

Super-resolution solar imaging exploiting satellite pointing jitter and phase-diversity-derived PSF

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ABSTRACT

Super-resolution imaging beyond the nominal diffraction and sampling limits remains a major challenge for space-based solar telescopes. Here, we demonstrate a novel approach that exploits intrinsic satellite pointing jitter, together with an observation-specific point spread function (PSF) derived from phase diversity, to achieve sub-diffraction-limited solar imaging. We apply this method to a series of CN-band (388.3 nm) filtergrams obtained with the 0.5-m Solar Optical Telescope (SOT) aboard the Hinode satellite. By temporarily disabling the correlation tracker, naturally occurring pointing jitter was preserved, providing sub-pixel spatial sampling without dedicated dithering or hardware modification. Five consecutive filtergrams acquired at 1.6 s cadence were combined using an iterative back-projection algorithm to reconstruct images with half-pixel sampling. The resulting super-resolved images reveal fine-scale solar structures at spatial scales of approximately 0.1 arcsec and extend the effective spatial frequency response to a cutoff of 0.16 arcsec. These results demonstrate that satellite pointing jitter, normally regarded as a source of image degradation, can instead be exploited as a valuable source of sub-pixel information for super-resolution imaging. The proposed approach provides a practical means of enhancing the spatial resolution of existing space-based solar telescopes without modifying their optical or detector systems.

Keywords: phase diversity, super-resolution, pointing jitter, space telescope

1. INTRODUCTION

High spatial resolution is essential for understanding the fine-scale structure and dynamics of the solar atmosphere. Space-based solar telescopes provide observations free from atmospheric seeing and have therefore played a crucial role in resolving small-scale solar features. Nevertheless, the spatial resolution of such observations is ultimately limited by the telescope aperture, optical diffraction, detector sampling, and instrumental point spread function (PSF). Once these limits are reached, recovering additional spatial information from conventional single-frame observations is intrinsically difficult.

Super-resolution techniques offer a possible means of overcoming these limitations by combining multiple observations that contain complementary sub-pixel information. In imaging systems, controlled sub-pixel shifts, or dithering, can provide additional sampling of the underlying scene and thereby improve the effective spatial resolution beyond the native detector sampling. Such approaches, however, generally require accurate knowledge or control of the relative image shifts and may require dedicated observing modes or additional hardware. For space-based solar observations, where observing time and instrument configurations are often constrained, a method that can utilize information already present in routine observations would be particularly advantageous.

Pointing jitter is generally regarded as an undesirable effect because it introduces image motion and degrades spatial resolution. However, small, naturally occurring image shifts can also provide precisely the sub-pixel sampling required for super-resolution reconstruction. If the relative shifts can be accurately determined and the telescope PSF is sufficiently well characterized, a sequence of jittered images can potentially be combined to recover spatial information beyond the nominal detector sampling limit. Thus, rather than suppressing pointing jitter entirely, it may be possible to exploit it as an additional source of spatial information.

An accurate PSF is essential for such a reconstruction, particularly when the goal is to approach or exceed the nominal diffraction limit. Phase diversity provides a powerful means of estimating the telescope wavefront and PSF directly from observations. By acquiring images at multiple known focus positions, the phase diversity technique enables the optical wavefront to be reconstructed, for example, in terms of Zernike polynomial coefficients, and thereby provides an

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observation-specific estimate of the PSF. Combining such PSF information with multi-frame super-resolution reconstruction offers a promising approach to recovering fine-scale structures from space-based solar observations.

In this study, we demonstrate this concept using CN-band (388.3 nm) filtergrams obtained with the Solar Optical Telescope (SOT) aboard the Hinode satellite. The observations were performed with the correlation tracker temporarily disabled so that the intrinsic pointing jitter of the spacecraft was preserved. Five consecutive filtergrams obtained at high cadence were used to provide sub-pixel sampling through the naturally occurring image motion. An iterative back-projection algorithm was then employed to reconstruct a super-resolved image with half-pixel sampling.

The resulting images demonstrate substantially improved spatial resolution, revealing solar structures on scales of approximately 0.1 arcsec and extending the effective spatial frequency response beyond that of the original sampling. These results show that spacecraft pointing jitter, normally treated as a source of image degradation, can instead be harnessed as a useful source of sub-pixel information. This approach provides a practical pathway toward super-resolution solar imaging using existing space-based instrumentation, without requiring modifications to the telescope optics or detector system.

