Adaptive Optics at the Big Bear Solar Observatory: Instrument Description and First Observations

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ABSTRACT

In January 2004, the Big Bear Solar Observatory (BBSO) was equipped with a high-order adaptive optics (AO) system built in collaboration with the National Solar Observatory/Sacramento Peak (NSO/SP). The hardware is essentially the same as the AO system operated at the Dunn Solar Tower (DST) incorporating a 97 actuator deformable mirror, a Shack-Hartmann type wavefront sensor with 76 subapertures, and an off-the-shelf Digital Signal Processor (DSP) system. However, the optical design is quite different and has to accommodate the BBSO 65 cm vacuum reflector and the downstream post-focus instrumentation. In this work, we will describe the optical design, demonstrate the open- and closed-loop AO performance, and present image reconstructions to illustrate the image quality that can be achieved with the new AO system.

Subject headings: Sun: photosphere — instrumentation: adaptive optics — techniques: speckle reconstruction

1. Introduction

Ground-based imaging is severely limited by wavefront phase deformations induced by the Earth’s atmosphere. For most solar observatories the spatial resolution thus achieved in the visible wavelength range is associated with diffraction limited apertures of \( \sim 10 \) cm only. This is opposed by the fact that a spatial resolution of at the order of the tenth of 1 arcsec corresponding to or smaller than the pressure height scale of the solar atmosphere is needed to answer fundamental questions that arise in our struggle to understand the Sun. It is therefore mandatory to correct the wavefront deformations in real time which allows for a higher dynamic range and sensitivity, for larger exposure times and thus higher signal-to-noise ratios. Real-time methods cover image motion stabilisation systems like correlation tracker systems (see e.g. von der Luehe et al. 1989; Schmidt & Kentischer 1995; Ballesteros et al. 1996), and the much more complex Adaptive Optics (AO) systems designed to also compensate for higher order wavefront deformations (Acton & Smithson 1992; von der Lühe et al. 2003; Berkefeld et al. 2003; Scharmer et al. 2003; Keller
Although devised to provide diffraction limited imaging in practice the performance can vary over a broad range from virtually no improvement to almost diffraction limited. The performance is compromised mostly by technical insufficiencies and limitations (e.g. the finiteness of the temporal response of the AO system, WFS light levels, spatial WFS sampling, and number of degrees of freedom) but also because of meteorological conditions prevailing at the observing site such as the distribution of the strength and height of turbulence (anisoplanasie) in the atmosphere above the site and the correlation of turbulence and wind speed. In particular the power distribution of turbulence plays an important role because it determines the angle resolution and defines the Fried parameter $r_0$ (Fried 1966).

As a result contemporary AO systems usually operate in a partial mode implying a residual wavefront error caused by a difference between the incoming wavefront and the mirror shape. Irregularities of the mirror shape on spatial scales smaller than the controllable domain further add to the residual wavefront error but are in most cases of negligible contribution. It seems naturally that the determination of this residual wavefront error (see e.g. Löfdahl et al. 2000) is an important task that not only leads to a better understanding of the performance of an AO system but most of all can lead to a fully compensating system. However, depending on the strength of the anisoplanatic effects the compensation of an AO system remains field dependent and typically decreases with increasing radial distance from the lock structure. In this context the application of image reconstruction techniques are a useful tool to measure the residual wavefront and minimize the effects of anisoplanatism. To this end image reconstruction techniques are routinely applied to AO supported observations (e.g. Löfdahl & Scharmer 2003).

The paper is organised as follows. In Sect. 2 we briefly describe the telescope and discuss one of the major problems related to the telescope that had to be solved first: the pupil stability. Section 3 and Sect. 4 are dedicated to the optical layout of the Coudé light path and the AO imaging system, and a detailed description of the AO components. In Sect. 5 we show first observations and apply speckle image restoration techniques in order to demonstrate the image quality that can be achieved with the existing system. We also briefly discuss the problems usually encountered when applying speckle techniques to already AO corrected data sets. In Sect. 6 results of a preliminary performance study based on a comparison between the sub-aperture shift values in open- and closed loop, respectively, are presented. Potential problem areas and future challenges are pointed out in Sect. 7. We conclude in Sect. 8.

