Impact of Anisoplanatic Effects on NVST High-Resolution Reconstruction Results (Postprint)

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Abstract

Based on the high-resolution reconstruction algorithm of the Fuxian Lake 1 m New Vacuum Solar Telescope, the influence of anisoplanatic effects on speckle interferometry and the speckle masking method is theoretically analyzed. Observed photospheric data are utilized to perform high-resolution data reconstruction with varying sub-block sizes. The impact of anisoplanatic effects is analyzed through comparison of the power spectra and phases of reconstructed images under different sub-block sizes. The results indicate that when the reconstruction region size exceeds the isoplanatic patch, anisoplanatic effects limit the effectiveness of speckle interferometry and the speckle masking method, resulting in reduced accuracy of modulus and phase reconstruction due to algorithmic failure. Finally, suggestions for further optimization of the algorithm are provided based on the specific implementation of the image processing program.

Full Text

The Influence of Anisoplanatism on High-Resolution Reconstruction Results

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Abstract

Based on the high-resolution reconstruction algorithm of the 1-meter New Vacuum Solar Telescope (NVST) at the Fuxian Lake Solar Observatory, this paper theoretically analyzes the effects of anisoplanatism on speckle interferometry and speckle masking. Using observed photospheric data, high-resolution reconstructions were performed with different sub-block sizes. By comparing the power spectra and phases of reconstructed images across various sub-block sizes, the impact of anisoplanatism was evaluated. The results demonstrate that when the reconstruction region exceeds the isoplanatic region, anisoplanatism limits the effectiveness of both speckle interferometry and speckle masking, leading to reduced accuracy in modulus and phase reconstruction due to algorithmic failure. Finally, considering the specific implementation of the image processing pipeline, recommendations for further algorithm optimization are provided.

Keywords: anisoplanatism; NVST; high spatial resolution reconstruction

1. Introduction

Atmospheric turbulence limits the imaging resolution of ground-based large telescopes to approximately 1 arcsecond. Real-time compensating adaptive optics technology and high-resolution image processing methods can overcome atmospheric turbulence effects to achieve diffraction-limited imaging with ground-based telescopes. Several high-resolution image processing methods have been applied to solar telescopes, including speckle reconstruction techniques (speckle interferometry, Knox-Thompson algorithm, and speckle masking) and solar multi-frame blind deconvolution. Within the isoplanatic region, the atmospheric imaging process can be approximated as a linear space-invariant system, where the point spread function (PSF) is considered identical across the field. In astronomy, the typical isoplanatic region size does not exceed 4.5 arcseconds. For high-resolution reconstruction of large-field targets, the image must be divided into sub-blocks for reconstruction, with the principle that sub-block size should match the isoplanatic region size. Atmospheric anisoplanatism causes speckle reconstruction algorithms to fail when the reconstruction region exceeds the isoplanatic region.

The 1-meter New Vacuum Solar Telescope (NVST) is China' s largest ground-based vacuum solar telescope, primarily used for high-resolution imaging and spectroscopic observations of the solar photosphere and chromosphere. The NVST employs speckle interferometry and speckle masking-based statistical reconstruction techniques to achieve high-resolution reconstruction of observed images. The current reconstruction sub-block size for the NVST is 10 arcseconds, determined empirically, which leads to imprecise sub-block sizing during image reconstruction. Since the actual isoplanatic region size varies with atmospheric conditions during observations, using a fixed empirical value for sub-block reconstruction may result in algorithm failure and reduced reconstruction accuracy.

Previous researchers have conducted extensive studies on atmospheric anisoplanatism. Nisenson and Stachnik used speckle interferometry to measure atmospheric isoplanatism and studied its effects on binary star speckle patterns. Lühe and Durrant analyzed the influence of anisoplanatism on high-resolution speckle imaging of solar small-scale structures. Fried investigated anisoplanatism in adaptive optics systems. This study utilizes actual solar telescope data and employs speckle reconstruction methods (speckle interferometry and speckle masking) to analyze the influence of anisoplanatism under different reconstruction sub-block sizes for the NVST.