2. OBSERVATIONS AND PSF ESTIMATION

To demonstrate the super-resolution imaging method developed in this study, CN-band (388.3 nm) filtergrams obtained with the Solar Optical Telescope (SOT) onboard the Hinode satellite were used[1-3]. To intentionally preserve the natural pointing jitter, the correlation-tracker-based image stabilization system of SOT was temporarily disabled. For the super-resolution imaging, five consecutive filtergrams were acquired at the highest cadence of 1.6 s, with an exposure time of 0.1 s and a pixel scale of 0.054 arcsec/pixel. This five-image sequence was repeated every 18 s over a period of 1.5 h.

Immediately prior to these observations, a focus scan was performed to enable PSF estimation using the phase diversity technique. The phase diversity method uses multiple images acquired at known defocus positions to estimate the optical wavefront. In this study, the wavefront was represented using annular Zernike polynomials, allowing an observation-specific PSF at 388.3 nm to be derived from the estimated wavefront[4].

Figure 1 shows an example of the pointing jitter estimated from the cross-correlation of the five consecutive filtergrams. The pointing variations in both the (x) and (y) directions are generally confined within approximately 0.5 pixel. Although the jitter is relatively small, its variation over the five consecutive exposures provides sub-pixel sampling information that can be exploited for super-resolution reconstruction.

Figure 2 shows an example of the focus-scan data, the SOT wavefront map at 388.3 nm estimated by the phase diversity analysis of the multiple defocused images, and the corresponding PSFs for the individual defocus positions. The estimated wavefront exhibits a characteristic trefoil aberration, which is consistent with the expected thermal deformation of the primary mirror (Figure 3).