The 65 cm Vacuum Reflector at BBSO

The telescope is based on a typical Gregory-Coudé design. A simplified sketch of the optical layout is shown in Figure 2. The focal length of the primary telescope mirror TM1 is 2500 mm resulting in a $f$-ratio of $f/3.85$. The focal length of the secondary mirror TM2 is 232 mm leading to an effective focal length of 32500 mm and a final $f$-ratio of $f/50$. The eccentricity of the secondary mirror is 0.8571428 and its curvature is 0.021538461 cm$^{-1}$. This results in a 13 times magnification and a corresponding image scale of 6.3 arcsec mm$^{-1}$ in the Coudé focus. A 59.9 mm diameter pupil image is formed close to the folding mirror in the hat section, which has been used in the past as the tip-tilt mirror for a spot tracker. The pupil image contains the secondary obscuration, which is 20% of the diameter of the entrance aperture, and the spider pattern from the four support trusses of the secondary mirror and the heat stop assembly.

2.1 Pupil wander

Several factors can degrade the performance on an AO system like, for example, the meteorological conditions of the observing site and factors related to technical aspects of the AO system itself. However, the most important and fundamental factor is omitted in many discussions: a stable pupil image on the DM. Shape changes, spider rotation, as well as drift and wander of the whole pupil image on the deformable mirror can severely impact the performance.

The 65 cm telescope showed a large pupil wander across the DM during the cause of the observations, which dramatically hampered the performance and operation of the AO system. The pupil wander – or better “wobble”, since the movement results from the superposition of a linear shift and a rotation – observed in the Coudé room is very large compared to other telescopes that suffer from the same degradation. For example, the pupil wobble at the DST is less than 1 mm
for a 77 mm diameter pupil over time intervals exceeding 1 h. The pupil wobble at BBSO is three to four times larger over a time period of just 15 min or less.

Experiments performed to visualise and describe the phenomenon monitored the pupil image during a whole observing day corresponding to a time period of about 7 h. The experiments demonstrated that the pupil wander is primarily caused by a misalignment of the right ascension and declination axes of the telescope. Since the right ascension and declination axes do not properly intersect, the two flat folding mirrors inside the Coudé box change their respective positions during the day and with changing declination this leads to a misalignment of the optical and mechanical axis. As a consequence, correct alignment is only temporary until declination changes make the wobble again unacceptable. In principle, the Coudé box should only add an inevitable rotation to the incoming beam, but the misalignment of the two flat mirrors dramatically aggravates the shift of the pupil. The pupil shift in the morning and afternoon is about 75 % of the diameter of the central obscuration. The pupil rotation is about 0.26° min⁻¹, which is very close to the expected value of 0.25° min⁻¹ due to the Earth’s rotation. Temperature effects play only a minor role for the pupil stability and rather contribute to the focus issues, meaning that the relative positioning of primary and secondary mirror changes during the day.

2.2. Pupil stability

To suppress the pupil wobble and ensure a stable beam over an acceptable time period (the whole observing day and longer) we proceeded as follows. In a first step, the Coudé box had to be modified in order to ease the alignment process by adding remote control actuators (Picomotor actuators by New Focus) to the fixed Coudé mirror TM5. The other Coudé mirror TM4 is mounted on a computer-controlled rotational mount and can be flipped out of the light path to direct the light to the optical benches mounted underneath the telescope tank. Along with this, the 20-year-old flat mirrors were replaced by new mirrors from Linos Photonics with higher optical quality (λ10) and coated with protective silver (96 % reflectivity in the NIR). In a second step a new alignment procedure had to be developed. The procedure is easy to perform and can be finished within an hour without sunlight before the actual observing run. The procedure involves a laser alignment fixture on the west telescope fork and an alignment optics inserted behind the polar axe approximately at the location of the tip-tilt mirror (Figure 2). A video camera is attached to the alignment optics and the pupil wander can be monitored while slewing the telescope from East to West. The three actuators of the New Focus mount are then adjusted to minimise the pupil movement.

