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Polarization Calibration of the Solar Optical Telescope onboard *Hinode*

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Abstract The Solar Optical Telescope (SOT) onboard *Hinode* aims to obtain vector magnetic fields on the Sun through precise spectropolarimetry of solar spectral lines with a spatial resolution of 0.2 – 0.3 arcsec. A photometric accuracy of 10^{-3} is achieved and, after the polarization calibration, any artificial polarization from crosstalk among Stokes parameters is required to be suppressed below the level of the statistical noise over the SOT's field of view. This goal was achieved by the highly optimized design of the SOT as a polarimeter, extensive analyses and testing of optical elements, and an end-to-end calibration test of the entire system. In this paper we review both the approach adopted to realize the high-precision polarimeter of the SOT and its final polarization characteristics.

Keywords Polarimeter · Stokes vector · Space telescope · Magnetic field · Optical telescope · Sun

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1. Introduction

The science goals of the Solar Optical Telescope (SOT; Tsuneta *et al.*, 2008) onboard *Hinode* (formerly *Solar-B*; Shimizu, 2004; Ichimoto *et al.*, 2005; Kosugi *et al.*, 2007) require high-precision polarimetry of solar spectral lines with a spatial resolution of 0.2 – 0.3 arcsec. *Hinode*/SOT thus provides the first quantitative and continuous measurements of full vector magnetic fields of the Sun that either resolve or isolate the solar fine-scale magnetic structures. The Focal Plane Package (FPP) of the SOT contains two sets of vector magnetographs (Tarbell *et al.*, 2008). The Spectropolarimeter (SP) performs the highest precision polarimetry with a photometric accuracy of $\approx 10^{-3}$ to provide full Stokes profiles of Fe I 630.25/630.15 nm lines with a spatial sampling of 0.16 arcsec. The Narrowband Filter Imager (NFI) of Filtergraph (FG), in contrast, produces two-dimensional images of Stokes parameters using a Lyot-type tunable filter (width ≈ 0.1 Å) in several photospheric and chromospheric lines with spatial sampling of $0.08''$/pixel and higher time cadence, but with lower wavelength resolution. The available spectral bands of the NFI contain Fe I 630.2/630.1/525.0/524.7 nm for photospheric magnetograms, Na I 589.6/Mg I 517.2 nm for chromospheric magnetogram/Dopplergrams, Fe I 557.6 nm for photospheric Dopplergrams, and H I 656.3 nm for chromospheric images/Dopplergrams. Both the SP and the NFI have a field of view (FOV) of 328×164 arcsec^2.

One of the most significant sources of error in high-spatial-resolution ground-based solar polarimetry is noise caused by atmospheric seeing. Since seeing produces rapid image motion, blurring, and distortion, if the polarization modulation is slower than 1000 Hz, seeing causes false "polarization" signals. Furthermore, attaining high spectropolarimetric precision (10^{-3} relative to the continuum intensity, I_c) at the telescope resolution demands integration times of at least several seconds. Even with adaptive optical correction, atmospheric seeing can significantly degrade image quality. As a result, an accuracy of 10^{-3} in Stokes vector measurements has rarely been achieved at a spatial resolution of less than 1 arcsec, and then never for an extended period of time. *Hinode*/SOT overcomes this difficulty by flying the telescope in space and stabilizing the residual pointing error with an image stabilization system (Shimizu *et al.*, 2004, 2008). The next major source of the error in polarization measurement is the instrumental polarization. Most large ground-based solar telescopes employ feed optics with oblique, time-varying reflective angles, which introduce considerable time variation in the instrumental polarization. In contrast, the SOT consists of symmetric optical system with constant, small-angle reflections. Since the entire observatory (satellite) points to the Sun, the instrumental polarization of *Hinode*/SOT is small and nearly constant. However, because on-orbit polarization calibration of the instruments and telescope is impractical, and because the SOT is exposed to significant thermal variation, a major design effort and comprehensive polarization tests of the system were required prior to launch.

In this paper, we review the methodology used for calibrating the SOT polarization and describe the final characteristics of the SOT polarimeter. The overview of the SOT as a polarimeter is described in Section 2, the goal of polarization calibration accuracy is defined quantitatively in Section 3, some component-level calibration tests are described in Section 4, and system calibration using the final SOT configuration is described in Section 5. Characterization and modeling of SOT polarization is discussed in Section 6 with additional information on data sampling schemes in Section 7. Section 8 summarizes the conclusions.