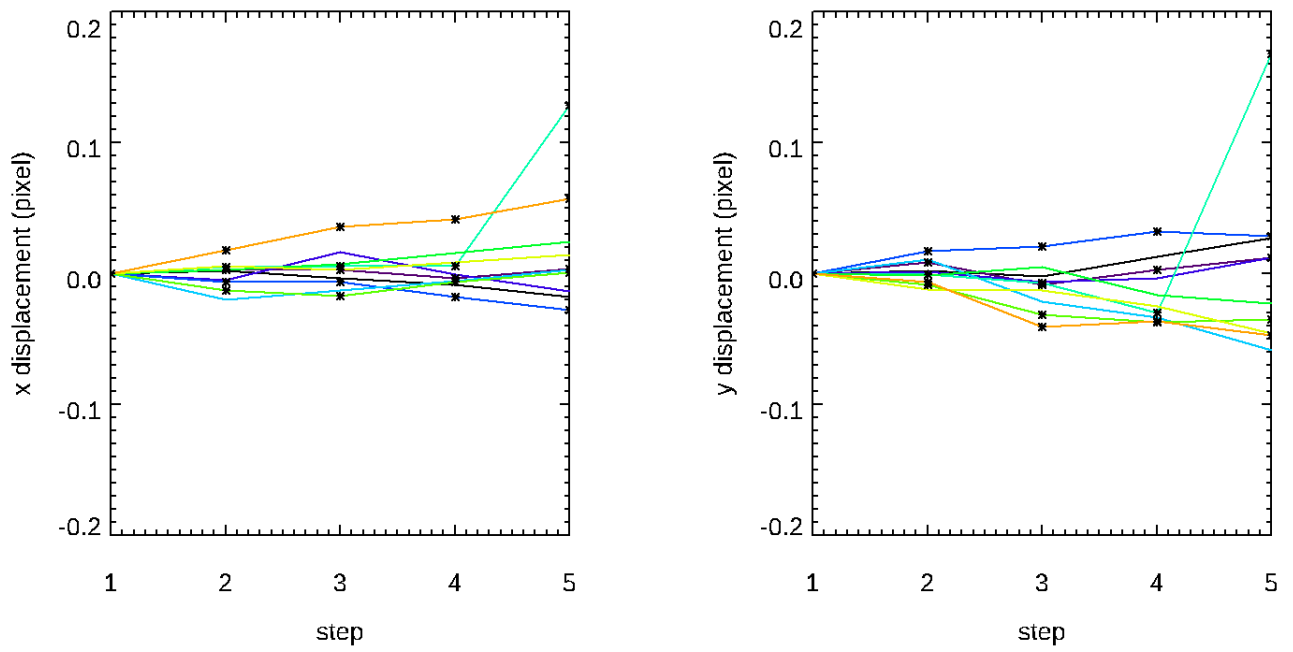


Figure 1. Example of pointing jitter estimated from the cross-correlation of five consecutive filtergrams. The left and right panels show the jitter in the (x) and (y) directions, respectively. The corresponding (x)-(y) positions are identified by the line colors and asterisks. Pixel=0.054 arcsec.

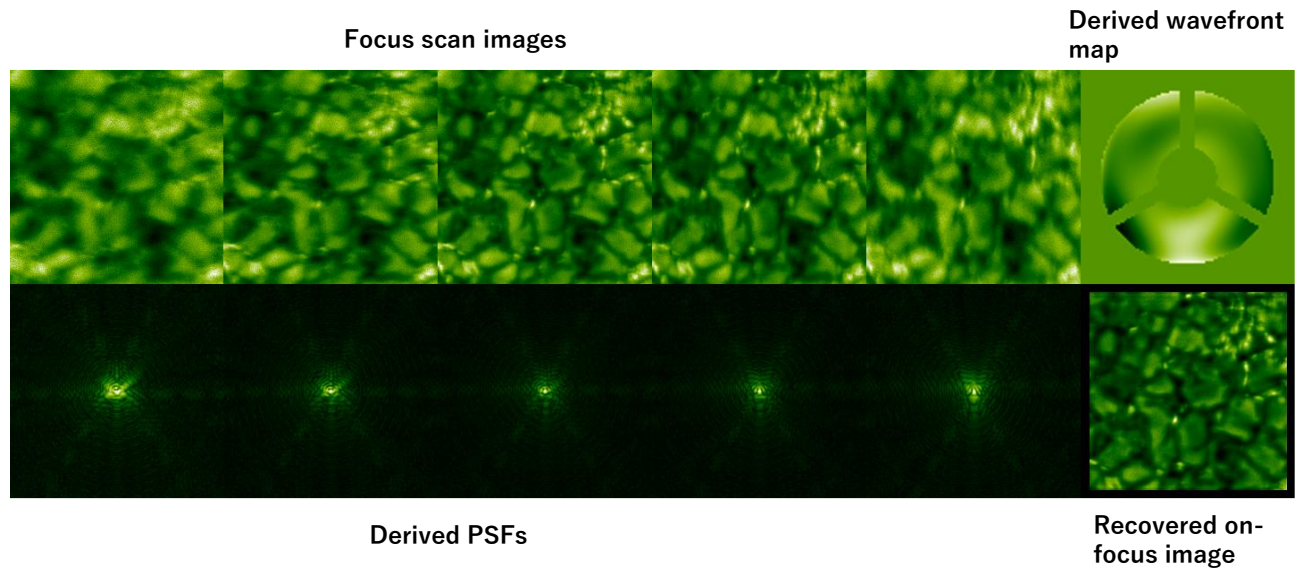


Figure 2. Optical performance of SOT at a wavelength of 388.3 nm estimated using the phase diversity method with multiple defocused images. The derived Strehl ratio is 0.51.