3. Optical Design

In the following, we concentrate on the optical layout of the AO system and post-focus instrumentation illustrated in Figure 2 as originally designed by Didkovsky et al. (2003). The best location to start is the Coudé focus, which allows us to describe telescope and AO system/post-focus instrumentation as two separate systems. The first pupil image P1 forms 3.5 m (diameter 59.9 mm) in front of the Coudé focus right inside the hat section near the folding flat TM3. The lens L1 re-images the pupil onto the first active element in the light path, the tip-tilt mirror TT, which also acts as a folding mirror feeding the light vertically down into the Coudé laboratory on the second floor of the observatory building. The pupil image P2 on the TT has a diameter of 250 mm. The lens L2 forms an image of the sun at the filter wheel position FS1 and changes the beam from an f/50 at the Coudé focus to an f/13 at the filter wheel position. The filter wheel is remote controlled and currently accommodates six positions including a grid target, a pinhole, an adjustable iris, a closed position to interrupt the light path, and two open positions. The lens L3 forms another pupil image P3 (60 mm diameter) on the deformable mirror DM. The sun is (almost) collimated after L3. The flat mirror M1 folds the light from vertical to horizontal onto an optical breadboard table. After the DM the light beam falls onto a dichroic beamsplitter plate BS1 that divides the light path into two beams feeding on the one side the Wave Front Sensor WFS and the Visible-light Imaging Magnetograph VIM, and on the other side the InfracRed Imaging Magnetograph IRIM. The visible part of the spectrum is reflected, while the infrared part is transmitted. For the purpose of our experiment, we replaced BS1 by a flat folding mirror. After the beamsplitter plate (mirror) L4 forms an image of the sun, which is relayed by the negative lens L12 just behind a 10/90 % beamsplitter BS2 to a field stop FS2. In addition, L12 forms a virtual image of the pupil P4 at about 4 m before L12. The 50/50 % beamsplitter BS3 is used to direct light to a high-cadence CCD camera for broad-band observations in combination with VIM. After FS2 the light beam enters another transfer optics L13 and L14 to provide the right image scale for the Hartmann-Shack type wavefront sensor WFS consisting of an adjustable field stop FS4, a lens L15 forming a pupil image P6 on the lenslet array LA, a re-imaging lens L16 collimating the sun light, and a detector CCD2.

4. The Adaptive Optics Subsystems

An AO imaging system is a complex optical and electronic system based on the combination of a wavefront sensor (WFS) measuring the wavefront deformations, a processor unit mapping the WFS measure-
ments into real-time control signals, and a deformable mirror (DM) whose face sheet can be modified at high speed in response to the electrical signals sent by the processor unit. In the following these components are reviewed in more detail.

4.1. Image Motion Compensation: Tip-Tilt Unit

The low-order compensation system incorporates a tip-tilt mirror and the control electronics. The Piezo tip-tilt platform is a fast and compact tilt unit manufactured by Polytec PI providing precise angular movement of the top platform in two orthogonal axes. The tilt range is ±1 mrad with sub-µrad resolution. The platform is designed for mirrors up to 50 mm diameter and features angular stability over a wide temperature range. The tip-tilt mirror is located in the pupil plane and currently also acts as a 45° folding flat feeding the light vertically down from the Dome floor to the Coudé laboratory. This solution reduces the number of optical surfaces and allows for fast image motion compensation with high bandwidth. In principle, the DM can compensate for image motion as well, but this reduces the bandwidth and dynamic range available for higher-order compensation.

4.2. Higher-Order Compensation: Deformable Mirror System

The higher-order compensation system employs a flexible mirror, whose surface shape can be modified at high speed and in response to applied electrical signals. The mirror figure is controlled by a number of actuators that push and pull on the back of the mirror membrane to flatten the turbulence-induced wavefront phase aberrations. The ideal position of the DM is in or close to the pupil plane, which is the conjugate plane to the turbulent layer close to the telescope aperture. The DM is a continuous 97 actuator system (lead magnesium niobate) manufactured by Xinetics. The 2 mm thick mirror surface made of silver-coated ULE glass, which has been polished and then bonded onto a grid of actuators. The actuator grid is spaced in ~7 mm increments (centre-to-centre) according to the numbering scheme shown in Figure 3 (right).

The voltages applied to the actuators are in the range from −40 V to +70 V accessible through 65536 digital data units. The actual values are in the 32768 range providing a mechanical stroke of 4 µm with a maximum inter-actuator displacement of 2 µm corresponding to 50 V. In order to prevent potential damage of the mirror surface, the Zener diode circuitry is activated if the maximum inter-actuator displacement is reached. The −32768 digital data units are mapped to −40 V while the +32786 values are mapped to +70 V.

4.3. The Wavefront Sensor

The currently used wavefront sensor (WFS) is a correlating Hartmann-Shack WFS. The Hartmann-Shack WFS is sensitive to the gradient of the wavefront phase across the pupil. The wavefront phase itself is obtained by using a modal phase reconstructor.

