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High resolution reconstruction of solar prominence images observed by the New Vacuum Solar Telescope

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HIGHLIGHTS

- We proposed a modified cross correlation method to align prominence data.
- We compared the alignment accuracy of the conventional method and the modified method.
- We successfully reconstructed the prominences and other off-limb objects observed by NVST.
- The results demonstrate that the high resolution observation of solar prominence by a ground-based solar telescope is feasible.

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ABSTRACT

A high resolution image showing fine structures is crucial for understanding the nature of solar prominence. In this paper, high resolution imaging of solar prominence on the New Vacuum Solar Telescope (NVST) is introduced, using speckle masking. Each step of the data reduction especially the image alignment is discussed. Accurate alignment of all frames and the non-isoplanatic calibration of each image are the keys for a successful reconstruction. Reconstructed high resolution images from NVST also indicate that under normal seeing condition, it is feasible to carry out high resolution observations of solar prominence by a ground-based solar telescope, even in the absence of adaptive optics.

1. Introduction

Solar prominences are thread-like clouds consisting of relatively cool, dense magnetized plasma suspended in the hot tenuous corona (Tandberg-Hanssen, 1995). They are one of the most striking features in the solar atmosphere. The study of prominences is very important for understanding their formation and equilibrium, even their connection and relationship with other activity phenomena (Yan et al., 2014). Recent high resolution observations obtained by meter-class telescopes show that there are many fine structures such as the sharp border of a bubble, details of mass flows, and vortices inside the prominences (Berger et al., 2008; Berger et al., 2010; Yan et al., 2015; Shen et al., 2015). Deeper understanding of these complex dynamic structures needs ever higher resolution data to address.

High resolution observations of ground-based solar telescopes mainly rely on the adaptive optics (AO) and the image reconstruction techniques. With the wavefront compensation of the AO, it is easier to achieve diffraction limit after the image reconstruction. In the past three decades, a great deal of solar activity phenomena (sunspots, flares, and so on) have been clearly observed by using image reconstruction techniques or in combination with the AO (von der Lühe, 1994; Denker, 1998; Denker et al., 2005; Mikurda and von der Lühe, 2006). Normally, the general AO is hard to lock onto faint prominence structures. During recent years a purpose-built off-limb solar AO that can directly lock onto solar prominences have been reported by Taylor et al. (2013; 2015). But overall, an applicable AO system to observe solar prominences is lacking on ground-based facilities. Therefore, most of the high resolution observations of solar prominences have to rely on image reconstruction.

Speckle imaging is one of the most effective image reconstruction techniques in high resolution solar observations. The popular methods are known as the Labeyrie (Labeyrie, 1970) method, the Knox–Thompson (Knox and Thompson, 1974) method, and the speckle masking (Weigelt, 1977; Weigelt and Wirnitzer, 1983; Lohmann et al., 1983). When applying the speckle imaging method for solar high resolution reconstruction, the image motion of each frame should be well corrected if the motion is significantly greater than the size of the seeing disk. For the normal observations of the solar disk activities, because the correlation tracker

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(Cao et al., 2010) of an AO system works effectively, the residual image motion is usually small and can be negligible (Denker et al., 2005). But, for the observations of the off-limb objects such as quiescent prominences or flare loops, without an applicable AO system, the image motion correction should be treated carefully by post processing.

Observing the fine structures of off-limb objects is one of the significant science cases of the New Vacuum Solar Telescope (Liu et al., 2014). Since the current AO system of NVST cannot track an off-limb object, speckle imaging is the only way to observe the fine structures in a prominence. In the next sections, we briefly describe the speckle masking algorism which is used to reconstruct solar prominences observed by NVST. In order to ensure the quality of a reconstructed image, the cross correlation algorithm (Smithson and Tarbell, 1977; von der Lühe, 1983) is modified to align raw data as accurately as possible. Non-isoplanatic effect in raw images is also calibrated by using the similar algorithm. Based on the speckle masking algorism and the careful alignment, the high resolution observations of off-limb objects are successfully implemented on NVST.

2. Data observation

The NVST is a vacuum solar telescope with a 985 mm clear aperture. It has come into operation since 2012. One of the most important instruments of NVST is the multi-channel high resolution imaging system which has five channels to observe the solar photosphere and chromosphere. All the channels can record images simultaneously. The channel which is used to observe the prominence is the Hα (6563 Å) channel. The filter is a tunable Lyot filter with a bandwidth of 0.25 Å.

