

Title of Investigation: 1.6-M Solar Telescope in Big Bear – The NST

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Project Summary

New Jersey Institute of Technology (NJIT), in collaboration with the University of Hawaii (UH) and the National Solar Observatory (NSO), has initiated a plan to upgrade Big Bear Solar Observatory (BBSO) by replacing its principal telescope with a modern off-axis, larger aperture instrument that is suitable for higher angular resolution and infrared solar research. This new telescope offers a significant incremental improvement in ground-based capabilities for studies of photospheric magneto-convection. This New Solar Telescope (NST) uses the existing BBSO equatorial mount (modified to accept a larger open telescope structure). The NST optical and software control design will be similar to the existing SOLARC (UH) and the planned Advanced Technology Solar Telescope (ATST) facility telescope of NSO – all three are off-axis designs. Given the background experience of the co-investigator team, we believe this collaboration is ideally suited for efficiently building the NST. Although the NST is a PI-class, and not a facility instrument, this collaboration with ATST and UH scientists and engineers offers a unique opportunity for risk-mitigation and early software development for the planned ATST facility. The MRI/NSF investment in the NST will be highly leveraged by support from private and other non-NSF funding sources. We plan for first light early in 2006. Here we are asking for support to complete designs and to implement the mechanical, thermal, and control systems. The total cost to finish this project is \$2580 K including \$1800K from the NSF, and a \$780K BBSO/NJIT match. Additional funds from private sources have already been applied to the costs of the primary and secondary mirror blanks and polishing.

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A Project Description

We plan to replace the 65-cm vacuum telescope at Big Bear Solar Observatory (BBSO) by an open, off-axis 1.6 m solar telescope – the NST (New Solar Telescope). The NST will feed all of the new instrumentation that we are presently developing and have developed over recent years. The total cost of this project is about \$4 M. Here we propose for \$1.8 M. New Jersey Institute of Technology (NJIT), which operates BBSO, is investing \$1.3 M in the NST. The remainder of the funds will come from non-NSF sources. Thus, the project is highly leveraged, and it will benefit the Advance Technology Solar Telescope (ATST) project and the solar community.

The NST project is a teaming of BBSO/NJIT, the University of Hawaii (UH) and the National Solar Observatory (NSO).

BBSO operates in sustained campaigns – essential for the broadly-based, high resolution observations needed to gather unique data to understand the fundamental nature of solar magnetism and its evolution.

A. 1 Results from Prior NSF Support

Goode is the PI on a current grant from NSF-ATM (00-86999), which provides backbone support for solar research using the facilities at BBSO. NJIT took over operation of BBSO on July 1, 1997. Since then, the observatory has undergone fundamental changes that are marked by significant achievements in science, instrumentation and education; and we have produced over 175 scientific papers. The synergy of the work proposed here with the solar community and other BBSO activities is discussed throughout the proposal.

A. 2 Overview

The highest resolution solar telescopes currently operating have diffraction limits allowing them to resolve features larger than 100 km in size on the sun, and are often photon starved in the study of dynamic events because of the combined effects of diffraction limited spatial resolution, short exposure times to minimize seeing effects, and high spectral resolution to resolve line profiles. Thus, understanding many significant solar phenomena remains tantalizingly close, but just beyond our grasp. With the NST at BBSO, an off-axis 1.6-m telescope (at an excellent site, outfitted with Adaptive Optics (AO) and the latest detector systems), we will advance our knowledge of the nature of the dynamic sun. The NST will be an open telescope that will have first light early in 2006. A schematic of the telescope is shown in Figure 1. The NST would be the world’s largest aperture solar telescope, probably until the 4-m

Project	Cost [K\$]	Vendor	Completion Date
Mechanical system	850	???	July 2005
Thermal control system	150	???	July 2005
Computer control system	300	???	July 2005
Assembly and alignment	500	BBSO staff & ???	April 2006
Total NSF investment to complete the NST	1800		July 2006

Table 1: 1.6-m telescope mechanical and thermal systems and assembly and alignment

ATST comes to fruition a few years after the NST. In detail, our 1.64 m blank will ultimately reside in a 1.6 m clear aperture telescope. The NST is designed to make high resolution observations of the sun in visible and infrared light. Here, *we propose for support to accomplish and implement the mechanical, thermal and control designs of the NST, which along with the assembly and alignment, would complete the NST*, see Table 1. We have already purchased the primary and secondary blanks, which are made of astrositall (extremely low thermal expansion glass of the highest quality). The two blanks are from LZOS (Moscow, Russia), and we expect delivery by late Spring of 2003. The primary mirror will be polished in partnership with the University of Arizona Mirror Lab (ONGOING DISCUSSIONS???). As part of the