A lens matrix (f ~ 24 mm) placed in the pupil plane creates 76 images of the same solar surface region covering the pupil. The geometry is visualised in Figure 3 (left). The 76 images differ only by the induced phase

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Fig. 2.—Schematic sketch of the optical layout of the the Coudé light path and the AO system. Left: Coudé feed on Dome etage. Right: Light path down into the Coudé laboratory and on the optical table.

Fig. 3.—Geometry and numbering scheme for the wavefront sensor subapertures (left) and the actuators (right).
aberrations corresponding to the location inside the pupil plane/aperture. Because of the design of the telescope, the central obscuration of the secondary mirror pod shadows the four centrally located subapertures. These subapertures are masked out by zeroing the corresponding xy-shifts before the wavefront reconstruction is done. The spider structure is not taken into account.

The WFS detector is a custom developed high-frame rate camera (~2500 fps for a 200 × 200 pixel imaging area) based on a 1280 × 1024 pixel Photobit PB-MV13 CMOS imaging sensor. The camera has 10 parallel output ports for fast readout. The entire 200 × 200 pixel array is read out in just 400 µs. The number of pixels per subaperture is software selectable. Subaperture sizes of 16 × 16 and 20 × 20 pixels can be used. For a detailed description see Richards et al. (2004).

4.4. Control System

The DM and the WFS are connected through a control system consisting of two parts, a real-time processor and a graphical user interface (GUI). The GUI (VisualC++) allows to control the subsystems and gives access to important system parameters. The real-time processor unit calculates the relative xy-shifts with subpixel accuracy by cross-correlating each individual subaperture against a reference (subaperture 31, see Fig. 3, left) in the spatial domain. The reconstructor subsequently recovers the actual wavefront and maps them in real-time control signals for the DM. Time delays in the control system determine the bandwidth of the AO system. Because of the parallel architecture of the problem a Digital Signal Processor (DSP) system is used to sense and reconstruct the wavefront. DSPs feature high processing power and high data throughput, which is essential to achieve low latency and thus high bandwidth. Further, the DSP approach can be easily expanded to a larger system by just adding additional DSP processor boards and is thus very flexible.

The DSP system is an off-the-shelf system based on the ADSP-21160 SHARC DSP (Hammerhead). The 76 subapertures of up to 20 × 20 pixel size are processed by 40 DSPs organized in clusters of four DSPs. Each DSP processes two subapertures. The DM actuator voltages are updated ~250 µs after the last pixel of the 200 × 200 pixel image array has been read. Together with the readout time of the whole imaging array of 400 µs this leads to a latency of 650 µs and a “theoretical” bandwidth of 1540 Hz. To practise the bandwidth is further limited. From studying the power spectra of Zernike coefficients we conclude that the closed-loop bandwidth is 100-200 Hz depending on the corrected Zernike mode (see Sect. 6).

5. High-Spatial Resolution Imaging

5.1. Observations

The speckle observations were taken in a red continuum window at 600 nm with a 10 nm FWHM-wide interference filter manufactured by Melles Griot. Data acquisition was accomplished by a high-speed, large-format (1024 × 1024 pixel) CCD camera (DALSA) with 12-bit digitisation. The field-of-view (FOV) of the speckle interferometry channel was 79.5 × 79.5 arcsec², which corresponds to an image scale of 0.078 arcsec/pixel⁻¹. The diffraction limited resolution of the 65 cm BBSO vacuum reflector at 600 nm is defined according to the Rayleigh criterion

\[ \theta_{\text{Rayleigh}} = \frac{1.22 \cdot \lambda}{D} = 0.23 \text{ arcsec}. \]

Comparing the diffraction limit and image scale indicates that the speckle images are oversampled by about 50%. A total of 80 sequences of short-exposure images (Δt = 10 ms) were taken with a 30 s cadence from 17:26 UT to 18:10 UT on May 2, 2005. Each sequence consists of a series of 100 short-exposure images, which were selected from a total of 200 images. The frame selection algorithm is based on the rms-contrast of the solar granulation. The images were acquired at a rate of 15 frames s⁻¹.

The following data processing steps and the combination of speckle masking imaging, frame selection, and high-order adaptive optics (AO) have been discussed in detail in Denker et al. (2005) for a similar observing run at the DST. Therefore, we only give a brief summary of the image processing procedure and reference the underlying theory.