2. Theoretical Analysis of Anisoplanatism Effects

2.1. Impact on Speckle Interferometry

Speckle interferometry, first proposed by Labeyrie, restores the Fourier amplitude of a target through statistical analysis of the average energy spectrum of speckle images. Each short-exposure image i can be viewed as the convolution of the target o and the system point spread function h. Under the isoplanatic assumption, the target power spectrum can be expressed as:

$$\langle |I(f)|^2 \rangle = |O(f)|^2 \langle |H(f)|^2 \rangle$$

where $\langle \cdot \rangle$ denotes arithmetic averaging. After statistical analysis of the speckle image energy spectrum and introducing the ergodicity assumption, we obtain:

$$\langle |I(f)|^2 \rangle = |O(f)|^2 \cdot STF$$

where STF is the speckle transfer function. The denominator is called the speckle transfer function. Deconvolution of this equation yields the target intensity.

Consider two point sources separated by angular distance θ, with intensities m_1 and m_2. When imaging through different atmospheric portions, their instantaneous point spread functions are h_1 and h_2, respectively. Under ergodic conditions, the average power spectrum of the speckle images is:

$$\langle |I(f)|^2 \rangle = m_1 \langle |H_1(f)|^2 \rangle + m_2 \langle |H_2(f)|^2 \rangle + 2\sqrt{m_1 m_2} \mathrm{Re}\{\langle H_1(f) H_2^*(f) \rangle\} \cos(2\pi f \cdot \theta)$$

When θ is sufficiently small such that both targets lie within the isoplanatic region, $h_1 \approx h_2$, and the equation simplifies to:

$$\langle |I(f)|^2 \rangle = |O(f)|^2 \langle |H(f)|^2 \rangle$$

However, when the reconstruction region exceeds the isoplanatic region size, regardless of which point source’ s speckle interferometry is used, the atmospheric anisoplanatism causes the speckle interferometry algorithm to fail. This algorithmic failure leads to inaccurate reconstruction of the target’ s Fourier modulus.

2.2. Impact on Speckle Masking Phase Reconstruction

Speckle masking, also known as triple correlation or bispectrum analysis, was developed by Weigelt. The bispectrum expression for speckle images is:

$$B_I(f_1, f_2) = \langle I(f_1)I(f_2)I^*(f_1 + f_2)\rangle$$

Under isoplanatic and ergodic assumptions, the bispectrum statistics of speckle images can be written as:

$$B_I(f_1, f_2) = O(f_1)O(f_2)O^*(f_1 + f_2) \cdot \langle H(f_1)H(f_2)H^*(f_1 + f_2)\rangle$$

The phase relationship is:

$$\Phi_B(f_1, f_2) = \phi_O(f_1) + \phi_O(f_2) - \phi_O(f_1 + f_2) + \phi_H(f_1) + \phi_H(f_2) - \phi_H(f_1 + f_2)$$

According to turbulence theory, the phase fluctuations of the wave follow a Gaussian distribution. For any real-valued Gaussian random variable z and any complex constant a, the relationship $\langle \exp(jaz)\rangle = \exp(-\frac{1}{2}a^2\sigma_z^2)$ holds. Therefore, the terms related to the transfer function in the bispectrum are real numbers and do not contribute to the bispectrum phase. The phase relationship simplifies to:

$$\Phi_B(f_1, f_2) = \phi_O(f_1) + \phi_O(f_2) - \phi_O(f_1 + f_2)$$

This equation allows recursive reconstruction of the target' s Fourier phase from low to high frequencies. However, when the extended target exceeds the isoplanatic region size, the relationship between the target phase and bispectrum phase no longer holds strictly. The anisoplanatism causes errors in phase recursion when using speckle masking.

