Title of Investigation: MRI: Development of High-Order Adaptive Optics System for the 1.6 Meter Solar Telescope in Big Bear
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Project Summary

New Jersey Institute of Technology (NJIT), in collaboration with the University of Hawaii (UH) and the Korean National Observatory (KAO), is building the 1.6-m aperture, off-axis, New Solar Telescope (NST). It will replace Big Bear Solar Observatory (BBSO)'s principal telescope with its 65-cm aperture. This largest solar telescope will play a leading role in solar physics research and education. The project is well under way; first-light is anticipated at the end of 2006. Under prior NSF/MRI support to NJIT, in collaboration with the National Solar Observatory (NSO), we have successfully developed two 76-element Adaptive Optics systems (AO-76) for the current BBSO 65-cm telescope and the NSO 76-cm Dunn Telescope.

An AO system to match the 1.6m aperture is a critical component to achieve the scientific goals of NST. AO-76 is a high-order system for the 65-cm BBSO telescope, which is successfully operating in both the visible and near infrared (NIR) ranges. It is insufficient for the correction in the visible for NST. This proposal seeks funding to build the 349 sub-aperture AO for NST. We estimate that, under median seeing conditions at BBSO, the predicted Strehl ratio at $0.5\mu m$ is above 0.7 with AO-349. The key tasks in this proposal include the optical design, building electronic system and subsequent setup/testing of the AO system under the NST. We are considering a design that will be as reflective as possible to make the system achromatic. The specific scientific objectives for the AO equipped NST are: (1) High cadence, high resolution studies of solar flares; (2) Evolution of magnetic fields associated with solar activity; and (3) Dynamics of Kilo-gauss magnetic flux tubes.

In sum, we directly address the two criteria required in any NSF proposal:

(1) Intellectual merit: The National Solar Observatory is building its flagship telescope: the 4-m Advanced Technology Solar Telescope (ATST). Until ATST is built, the AO equipped NST will be the largest aperture solar telescope, located in one of the best observing sites. While the ATST's primary science focus is on the physics of small scale flux tubes and solar corona, NST with its unique seeing condition, will enable new, cutting edge science in study solar activity. We have already demonstrated our abilities by developing the two most successful solar AO systems in the world.

(2) Broad Impact: The development of the proposed AO system will enable us to further explore Multi-Conjugate Adaptive Optics (MCAO). This effort is highly relevant to the development of MCAO systems for the nighttime telescopes. The scientific results will be extremely important in the understanding of the dynamics of magnetic fields on a fine spatial scale, as well as space weather monitoring and forecasting. The scientific objectives will also be closely linked to several key research topics in nighttime astronomy: the physics of stellar coronal heating, stellar magnetic fields and stellar flares. This project has strong integrated research and education components. A Ph.D. student, a undergraduate and a post-doc will participate in the project. The data will likely to be used in many Ph.D. theses. Our data will be open to the scientific community and about 50% of observing time will be open for competition.

A Project Description

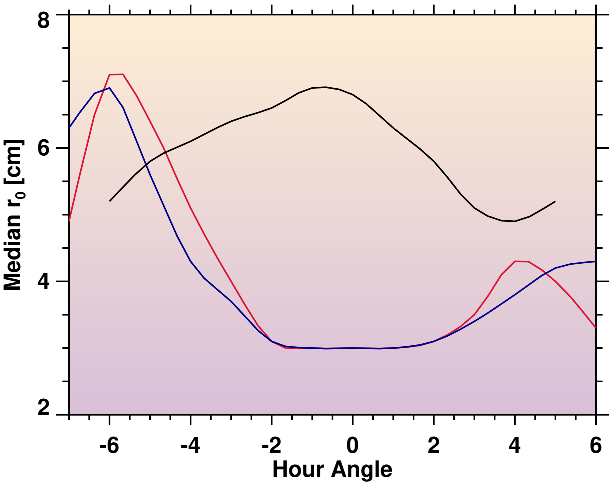
A.1 Research Activities

Of the two US observatories capable of making high-resolution observations of the Sun, BBSO is the one operating in a campaign mode. We believe that a more fundamental understanding of solar magnetic fields and the solar atmosphere depends on sustained, higher resolution and higher cadence observations. Over the past few years, we have substantial accomplishments that position us to advance to the next level of our scientific objectives, which will center on understanding energy release and transport on different scales in the solar atmosphere, as well as the associated evolution of magnetic fields. Our research requires a continuing effort in instrument development, and a dedicated scientific team to make and analyze new observations. Building the new off-axis 1.6-m telescope at BBSO is a crucial step toward this goal.