5.2. Image Reconstruction

We used the speckle masking method (Weigelt 1977; Weigelt & Wirnitzer 1983; Lohmann et al. 1983; de Boer 1993) to obtain the Fourier phases of the object and applied it to AO corrected images. The Fried-parameter \( r_0 \) was derived with the spectral ratio technique (von der Luehe 1984). To measure the Fried-parameter, the observed spectral ratios are compared with tabulated theoretical values of the speckle transfer function (STF, Korff 1973) and the average short-exposure modulation transfer function (MTF, Fried 1966). In Denker et al. (2005), we discuss the spectral ratio technique in the context of AO observations and its effect on the photometric accuracy. The seeing cut-off frequency is encoded in the spectral ratio but the work on a proper theoretical foundation is still in progress. The amplitudes of the object’s Fourier transform were corrected according to the classical method of Labeyrie (1970). A detailed description of the technical aspects of the phase reconstruction algorithm is given by Pehlemann & von der Luehe (1989). Because of the effects of anisoplanatism the whole FOV is divided into partially overlapping subfields that are
individual reconstructed (von der Luehe 1993). A sensitive noise filter is applied during the calculation of the phases (de Boer 1996). Back-transformation of the modulus and phases of the object’s Fourier transform yields a mosaic of speckle reconstructed subfield scenes that are subsequently patched together.

5.3. Results

In Figure ??, we present a comparison of long- and short-exposure images, which were taken with the high-order AO system at BBSO. As an example, we show a small part of active region NOAA 10756 observed at 17:01 UT on May 2, 2005. The insert in the left panel of Figure ?? shows the root-mean-square (RMS) granular contrast of the 100 sharpest images out of a sequence of 200 short-exposure images acquired within in a time period of just 15 s. Note that the descending order of the RMS contrasts are an artifact of the frame selection algorithm. Granular contrasts of about 3% at 600 nm indicate fair to good observing conditions during the data acquisition. A more detailed description of the seeing conditions is deferred to the following section (see Table 1). The background image in the left panel of Figure ?? is the average of these 100 images corresponding to an effective exposure time of 1 s. Exposure times in the order of one second or more are typically encountered in spectroscopic or polarimetric applications. It is the strength of an AO system to provide high Strehl ratios even for these relatively long exposure times. The right panel of Figure 4 displays the image with the highest RMS out of the sequence of 100 short-exposure images. Even though this frame-selected image already contains spatial information close to the diffraction limit of the 65 cm telescope, image reconstruction techniques such as phase diversity methods (e.g. van Noort et al. 2005) or speckle interferometry (e.g. Denker et al. 2005) can further improve the spatial resolution and quality of these short-exposure images. Figure 5 demonstrates the image quality that can be achieved with the speckle masking technique. One of the shortcomings of this technique in the context of AO-corrected observations has been the proper calibration of the Fourier amplitudes (see Denker et al. 2005). Based on the results by Wang & Markey (1978) for the long exposure transfer function (LETF) the Korff model (Korff 1973) for the STF was analytically modified to take into account the correction of an arbitrary AO system. The performance of the correction can be adjusted in the model by parameters which can be easily extracted from the wave front sensor data of the specific AO system used. Using a Monte-Carlo integration algorithm to solve for the LETF as well as the STF, models for spectral ratios (SR, von der Luehe 1984) are calculated. In this way, a look-up table of transfer functions and SRs for different seeing and correction conditions is generated.

During the reconstruction process the SR is retrieved from the observational data within subfields which overlap by half of their size. The models are fitted to the measured SRs using a weighted least squares fit. In the first step we identify the lockpoint, and - keeping the correction level constant - estimate Fried’s parameter $r_0$ from the subfields far away from the lockpoint in the FOV. In a second step the correction level is estimated now keeping $r_0$ constant. Once these parameters are known, the STF is chosen from the look-up tables and used for the estimation of the Fourier amplitudes by means of the Labeyrie method (Labeyrie 1970). The details of this method will be elaborated in depth in a forthcoming publication.

In Figure 6 we present first results using the described algorithm for the estimation of the Fourier amplitudes. The left panel displays the reconstructed scene: a pore with a rudimentary penumbra located close to disk centre. The middle panel
Fig. 4.—Left: Long-exposure image of active region NOAA 10756 at 17:01 UT on May 2, 2005 observed with the 65 cm vacuum reflector at BBSO. This image is the average of 100 individual short-exposure images acquired within 15 s corresponding to an effective exposure time of 1 s. The insert shows the granular rms-contrast of all images in the sequence. Middle: The short-exposure “reference” image, which is a frame selected image with the highest granular rms-contrast out of a sequence of 200 individual images.