3. Data Processing and Analysis

3.1. Data Processing Workflow

The NVST data processing pipeline is shown in [Figure 2: see original paper]. The main steps include data preprocessing, amplitude and phase reconstruction, and image mosaicking. Data preprocessing comprises flat-field and dark-field corrections. Image division should ensure the reconstruction region lies within the isoplanatic region. The NVST uses speckle interferometry to restore the Fourier amplitude of each sub-block and speckle masking to reconstruct the Fourier phase. After reconstructing the amplitude and phase of each sub-block, they are combined into a complex variable, and high-resolution sub-images are obtained through inverse Fourier transform. Finally, all sub-images are mosaicked into a full-field image.

3.2. Reconstruction Results

Photospheric data from the NVST were collected for 30 seconds using an Andor sCMOS camera with a wavelength of 705.8 nm and image size of 2560 × 2160 pixels. The data were reconstructed with sub-block sizes of 5 , 10 , 15 , and 20 . [Figure 3: see original paper] shows one raw data frame, and [Figure 4: see original paper] presents the reconstruction results corresponding to the red box region.

Comparison of the results reveals that isolated magnetic bright points between granules show the highest resolution and best image quality at 5 sub-block size. At 10 , the bright points appear as elongated chain-like structures, and the contrast between magnetic bright points and granular structures decreases. At 15 and 20 , image resolution degrades significantly, with noticeable quality deterioration. The 15 results demonstrate that image quality declines progressively as sub-block size increases.

3.3. Power Spectrum Analysis

The power spectrum of an image is obtained from the squared modulus of its Fourier transform:

$$P(f) = |FFT\{f(x)\}|^2$$

The power spectrum reflects only the modulus information, not the Fourier phase. [Figure 5: see original paper] shows the average power spectrum curves for reconstruction sub-block sizes of 5 , 10 , 15 , and 20 . The power spectra are similar at low frequencies, but significant differences appear from mid to high frequencies. The 15 power spectrum curve shows changes in mid-frequency resolution, while the 20 curve is lower than the 10 curve near mid-frequencies. The gap between power spectra decreases and concentrates in the mid-frequency range as sub-block size increases, indicating that anisoplanatism primarily affects mid-to-high frequency information.

3.4. Phase Analysis

Since both phase and modulus determine reconstruction quality, we analyzed phase effects by combining a fixed modulus with phases from different reconstructions. The fixed modulus was obtained from 5 sub-block reconstruction, while phases were taken from 10 , 15 , and 20 reconstructions. [Figure 6: see original paper] shows these combinations.

Image quality degrades progressively with increasing sub-block size, all inferior to the 5 reconstruction. Since the modulus is fixed, quality degradation arises from reduced phase reconstruction accuracy. The 10 reconstruction shows the highest phase accuracy, closest to the true target phase.

To quantify phase differences, we calculated the modulus of the difference between complex exponentials of reconstructed phases:

$$\Delta\Phi = |\exp(j\phi_{10}) - \exp(j\phi_x)|$$

where x represents 10 , 15 , or 20 . [Figure 7: see original paper] shows these phase difference maps. The differences increase with sub-block size, particularly in the low-frequency region, confirming that phase reconstruction accuracy decreases as the reconstruction region exceeds the isoplanatic region.

4. Discussion and Conclusion

When reconstruction sub-block sizes of 10 , 15 , and 20 exceed the typical astronomical isoplanatic region, anisoplanatism causes speckle interferometry and speckle masking to fail. The resulting reduction in Fourier modulus and phase reconstruction accuracy leads to decreased image resolution. The analysis demonstrates that larger sub-blocks, exceeding the isoplanatic region by greater margins, suffer more severe anisoplanatism effects.

For optimal reconstruction resolution, sub-block size should match the isoplanatic region. However, real-time measurement of the isoplanatic region is difficult. Smaller sub-blocks are not always better, as data alignment is required before speckle reconstruction to mitigate telescope jitter or tracking errors. Overly small sub-blocks reduce alignment precision and also affect image quality.

Based on the NVST high-resolution reconstruction algorithm' s practical implementation, we recommend: when reconstructing high-resolution images from observational data, first reconstruct a small sample with different sub-block sizes and compare the results to determine the most appropriate size before processing the entire dataset. This approach should consider multiple factors including daily atmospheric seeing conditions.

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Note: Figure translations are in progress. See original paper for figures.