The Advanced Technology Solar Telescope (ATST) site survey was initiated in 2000 and has identified at the end of a four-year survey three excellent sites for solar observing: Big Bear Solar Observatory, California – Mees Solar Observatory, Haleakala, Maui, Hawaii – Observatorio Roque de los Muchachos, La Palma, Canary Islands, Spain (Hill et al. 2004). All three sites are suitable for high-spatial resolution observations. Haleakala and La Palma have strong advantages for coronal science. However, only BBSO – the mountain-lake site – provides consistent seeing conditions with extended periods of excellent seeing from sunrise to sunset (see Figure 1). For any ground-based modern solar telescope, an Adaptive Optics (AO) system is required to correct seeing induced image smearing and distortions. A minimum Fried parameter, 6 cm, is required for AO correctibility. Obviously, BBSO is uniquely qualified to be a site for building a large aperture solar telescope and achieving diffraction limited resolution with AO for long periods of time. Periods of excellent seeing (sufficient to be corrected by AO) are limited to one or two hours in the early morning for the Pacific/Atlantic mountain-island sites, Haleakala/La Palma, where the seeing deteriorates once the ground heats up and a turbulent boundary layer has been established. Haleakala was selected as the ATST site to achieve its primary scientific objectives: extreme fine structure of magnetic fields that can be studied with exceptional seeing for short periods of time and physics of solar corona. The lake at BBSO effectively suppresses the boundary layer and makes the observatory ideally suited for sustained high-resolution and synoptic observing programs, and the 1.6-m NST is being built for this purpose.

We now report on the significant progress on two major instrumentation projects that are relevant to the development of the proposed AO system: the on-going NST project and the finished 76-element AO project.

Figure 1: The median value of the r_0 (Fried parameter, a rough measure of the diffraction limit, $r_0 \geq 5.5$ cm is required for correction by AO) measurements from the S-DIMM instrument (principal ATST site survey instrument, see http://atst.nso.edu/site/ for details) for the three finalists to be the ATST site (**Big Bear**, **Haleakala**, and **La Palma**) as a function of hour angle (adapted from Figure 10.13 in Hill et al. 2004, ATST Site Survey Report).



A.1.1 New Solar Telescope at BBSO

Supported primarily by a current NSF MRI grant (ATM-0320540), BBSO/NJIT, in collaboration with the University of Hawaii (UH) and Korean National Observatory (KAO), have formed a team to upgrade BBSO by replacing its principal 65-cm aperture telescope with a modern, off-axis 1.6-m clear aperture instrument with a $180'' \times 180''$ field of view (FOV) (Goode et al., 2003). The new telescope offers a significant improvement in ground-based high angular resolution capabilities, and enhances our continuing program to understand photospheric magneto-convection and chromospheric dynamics. These are the drivers for what is broadly called space weather – an important problem, which impacts human technologies and life on Earth. This New Solar Telescope (NST) is a whole new system starting with being the largest aperture off-axis telescope. We have made strides in implementing this project, including the design of the optical support structure with active optics, a new dome to house the larger telescope, and a whole new control system.

The project is described in detail in `http://www.bbso.njit.edu/newtelescope`. To minimize the risk to the NST project, we have borrowed on the design of existing telescopes as much as possible. For example, the new, larger dome follows the SOAR design, with minimal, but required modification: the NST dome has louvers to ensure proper airflow inside the dome, so the long-standing dome-seeing problem at BBSO can be solved. The NST optical and software control designs are similar to the existing SOLAR-C (UH) and the planned ATST facility led by NSO – all three are off-axis designs. We have full funding for the NST, except for the funding for its AO system. Figure 2 shows the mechanical schematics and optical layout of NST. Full operation is expected by the spring of 2007. The specific details of our progress are:

(a) All optical and mechanical designs are completed. The telescope has a 1.7-m primary mirror with the 1.6-m clear aperture. It has the off-axis Gregorian configuration consisting of parabolic primary, heat-stop, elliptical secondary and two diagonal flats. The focal ratio of the primary mirror is f/2.4, and the final ratio is f/50. The working wavelength will cover from 0.39 to 1.7 μm in the Coude Room one floor beneath the telescope and all infrared wavelengths at the Nasmyth focus on the dome floor. We chose an off-axis design primarily because of its vastly reduced stray light, since there is no central obscuration, which reduces the telescope's MTF (Modulation Transfer Function) at high spatial frequency.