Fig. 6.—Left: Speckle reconstruction using an extended Knox-Thompson algorithm including calibrated Fourier amplitudes after AO correction. Middle: Mean subfield shifts determined from a local correlation tracking technique. Right: The generalised Fried parameter.

6. System Performance of the AO System

The AO control system offers the option to write real-time system information, e.g. x- and y-subaperture shifts and/or actuator control signals, into the memory of the control computer. For the following preliminary study we employ the xy-subaperture shifts only.

The xy-shifts and thus the shift vectors, measured with respect to a reference subaperture, are directly related to the magnitude of the wavefront gradient vector over a given subaperture by

\[ |s| = k \frac{r}{f}, \]

where \( r = \sqrt{x^2 + y^2} \) is the magnitude of the shift vector, \( f \) is the focal length of the subaperture lens (lenslet array), \( k = 2\pi/\lambda \), and \( \lambda \) denotes the wavelength. The subaperture FOV of 26 × 26 arcsec is mapped to 20 × 20 pixels. The shift vectors are determined for all 76 subapertures shown in the left panel Figure 3 including the
central obscuration of the secondary mirror pod. However, in the subsequent data analysis, the shift vectors corresponding to the central obscuration (indices 33, 34, 43, and 44) are omitted. During a time period of about 10 min, we captured 13 data files (six with AO and seven without AO) with the AO WFS and CCD camera on April 29, 2005. Each data file consists of a 8666 individual data sets acquired at a cadence of about 2500 fps covering a time interval of just 3.5 s. The xy-shifts are saved in fractions of a pixel with two significant digits. In all calculations, we used a telescope aperture of 60 cm (see Sect. 2) and a wavelength of 550 nm. The following results are based on these data sets.

### 6.1. Results

In the left panel of Figure 7, we show a comparison of the average shift vectors for the entire data set with the AO system turned on and off, respectively. The grey background indicates the 1σ variation in the data set, which corresponds to the temporal variation due to seeing in the measurements. During the first half of the observations, the AO system was turned on, while it was turned off for the last seven data sets. At a first glance, the AO corrected data shows a decrease of the average xy-shifts by a factor of about six. Note that the data taken without the AO systems includes the tip-tilt component of the seeing and a component due to image rotation in the Coudé laboratory, since the reference frame was taken about 10 to 15 min earlier. This might explain the slow increase of the average xy-shifts towards the end of the observing run. The fact that the average xy-shifts are not close to zero in the AO corrected data indicates a potential problem in accurately measuring higher order Zernike modes, which are still present as residuals in the shift vectors, thus effectively reducing the bandwidth of the AO system.

We chose two data sets consisting of 8666 individual measurements shown in the right panel of Figure 7 to illustrate the system performance. The AO-corrected values are again a factor of six lower and show almost no variation. However, the open-loop data shows variations on time scales of about 100 ms, which corresponds roughly to the correlation timescale of the seeing.

#### 6.1.1. Seeing characterisation

In a first step of quantifying the seeing conditions at BBSO, we can simplify the WFS geometry and use it as a Solar-Dual Image Motion Monitor (S-DIMM, Beckers 2001). Preliminary attempts to characterise the seeing conditions at a lake-site observatory were presented in ?, who compared seeing characteristics derived from wavefront sensing, solar scintillometry, and imaging data. However, an AO system was not operational at that time. The theory of night-time DIMMs has been described in Sarazin & Roddier (1990), who derived the following equations for the relation between the differential image motion and the Fried-parameter $r_0$:

$$\Sigma^2_L = 2 \lambda^2 r_0^{-5/3} \left(0.179 D^{-1/3} - 0.0968 d^{-1/2}\right)$$

and

$$\Sigma^2_T = 2 \lambda^2 r_0^{-5/3} \left(0.179 D^{-1/3} - 0.1450 d^{-1/2}\right),$$

where $\Sigma^2_L$ and $\Sigma^2_T$ are the RMS values of the differential image motion along and perpendicular to the line between the two subapertures. We selected four pairs of subapertures with indices (2, 74), (3, 75), (29, 38), and (39, 48) according to the numbering scheme of the left panel in Figure 3. We used the $D = 6.0$ cm for the subaperture size with a separation of $d = 57.0$ cm. These are approximately the dimensions, if the WFS geometry would have been mapped to the size of the entrance aperture (pupil). The Fried-parameters $r_0$ were
Table 1: Seeing characteristics as determined with the AO WFS on April 29, 2005.