The high order AO system of the NVST is unsuitable for the observation of solar prominence, so high resolution images are obtained by using the speckle reconstruction technique. Each high resolution Hα image is reconstructed from at least 100 frames of short exposure images (speckle images). The exposure time of each frame is 10 or 20 ms. Serial short exposure images are recorded by a $2K \times 2K$ CCD which covers a $168'' \times 168''$ field of view (FOV). The scale of each pixel is $0.082''$. In order to improve the signal to noise ratio (SNR) of the data and shorten the sampling interval between images, the image could be binned to $1K \times 1K$ by using the binning mode of the camera. After binning, the scale of each pixel is $0.164''$.

3. Prominence reconstruction

3.1. Solar speckle imaging

The fundamental principle of speckle imaging is the linear space invariant imaging in a turbulent atmosphere. If the exposure time of an image is shorter than the atmospheric coherent time and the image's FOV is within the isoplanatic patch, the Fourier spectrum $I(q)$ of this image can be expressed as

$$I(q) = O(q) \cdot H(q), \tag{1}$$

where q denotes the two-dimensional frequency variable, $O(q)$ is the Fourier spectrum of the intensity distribution of the object, and $H(q)$ is the instantaneous optical transfer function (OTF) of the whole system.

The image reconstruction algorithm is based on high-order statistics for a sequence of speckle images. Normally, the Fourier amplitude of the reconstructed image is calculated from the average power spectrum,

$$|I(q)| = (\langle I(q) \cdot I^*(q)\rangle / \langle H(q) \cdot H^*(q)\rangle)^{1/2}, \tag{2}$$

In this equation, $|I(q)|$ denotes the Fourier amplitude (module) of the reconstructed image. $\langle I(q) \cdot I^*(q)\rangle$ is the average power spectrum of speckle images. $\langle H(q) \cdot H^*(q)\rangle$ is called the speckle interferometry transfer function (SITF). The superscript symbol $*$ denotes the conjugate operator. For night time observations, SITF could be obtained by observing a single star. For solar observation, supposing the Fried parameter r_0 is known, the SITF is usually constructed by using a numerical model (Korff, 1973). The Fried parameter can be estimated by calculating the spectral ratio (von der Lühe, 1984) or measured by a seeing monitor.

The Fourier phase reconstruction is more complex compared with the amplitude reconstruction. The bispectrum is the basis of phase reconstruction for speckle masking algorithm.

$$\langle B(p, q)\rangle = \langle I(p) \cdot I(q) \cdot I^*(p+q)\rangle, \tag{3}$$

where $\langle B(p, q)\rangle$ denotes the average bispectrum of speckle images. It is a four-dimensional function calculated from the image spectrum $I(p)$, $I(q)$ and $I(p+q)$. p and q are both two-dimensional frequency variables. As the OTF of the average bispectrum is real (Lohmann et al., 1983), the object phase ϕ_O and the average bispectrum phase ϕ_B are connected by

$$\phi_O(p+q) = \phi_O(p) + \phi_O(q) - \phi_B(p, q). \tag{4}$$

Accordingly, phases of all frequencies can be reconstructed by using a recursive method (Pehlemann and von der Lühe, 1989).

The essential process of high resolution reconstruction of solar image has been summarized by several researchers (von der Lühe, 1993; Mikurda and von der Lühe, 2006). The image preprocessing normally includes dark removal, flat-fielding, and image motion correction if necessary. After preprocessing, as a key step of speckle imaging, each image should be divided into many overlapping subblocks because the speckle reconstruction is more efficient within the isoplanatic patch of the turbulent atmosphere. Thus, a sequence of raw images is divided into a number of subsequences for speckle reconstruction separately. Finally, all the reconstructed subimages are combined to form the entire high resolution image (see Fig. 1).

3.2. Key points for prominence reconstruction

3.2.1. Alignment method

The basic process for prominence reconstruction is similar to that for other on-disk solar objects such as the granulation or sunspots. However, as mentioned in Section 1, the current AO system of NVST cannot track an off-limb object. So, additional processes especially for the image motion correction are necessary. Cross correlation is the commonly used method for image motion correction. The cross correlation function $C(d_x)$ of a target image $i(x)$ and a reference image $k(x)$ can be described as

$$C(d_x) = i(x) \star k(x). \tag{5}$$

Where the symbol $\star$ is the correlation operator, and x denotes two-dimensional spatial variable. Normally, assuming the origin of the coordinate is the center of the image, the position x_M of the maximum value of correlation function represents the offset between the target image and the reference image. Shifting this offset can make the target image well aligned with the reference image. In the case of prominence, due to the dimness of the object and the brightness sudden change at solar limb (see Fig. 2), x_M is usually not the correct image offset. This is called the correlation error. Therefore, a modified cross correlation is adopted to reduce the correlation error and improve the alignment accuracy. This modified cross correlation function could be expressed as

$$C'(d_x) = [i(x) * f_1(x)] \star [k(x) * f_2(x)], \tag{6}$$