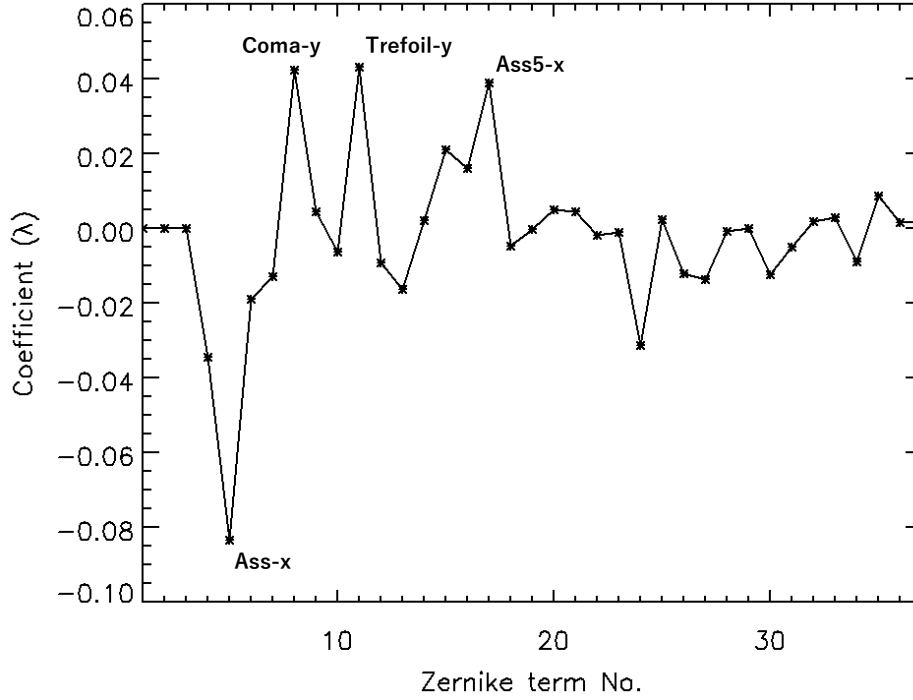


Figure 3. Annular Zernike polynomial coefficients estimated by the multiple phase diversity analysis. $\lambda = 388.3$ nm. The ordering of the polynomials follows the definition of Zernike Fringe Polynomials as used in Zemax.

3. SUPER-RESOLUTION RECONSTRUCTION

First, the five consecutive filtergrams were resampled onto a grid with half-pixel sampling, and the pointing jitter of each image relative to the first image was estimated using a cross-correlation method. The measured pointing offsets were then used to perform sub-pixel image registration. After the registration, the five half-pixel-resampled images were averaged to produce a single image with improved sampling and reduced random noise.

Iterative Richardson–Lucy deconvolution was subsequently applied to the averaged image using the PSF derived from the phase diversity analysis. This procedure can be regarded as a form of iterative back-projection, in which the sub-pixel information contained in the multiple jittered images is combined with the estimated PSF to reconstruct spatial information beyond that contained in a single input image. The complete procedure was applied to 255 sets of five consecutive filtergrams acquired over 1.5 h, allowing the temporal evolution of super-resolved solar surface structures to be investigated (Figure 6).

Figure 4 shows an example of the original image, corresponding to the first image in a sequence of five consecutive filtergrams, and the resulting super-resolved image. A comparison of the bright-point structures on the solar surface indicates that the super-resolved image provides enhanced spatial resolution and reveals finer structures that are not clearly resolved in the original image.

Figure 5 shows the azimuthally averaged radial power spectra of the original image, the registered and averaged image obtained from the five consecutive filtergrams, and the super-resolved image. In the power spectrum of the original image, a noticeable enhancement is observed near the diffraction-limit spatial frequency, which is likely associated with noise. This enhancement is substantially reduced in the registered and averaged image, indicating that the averaging process effectively suppresses random noise. In contrast, the power spectrum of the super-resolved image retains significant power near and beyond the nominal diffraction-limit spatial frequency. This extension of the spatial-frequency response, together with the corresponding fine-scale structures visible in the reconstructed images, indicates that the super-resolution process recovers spatial information beyond the nominal diffraction limit rather than merely amplifying high-frequency noise.

