

High-Order Adaptive Optical System for Big Bear Solar Observatory

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Abstract. A high-order Adaptive Optical (AO) system for the 65 cm vacuum telescope of the Big Bear Solar Observatory (BBSO) is presented. The Coudé-exit of the telescope has been modified to accommodate the AO system and two imaging magnetograph systems for visible-light and near infrared (NIR) observations. A small elliptical tip/tilt mirror directs the light into an optical laboratory on the observatory's 2nd floor just below the observing floor. A deformable mirror (DM) with 77 mm diameter is located on an optical table where it serves two wave-front sensors (WFS), a correlation tracker (CT) and Shack-Hartman (SH) sensor for the high-order AO system, and the scientific channels with the imaging magnetographs. The two-axis tip/tilt platform has a resonance frequency around 3.3 kHz and tilt range of about 2 mrad, which corresponds to about 25'' in the sky. Based on 32 × 32 pixel images, the CT detects image displacements between a reference frame and real-time frames at a rate of 2 kHz. High-order wave-front aberrations are detected in the SH WFS channel from slope measurements derived from 76 sub-apertures, which are recorded with 1,280 × 1,024 pixel Complex Metal Oxide Semiconductor (CMOS) camera manufactured by Photobit camera. In the 4 × 4 pixel binning mode, the data acquisition rate of the CMOS device is more than 2 kHz. Both visible-light and NIR imaging magnetographs use Fabry-Pérot etalons in telecentric configurations for two-dimensional spectro-polarimetry. The optical design of the AO system allows using small aperture prefilters, such as interference or Lyot filters, and 70 mm diameter Fabry-Pérot etalons covering a field-of-view (FOV) of about 180'' × 180''.

Key words: instrumentation: adaptive optics, instrumentation: polarimeters, Sun

1. Introduction

Adaptive optics is one of the most important tools for obtaining high-resolution spectro-polarimetric data, which is essential for advancing our knowledge of the dynamics of small-scale magnetic fields on the Sun. However, why do we have to develop a 'high-order' AO systems for meter-class telescopes such as BBSO's 65 cm vacuum telescope (Zirin & Mosher 1988) and the 76 cm Dunn Solar Telescope (DST) of the National Solar Observatory (NSO)? Current installations of solar AO systems have typically DMs with 50 actuators or less. Our AO design uses a DM with 97 actuators and a SH WFS with 76 sub-apertures. Today's technology allows the analysis of WFS data in real-time with a bandwidth in excess of 500 Hz. The high-order AO systems are also an important building block for developing Multi-Conjugate Adaptive Op-

tics (MCAO) for solar observations (Rimmele 2000). Finally, the Advanced Technology Solar Telescope (ATST) with its 4-meter aperture could not perform its scientific objectives without an high-order AO system.

2. System Overview

Lyot filters and scientific cameras are mounted on three one to two meter-long, T-shaped optical benches attached underneath the 65 cm vacuum reflector. A computer controlled fold mirror can direct the light into the Coudé axis, which originally accommodated a spectrograph. The limited space of the optical benches attached to the equatorially mounted telescope made it necessary to redesign the Coudé path. In addition to serving the spectrograph, it now sends the light to an optical laboratory below the observing floor. The AO system for the Coudé path provides 'slow' beams, which are required

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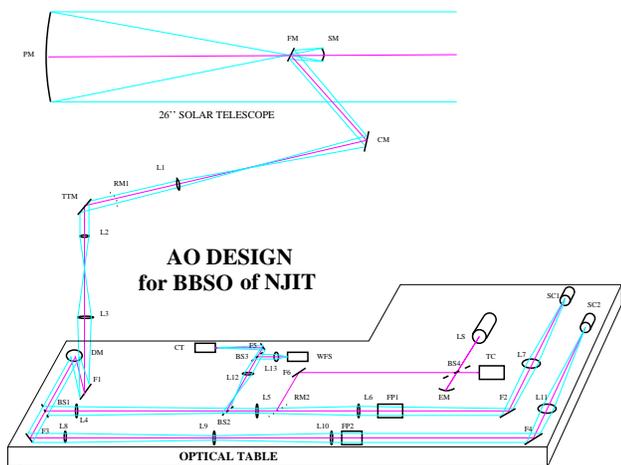


Fig. 1. Optical design for the AO system of BBSO's 65 cm vacuum telescope.

to minimize the passband broadening across the aperture of the Fabry-Pérot etalons in telecentric configuration.