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<th>18:01:43</th>
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</tbody>
</table>

The current implementation of the AO system uses Zernike polynomials to parametrise the wavefront. The values for the reconstruction matrix are tabulated in an ASCII text file, which is read during the initialisation of the AO system. We use a package of routines written in the Interactive Data Language (IDL) to analyse the time-series of shift vectors captured with the AO system. It is based on Zernike polynomials \( Z_j \) with a specialised normalisation scheme introduced by Noll (1976), which is more convenient for statistical analysis. The index \( j \) is a mode ordering number (see Table I in Noll 1976), which also provides the identification of Zernike polynomials in terms of the classical optical aberrations and a function of the radial degree \( n \) and the azimuthal frequency \( m \), which are always integral and satisfy the condition \( m \leq n \) and \( n - |m| = \text{even} \). The wavefronts are parametrised with Zernike polynomials with a mode ordering number up to \( j = 35 \) corresponding to radial degrees \( n \leq 7 \) and azimuthal frequencies \( |m| \leq 7 \). This choice was based on the fact that we could not see any significant contributions from higher order Zernike modes. We expect to measure and correct contributions from even higher modes once we have resolved some issues related to the proper pupil size at both the location of the DM and WFS. Therefore, the results presented in this section should be seen as a lower performance limit of the current AO system with a potential for major improvements. We used standard singular value decomposition (SVD, 2) to solve the linear least-squares problem of determining the coefficients of the Zernike polynomials. The pupil geometry on the WFS was taken into account including the central obscuration and partially illuminated subapertures. However, we neglected the shadowing of the spiders and only corrected this influence by taking new flat field frames every 30 min. The Zernike coefficients are determined by fitting the derivatives of the Zernike polynomials to the observed shifts. In principle, the IDL package can handle any pupil/WFS geometry. Further tests to improve the reconstruction process are currently carried out at BBSO and NSO/SP.

Noll (1976) provide a theoretical description of atmospheric statistics, i.e., the wave propagation through the turbulent atmosphere. In particular, he derived the Zernike matrix representation of the Kolmogoroff phase spectrum (see Equations 22 to 25 in Noll 1976). In Figure 8, we compare the variances of the Zernike coefficients for a mode ordering number of up to \( j = 35 \) for open- and closed-loop data. The variances are a factor of about 100 smaller for the AO-corrected data. In this graph, all data sets were merged, i.e., six data sets for the AO-corrected and seven for the uncorrected observations, to show the trend in the data more clearly. The solid curve is a fit to the Kolmogoroff phase spectrum of the open-loop data for \( D/r_0 = 12.10 \). The temporal power spectra were slightly smoothed to improved the clarity of the graphs.

Fig. 8.—Comparison of the variance of the Zernike coefficients for open- (asterisks) and closed-loop (caret) data determined from the AO WFS data. The solid curve represents a fit to the Kolmogoroff spectrum of the open-loop data for \( D/r_0 = 12.10 \). The temporal power spectra were slightly smoothed to improved the clarity of the graphs.

Shift vectors. In principle, the IDL package can handle any pupil/WFS geometry. Further tests to improve the reconstruction process are currently carried out at BBSO and NSO/SP.
mogoroff turbulence, which might not be obvious in a case where the boundary layer seeing is strongly suppressed. This was one of the questions addressed in the final site survey report for the Advanced Technology Solar Telescope (ATST, ??). Since our results were determined from only seven data sets, we intend to repeat this type of measurements on several days from sunrise to sunset, which should settle the questions related to Kolmogoroff-type turbulence in the presence or absence of boundary layer seeing. We also performed similar fits for the individual open-loop data sets and the results are summarised in Table 1. Note that the last row is the average of the individual data sets and not that of the merged data sets. Summing the variances for all Zernike coefficients provides us with an estimate of the average wavefront error Δ in radians^2, which is also listed in Table 1. Figure 8 is actually very similar to Figure 1 in Rimmlele et al. (2003), which shows observations with the low order AO system at the DST. However, in the high-order BBSO AO system, the separation of the variances of open- and closed-loop data is much more pronounced – all the way to Zernike coefficients with a mode ordering number of up to j = 35 show this clear separation, whereas the cross-over occurred already at j = 15 for the now obsolete low-order AO system at the DST.