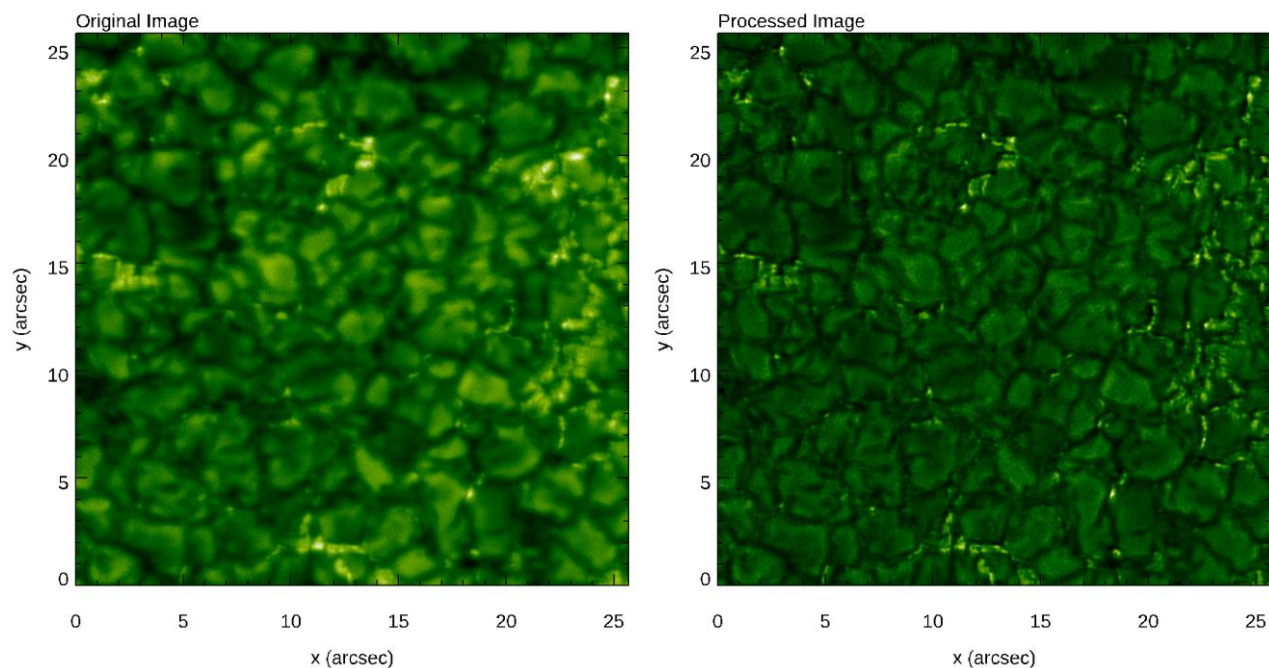


Figure 4. Original image (left) and super-resolved image (right).

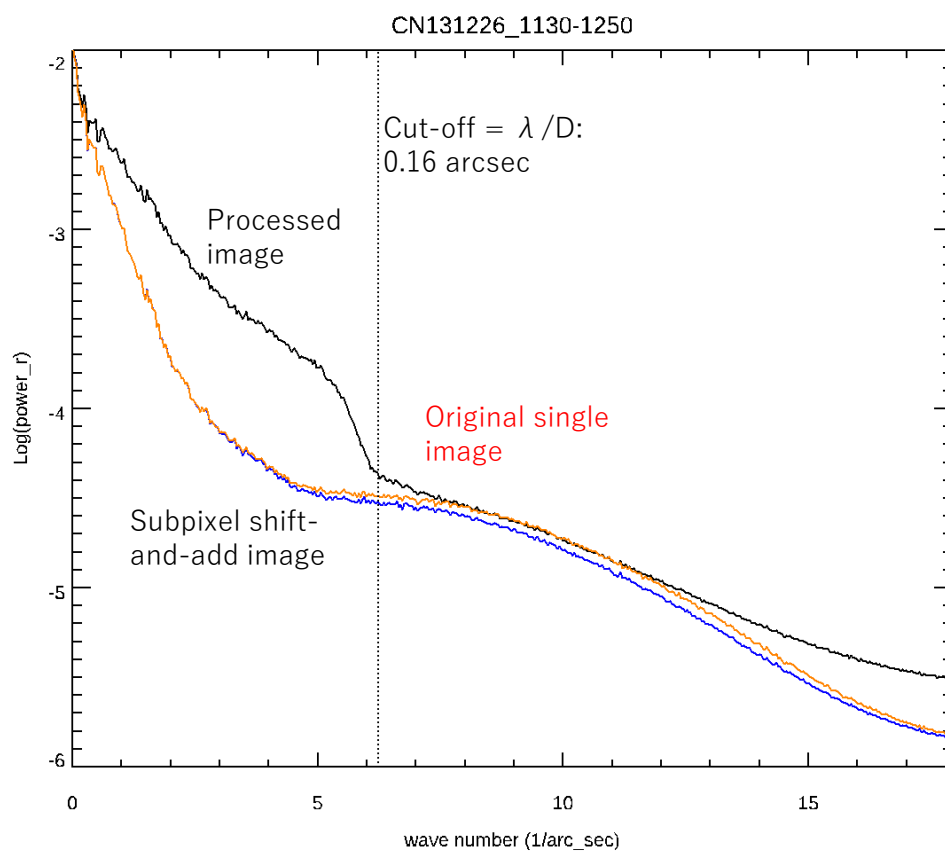


Figure 5. Azimuthally averaged radial power spectra of the original image, the registered and averaged image obtained from five consecutive filtergrams, and the super-resolved image.

