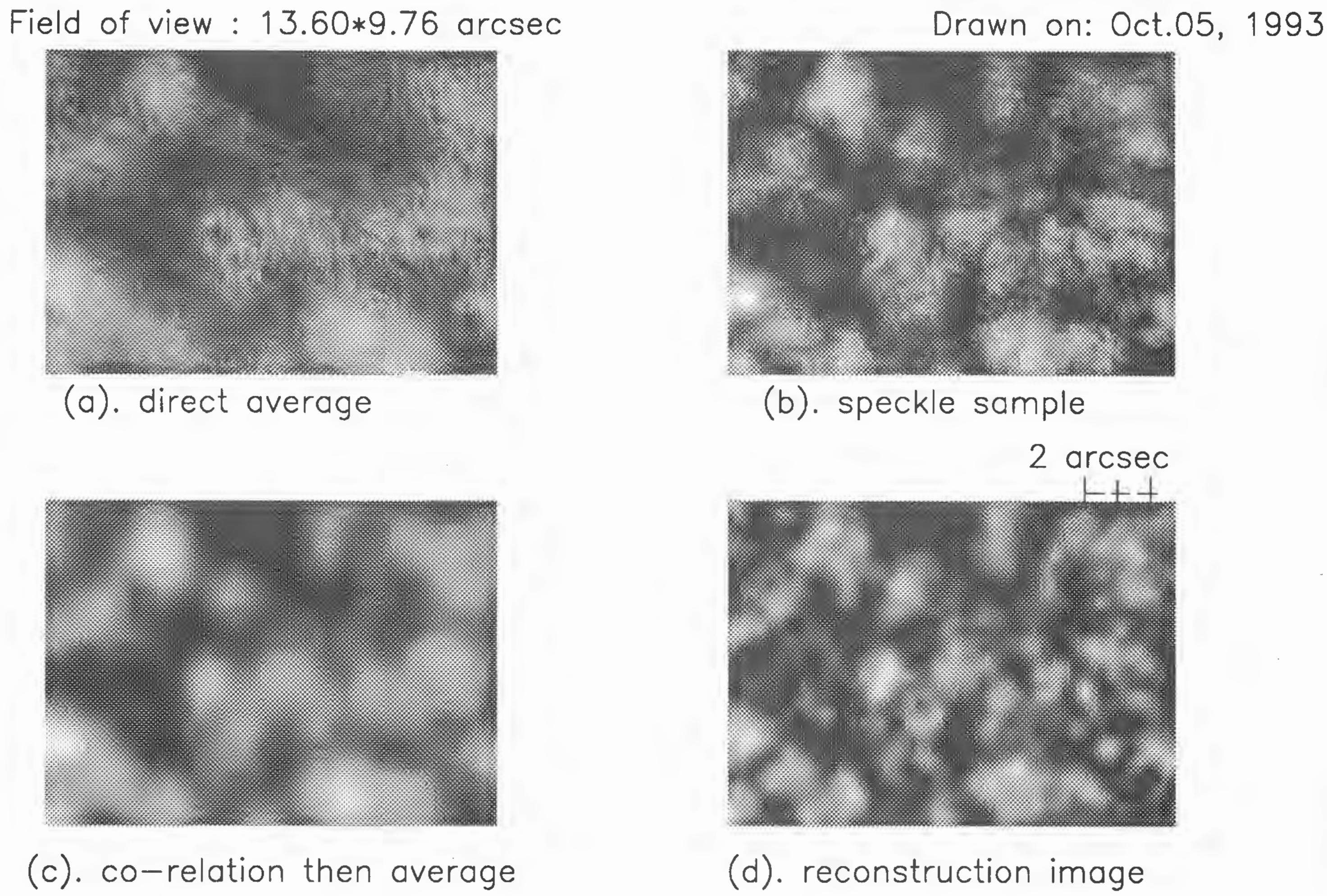


Fig.1 RESULTS OF IMAGE RECOVERY

spectrum ratio

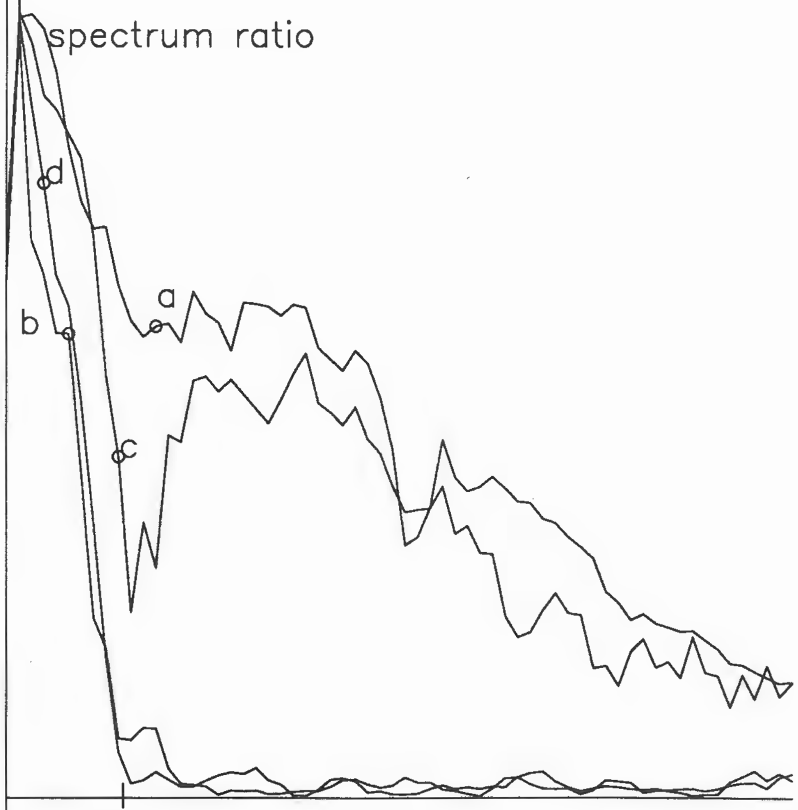
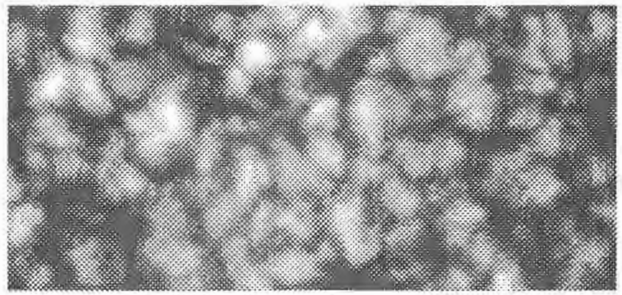
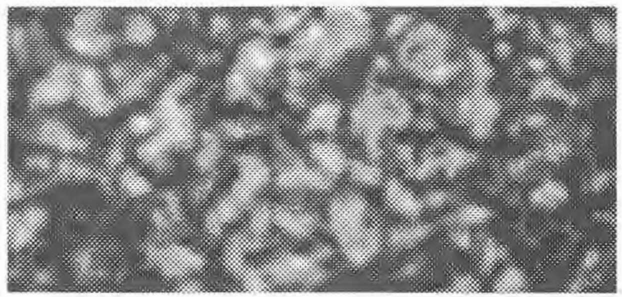


Fig.2 CURVE OF SPECTRUM RATIO

Field of view : 29.3*13.6 arcsec



(a). speckle sample



(b). reconstruction image
made by three segments

Fig.3 COMPARSION BETWEEN SPECKLE AND RECONSTRUCTION IMAGE