Figure 1 shows the optical design for the BBSO AO system. The optical design is based on cemented doublets. Lenses L1 through L3 were optimized together with other lenses to supply scientific cameras with diffraction limited images in two main spectral windows for spectropolarimetry: (1) Fe I at $\lambda = 630.15$ nm and 630.28 nm or H α at $\lambda = 656.28$ nm and (2) Fe I at $\lambda = 1,564.85$ nm and 1,565.29 nm. In addition, they are also adapted to the spectral window from 463 to 473 nm for the WFS. The other lenses in the visible-light or NIR channel only have to cover a small spectral range. Therefore, doublets can be used instead of triplets, which increases the transmission and makes the optics less expensive.

The light from the 65 cm telescope is reflected by Coudé Mirror (CM) to the Coudé tube, where the primary focal plane is located (see Figure 1). Lens L1 behind the Coudé tube re-images the telescope pupil onto the Tip/Tilt Mirror (TTM). Lenses L2 and L3 resize the pupil and transfer it through the focal plane F1 to DM. F1 in front of DM forms an almost circular beam on DM. A dichroic beam-splitter BS1 splits the beam reflected by DM into the visible-light and the NIR channel. Each of these channels consists of four lenses and one fold mirror. Lenses L4 and L5 or L8 and L9 reduce the beam size from 77 mm smaller to a size small enough to fit through the corresponding prefilters IPF or LYOT PF. The transfer optics also changes the input f -ratio to one suitable for the Fabry-Pérot etalons. Lens L6 or L10 produce a beam exactly as required for a telecentric configuration. Lens L7 or L11 are re-imaging lenses and adapt the image scale of the final focal plane to the dimensions of the visible-light and NIR detectors.

2.1. Wave-Front Sensors

The dichroic beam-splitter BS2 reflects the visible light to a blue spectral window from 463 to 473 nm, which feeds both the CT and SH WFS channels. L12 doubles the f -ratio to

obtain a convenient size for the field-stop diaphragm, which is placed in a focal plane located between F5 and BS3. Beam-splitter BS3 reflects about 20% of light to L14 and the CT camera. L13 re-images the pupil onto a lenslet array.

The TTM channel is based on a Polytec P S-330.30 piezoelectric tilt platform with an elliptical flat mirror ($a = 52$ mm and $b = 30$ mm). The tilt range is ± 1 mrad and the resonance frequency without mirror is about 3.3 kHz. The TTM channel uses a Dalsa CCD camera with 64×79 pixel ($16 \times 16 \mu\text{m}$), which is running in the 2×2 pixel binning mode recording effectively a 32×32 pixel frames. In this mode, the frame rate is 2,000 Hz.

The SH WFS channel is based on a Photobit CMOS camera with $1,280 \times 1,024$ pixels and a nominal frame rate of more than 500 Hz and more than 2,000 Hz in the 4×4 pixel binning mode corresponding to 320×256 pixel images. Either 9×9 or 10×10 sub-apertures are projected onto the central portion of the CMOS device for detecting wave-front aberrations. The lenslet array for the SH WFS channel has a $417 \mu\text{m}$ pitch with a focal length of 45 mm for 16×16 lenses.

2.2. Scientific Instruments

The optical layout shown in Figure 1 was developed to accommodate two scientific channels, one for visible-light and another for NIR observations. The visible light channel was designed for imaging polarimetry of either the Fe I lines at 630.15 and 630.28 nm or H α spectrometry at 656.28 nm. In principle, the whole wavelength range from 550 to 700 nm can be observed with appropriate interference filters and moving L6 and SC1 to adapt image scale and focus.

The NIR channel was designed for observations of the Fe I 1,564.85 nm and 1,565.29 nm spectral lines. A custom-build NIR Lyot filter is installed in front of the Fabry-Pérot etalon. The Lyot filter has a 35 mm aperture, a passband of about 0.25 nm, and a tuning range of 1.6 nm. The NIR camera is a $1,024 \times 1,024$ pixel, 14-bit CMOS focal plane array with $18 \mu\text{m}$ square pixels. A detailed description of the NIR imaging magnetograph is presented by Denker et al. (2002).

The two polarimeters are based on single Fabry-Pérot etalons in telecentric configuration. A discussion of Fabry-Pérot etalons in telecentric configuration is given by Kentischer et al. (1998). Both etalons are located in vicinity of focal planes with an f -number of about 120 and beam size adapted to the clear aperture of the Fabry-Pérot etalons of about 70 mm.

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