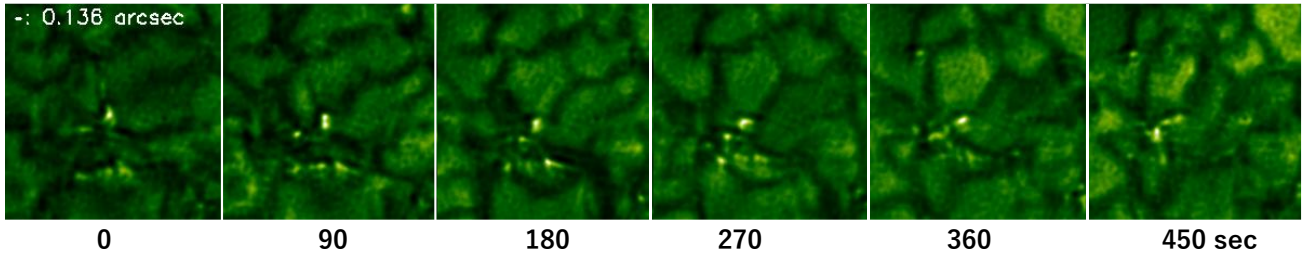


Figure 6. Example of the temporal evolution of super-resolved solar surface structures

4. SUMMARY

We have demonstrated a super-resolution imaging method for solar observations that exploits natural satellite pointing jitter as a source of sub-pixel sampling information. Using CN-band (388.3 nm) filtergrams obtained with the Solar Optical Telescope onboard the Hinode satellite, the correlation-tracker-based image stabilization system was temporarily disabled to preserve the intrinsic pointing jitter. Five consecutive filtergrams acquired at 1.6-s cadence were used to reconstruct a half-pixel-sampled image by sub-pixel image registration and averaging.

An observation-specific PSF was independently estimated from a focus-scan observation using the phase diversity technique, in which the telescope wavefront was represented by annular Zernike polynomials. The derived PSF was then incorporated into an iterative Richardson–Lucy deconvolution, providing a super-resolution reconstruction that can be regarded as a form of iterative back-projection.

The method was applied to 255 sets of five consecutive filtergrams acquired over 1.5 h, producing a time series of super-resolved CN-band images. The reconstructed images show enhanced fine-scale solar structures, with spatial information extending beyond the nominal diffraction limit. The power-spectrum analysis also indicates that the reconstruction recovers significant spatial-frequency components near and beyond the nominal diffraction-limit frequency.

A key feature of the proposed method is that the naturally occurring pointing jitter of a spacecraft, which is normally regarded as a source of image degradation, is instead utilized as a source of sub-pixel sampling information. This approach requires neither dedicated dithering mechanisms nor modifications to the existing telescope optics. The combination of natural pointing jitter with an observation-specific PSF derived by phase diversity therefore provides a practical means of achieving super-resolution solar imaging with existing space-based telescopes.

REFERENCES

- [1] Tsuneta, S., Ichimoto, K., Katsukawa, Y., et al., "The Solar Optical Telescope for the Hinode Mission: An Overview", *Solar Phys.* 249, 167-196 (2008).
- [2] Suematsu, Y., Tsuneta, S., Ichimoto, K., et al., "The Solar Optical Telescope of Solar-B (Hinode): The Optical Telescope Assembly", *Solar Phys.* 249, 197-220 (2008).
- [3] Shimizu, T., Nagata, S., Tsuneta, S., et al., "Image Stabilization System for Hinode (Solar-B) Solar Optical Telescope", *Solar Phys.* 249, 221-232 (2008).
- [4] Suematsu, Y., "Evaluation of telescope optical performance using the phase diversity method with multiple focus phase shifts", *Proc. SPIE* 13624, id. 136240S 9 pp. (2025).