6.1.2. Fixed aberrations

The open-loop data can also be used to measure fixed aberrations of the optical system. Assuming that the seeing variations are random, the average of all 7 x 8666 shift vectors (see left panel of Figure 9) should represent the wavefront of the uncorrected optical system. The right panel of Figure 9) shows this wavefront assembled from Zernike polynomials with a mode ordering number of up to j = 35. The optical aberrations amount to 1.9 rad RMS and 11.3 rad peak-to-valley (PTV). Major contributions arise from the defocus and 3rd order astigmatism terms, which can be most likely attributed to the entrance window of the telescope. The corresponding values for the AO corrected data are 0.040 rad RMS and 0.35 rad PTV, respectively.

6.1.3. Bandwidth

An important parameter to characterise the performance of an AO system is the system bandwidth. The system bandwidth defines how fast the AO system can respond to changes of the wavefront deformations.

Figure 10 shows a comparison of the temporal power spectra of open- and closed-loop data for selected Zernike polynomials (tilt j = 2, defocus j = 3, 3rd order astigmatism j = 4, and 5th order spherical aberration j = 21). The grey lines correspond to a power law fit with an exponent of −8/3. From the intercept of the power law fit and the temporal power spectra in the right column of Figure 10, we can determine the bandwidth of the AO system to be in the range from about 100 to 200 Hz depending on the mode ordering number j, i.e., the higher j, the lower is the bandwidth. Examining the bottom two panels in Figure 10, we find that the power spectra of open- and closed-loop data become very similar. The power of the low-frequency component of the uncorrected 5th order spherical aberration term approaches 10^-4 close to the 10^-5 level of the AO-corrected data. Indeed, once we reach a mode ordering number of j = 35, we do not see any statistically significant difference between open- and closed-loop data. Thus, we conclude that only the first 35 Zernike modes are corrected.

7. Future improvements

Many of the problems encountered with the 65 cm vacuum reflector during the implementation of the AO system are founded in its history. One of the major issues – the pupil stability – we addressed in Sect. 2.1. However, we are left with the inevitable pupil rotation. As a consequence the spiders holding the secondary pod begin to shadow subapertures shortly (∼2 min) after the WFS flatfield calibration is performed. This fact does not seem to compromise the performance if the lock structure has sufficient contrast like a small spot or a large pore but it certainly has an effect if low contrast structures are encountered like the solar granulation. With the current optical design of the WFS and its relay optics we achieve an image scale in the subapertures (∼26 x 26 arcsec^2) of about 1.3 arcsec pixel^-1, so it is beyond the capability of the system to lock on solar granulation, although this is a highly desirable task. The comparably large subaperture FOVs also implies WFS measurement errors leading to wavefront fit errors. This might explain the rather large aperture averaged mean squared wavefront error of 0.58 rad^2 (closed-loop). It is therefore one of the important future tasks to modify the WFS optics to achieve smaller FOVs in the range ∼15 arcsec to first minimize WFS
measurement errors and second resolve the solar granulation spatially.

The upstream imaging system forms a pupil image on the DM that does not fully illuminate the mirror: only \(~76\%\) of the mirrors surface are currently covered by the pupil image.

Another issue is the fact that only up to 47 Zernike modes are used to parameterize the wavefront.

### 8. Conclusions and Prospects

We have demonstrated that the AO system at BBSO is operational and can be combined with the post-focus instrumentation (VIM, IRIM, and RTIR). The system performance has been studied in detail including measurements of the Fried-parameter \(r_0\) and the isoplanatic patch size, temporal power spectra of the Zernike coefficients, residual wavefront errors, Kolmogoroff turbulence spectra, and direct imaging. Especially, the combination of post-facto image restoration and AO correction has produced some of the best data sets obtained at BBSO so far. However, after over 35 years of continuous operation and countless modifications and upgrades, the time has come for a new telescope that can serve the needs of modern post-focus instruments for high-resolution solar physics. The New Solar Telescope (NST) at BBSO (Goode et al. 2003; Didkovsky et al. 2004) is now in its construction phase with first-light expected in late 2006. The AO system as well as the current post-focus instruments provide the baseline for the NST first-light instrumentation. The design of the NST and its suite of dedicated instruments are tailored towards space weather research, which has been a corner stone of research at BBSO for many decades (?). This type of research requires continuous monitoring of active regions with high resolution over extended periods of time under very good seeing conditions. The ATST site survey (Hill et al. 2004; ?) has identified BBSO as the ideal site for this type of research. The NST will perfectly complement the proposed ATST (Keil et al. 2003), which will exploit the periods of excellent seeing on Haleakala, Maui, Hawaii to study the Sun and the solar corona with even higher resolution to address the fundamental physics questions related to solar fine-structure.

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