We have designed an open telescope structure with an equatorial mount. A key design issue for a large aperture open solar telescope the thermal is the control system, including keeping the temperature of the mirrors very close that of the air. We are using the wind-gate system in the new dome (discussed below) to control the airflow from the wind and help maintain the same temperature inside and outside the dome. In addition, we will implement an airknife system to limit so-called "mirror seeing".

(b) The central and risky part of the NST project is the figuring of the primary mirror to high optical quality. The Zerodur primary mirror is being polished at Steward Observatory Mirror Lab, University of Arizona (UA Mirror Lab), as part of their 20/20 project (`http://www.optics2001.com/telescope.htm`). This is the optimal facility for figuring the NST primary mirror. The lab is funded to polish a fast, off-axis 1.7-m mirror as a proof-of-concept study for figuring seven 8.4-m mirrors for twin 21-m telescope. The end product of the proof-of-concept will be the primary mirror for the NST. The precision of the primary is targeted at 10 nm. The polishing of the primary is progressing well and is scheduled for completion no later than February 2006. The progress is sufficient enough that we now know that the project is no longer risky. The risk concerned the characterization of the figure of the primary. For the testing of the figure, Steward built a testing tower with a 0.5 spherical mirror at its top and a special holographic system to account for the off-axis nature of the mirror. It turns out that profilometer and holographic testing of the primary yielded the same result over the visible, so we are confident of the testing, and the polishing continues with the rms error being about 200 nm as of this writing (see Figure 3).

(c) The 145-mm concave secondary and its backup are also in the final polishing stage at Space Optics Research Lab (SORL). Shortly after February 2006, the primary and the secondary will be tested in tandem

