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Image Stabilization System for *Hinode* (Solar-B) Solar Optical Telescope

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Abstract The *Hinode* Solar Optical Telescope (SOT) is the first space-borne visible-light telescope that enables us to observe magnetic-field dynamics in the solar lower atmosphere with 0.2 – 0.3 arcsec spatial resolution under extremely stable (seeing-free) conditions. To achieve precise measurements of the polarization with diffraction-limited images, stable pointing of the telescope (< 0.09 arcsec, 3σ) is required for solar images exposed on the focal plane CCD detectors. SOT has an image stabilization system that uses image displacements calculated from correlation tracking of solar granules to control a piezo-driven tip-tilt mirror. The system minimizes the motions of images for frequencies lower than 14 Hz while the satellite and telescope structural design damps microvibration in higher frequency ranges. It has been confirmed from the data taken on orbit that the remaining jitter is less than 0.03 arcsec (3σ) on the Sun. This excellent performance makes a major contribution to successful precise polarimetric measurements with 0.2 – 0.3 arcsec resolution.

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1. Introduction

Of the principal scientific goals of the *Hinode* (formerly Solar-B) mission (Kosugi *et al.*, 2007), precisely measuring the properties of magnetic fields and their dynamics at the photospheric and chromospheric layers is the prime observational requirement for the Solar Optical Telescope (SOT; Shimizu, 2005; Tsuneta *et al.*, 2007). Magnetic fields at the photosphere are extremely fragmented with fine structures on scales that are especially difficult to resolve from the ground where seeing effects degrade spatial resolution. The SOT is the largest aperture (50 cm in diameter) and most advanced space telescope dedicated to solar observations in visible-light wavelengths. After the successful launch of the *Hinode* spacecraft, SOT has successfully begun observations from November 2006 to provide a continuous series of diffraction-limited images (0.2 – 0.3 arcsec at 388 – 668 nm) and precise measurements of polarization. The image stabilization system installed in SOT, which is described in this paper, makes a major contribution to realizing SOT's superior performance for spatial resolution and polarization measurements. The aim of the image stabilization system is to remove the motion of the solar images on the focal plane of SOT.

Image stabilization systems have been developed at ground-based observatories in the past couple of decades to remove jitters in solar images on the focal plane of the telescope that are due to atmospheric seeing effects and mechanical vibrations caused by wind shaking. Starting from spot trackers, which track a pore, sunspot, or other high-contrast features on the solar disk, granulation correlation trackers have recently become the standard image stabilizer for ground-based observations. These measure motions based on the solar granulation pattern at the region of interest. Until now, only a limited number of granulation correlation trackers have been stably operated at some ground-based optical observatories (van der Lühe *et al.*, 1989; Ballesteros *et al.*, 1996; Molodij *et al.*, 1996), giving significant improvements to observational capabilities on the ground. The image stabilization system of SOT is the first successful application of a correlation tracker for a space-based instrument. Other recent space-based instruments with high spatial resolution capabilities have used an error signal from a limb sensor or positional sensor on the focal plane of a guide telescope to remove jitter. The *Transition Region And Coronal Explorer* (TRACE) satellite has an image stabilization system that provides jitter removal better than 0.1 arcsec rms based on an error signal from a guide telescope attached beside the main telescope (Handy *et al.*, 1999). This kind of system is an open-loop control system in the sense that the error signal from the guide telescope is used to control the tilt of the secondary mirror of the main telescope without feeding back image motions measured on the focal plane of the main telescope.

To achieve diffraction-limited resolution for precise measurements of polarization with polarimetric accuracy of about 0.1% or better (Ichimoto *et al.*, 2007), stable pointing better than 0.09 arcsec (3σ) is required for the SOT observations. This level of stabilized pointing during multiple exposures taken at different phases of the polarization modulator significantly reduces false signals in the combined (added and/or subtracted) data representing the polarization, such as the longitudinal magnetogram and Stokes $IQUV$ parameters. Note that the Spectro-Polarimeter, which is one of the focal plane instruments of SOT, also records two spectra simultaneously in orthogonal linear polarizations for further reduction