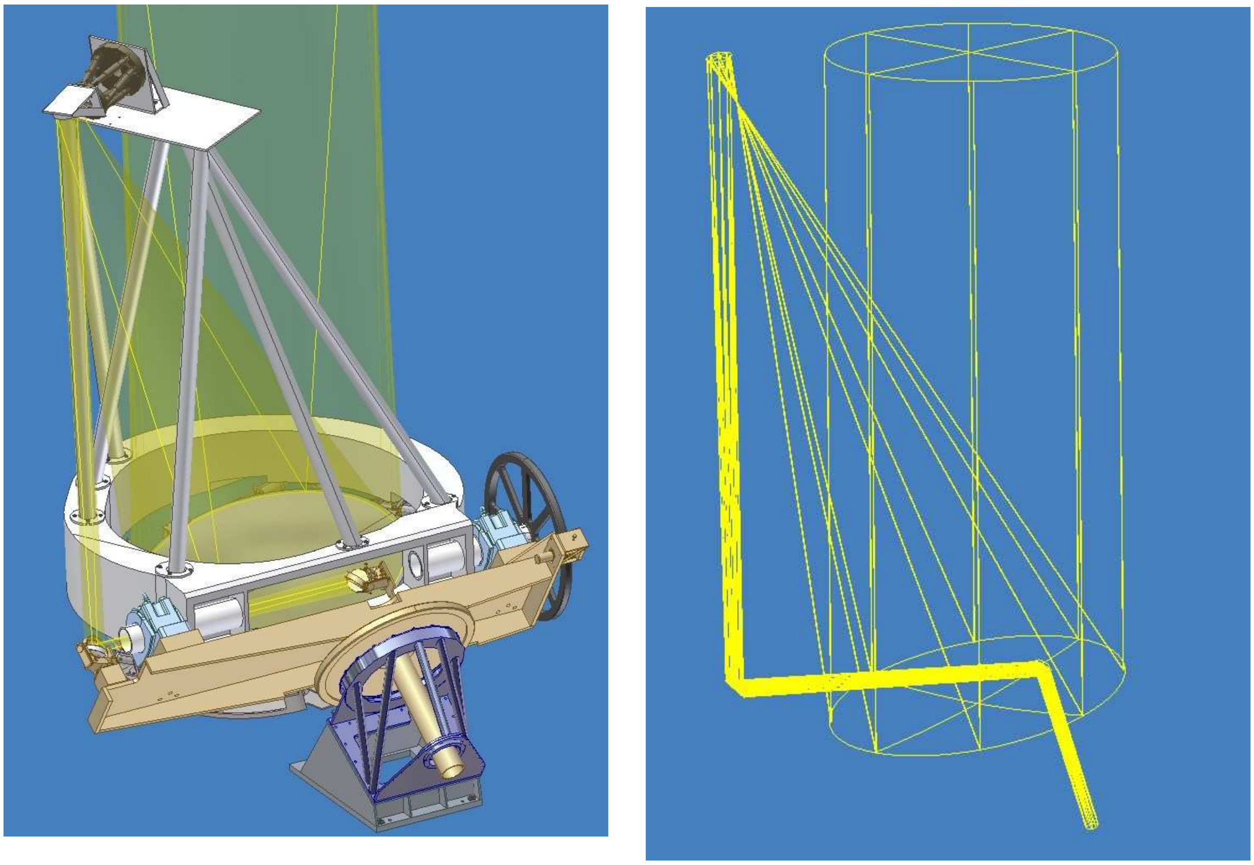
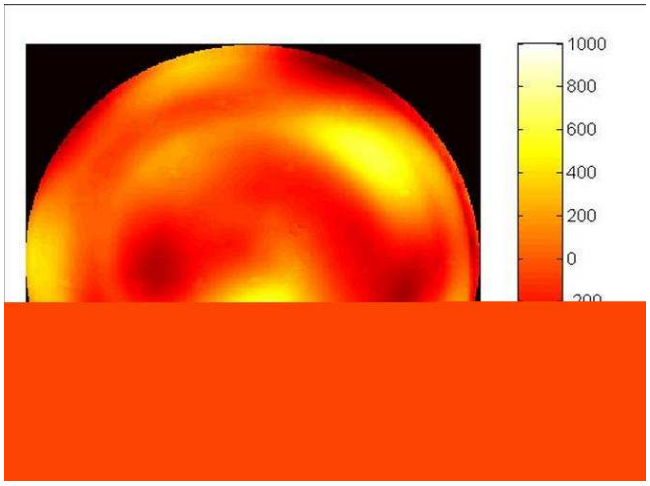


Figure 2: Schematic of the 1.6 m off-axis, open NST and its optical layout.

in the UA Mirror Lab or Optical Sciences Center. Testing equipment will be set-up for this final system test of the principal optics of the NST. The downstream mirrors of the NST are all flats.

(d) The heatstop is the responsibility of the UH part of our team, and will follow that of SOLAR-C. A reflective surface with a 3.8 mm opening is located at the prime focus of the telescope. This opening is the field stop for the system and the reflective surface rejects most of the solar image, limiting the radiation that passes on to the downstream optics. The surface will be cooled by liquid jets. The rejected light will be collected in a beam absorber. The heat load will be removed from the telescope via circulating, chilled fluid. The heat stop system will remove about 2 Kilowatts of heat, allowing less than 30 Watts to pass on to the secondary optics.

(e) The last piece of hardware needed for the NST is the Optical Support Structure and its Equatorial Mount. DFM (of Longmont, Colorado) has been contracted to build the system based on their standard designs, which they have successfully implemented for many telescopes with pointing and stability specifications equivalent to those required for the NST. An important part of the system is the primary mirror cell. The primary mirror is supported by 36 axial and 6 tangential actuators. These force based servos will compensate for gravity and thermally induced errors in the mirror figure. The secondary mirror will be mounted on an agile hexapod. The M850 system made by PI (Physik Instrumente of Germany) has been purchased and tested. A wavefront sensing system is being developed to control the active optics components. This system will be placed immediately before M3 (first flat mirror, which directly feeds the Nasmyth focus, or feeds flip mirror M4 that in turn feeds light to the Coude Room beneath, where the adaptive optics system resides).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