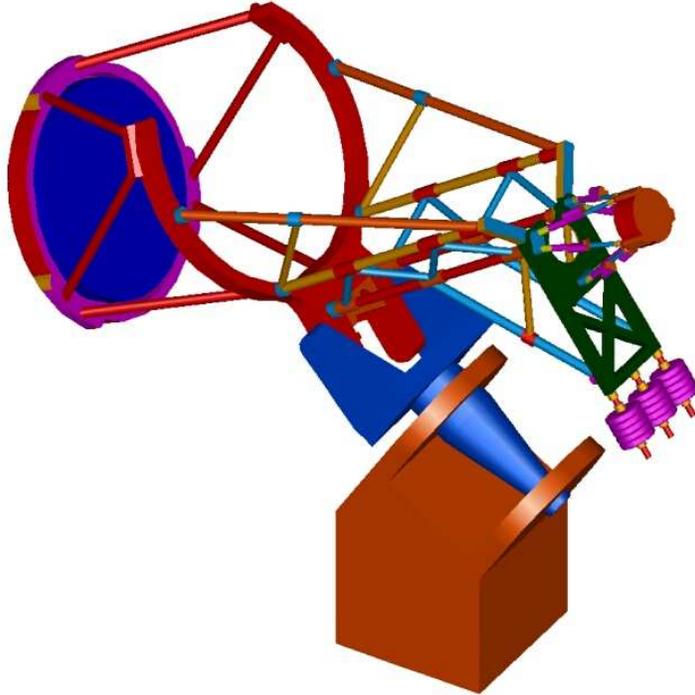


Figure 1: Schematic of the 1.6 m off-axis, open NST

20/20 project (see www.optics2001.com/telescope.htm), the Lab is funded to polish a fast, off-axis 1.6 m mirror (as a proof-of-concept for figuring seven 8.4 m mirrors for a 30 m telescope). The end-product of the proof-of-concept will be the primary mirror for the NST (figured to $\sim \lambda/30$ with a micro-roughness of $\sim 10 \text{ \AA}$). In the partnership, they can figure the mirror as a proof-of-concept and the polished 1.6 m mirror is demonstrably scientifically useful. Our financial contribution will be the relatively nominal cost of using our astrositall blank, rather than their boro-silicate blank. The delivery date is mid-2004. We are contracting for the polishing of the secondary mirror. The funds for this phase of the project are not part of this proposal. In addition, we have the funds for the collapsible dome for the NST. As for this proposal, the removable heat stop will be a metal (like brass, covered with a reflecting layer) that will be cooled by a circulating, chilling agent operating in a closed loop. In parallel, we will undertake the initial mechanical, thermal and control systems work for which we propose support here. The budget for this phase, and the final phases of the project is given in Table 1. The total cost for the project is quite comparable to that of the GREGOR (the German 1.5 m telescope now under development).

The NST will utilize the leading-edge instrumentation developed in BBSO, in part, from prior NSF-ATM support to make unique high resolution studies of the sun. High resolution studies of the sun and its magnetic field are at the frontier of efforts to understand the nature of our variable star and its effects on human technologies. We plan for first light in early 2006, and full-time, high-resolution observations by the summer of 2006 when the work proposed here would be complete.

First light for NST will come at about the same time as the presently scheduled time for the critical design review of the ATST. Thus, NSO will have access to the NST for testing purposes. In Table 2, we list some of the technical concerns that NST will face that will guide the ATST. The NST will be nearly two orders of magnitude less expensive than the ATST. Nonetheless, it will be a significant risk mitigator for the 4-m ATST, which will have its first light several years after the NST. In the same way, the NST is benefitting from SOLAR-C (0.5-m off-axis coronagraph, Kuhn et al., REFERENCE). In particular, mirror cell support technologies, thermal issues, active optics and computer control are common concerns that will benefit the NST and SOLAR-C by a teaming of BBSO, the SOLAR-C group at UH, and NSO in a

Feature	NST	ATST	Details or Trade-off
Primary mirror support	Blank is 10 cm thick (looks like a portion of ATST)	Blank is 10 cm thick	Electro-mechanical or hydraulic support system
Secondary mirror tilt of 0.001° ($3.6''$) (+X direction)	It changes Strehl ratio from 0.99 to 0.99	It changes Strehl ratio from 0.99 to 0.36	Needs a special control system to maintain the telescope alignment How does it work?
Secondary mirror de-center of 0.02 mm (+X direction)	It changes Strehl ratio from 0.99 to 0.95	It changes Strehl ratio from 0.99 to 0.69	Need a special control system to maintain the telescope alignment How does it work?
Primary Mirror Seeing	Cooled and clean airflow from an air knife (knives) above the mirror	Cooled and clean airflow from an air knife (knives) above the mirror	What temperature below the ambient is better? What flow speed is better for current wind speed?
Heat-stop mirror seeing	A removable reflective Heat-stop mirror	Under development	How small-scale plume turbulence affects AO system performance
AO issues	A prototype of the current NSO-BBSO high-order AO used	A prototype of the current NSO-BBSO high-order AO used	How to optimize them to larger apertures?

Table 2: NST and ATST are off-axis Gregorian telescopes with similar optical layouts and similar technical (optical) requirements for obtaining diffraction-limited image quality. This table shows some of the concerns that would be first faced by the NST and would then be applicable to the ATST.

way that highly leverages NSF funds. In detail, the ATST faces the same four aforementioned technical issues and the effort of ATST engineers can be used to deal with these problems for the NST. Steve Keil (Director, NSO and PI, ATST)/Thomas Rimmele (NSO, Project Scientist ATST) (PLACEHOLDER???) will be the co-PI here to ensure a coordination of effort. The MRI support will leverage the ATST staff, and in 2005-6 they can use the NST for engineering runs. We are also working with the GREGOR team (1.5-m on-axis solar telescope scheduled for first light in 2006???, REFERENCE) on thermal control issues for the NST. The NST is a university-based facility meant to make sustained, campaign-style, high resolution observations of the sun, and will be in a position to extract the maximal science from upcoming space missions, like SDO (Solar Dynamics Observatory, launch 2007), STEREO (Solar TERrestrial RELations Observatory, launch 2006) and SOLAR-B (launch 2006). Whereas, the ATST will be a national facility, typically serving individual investigators for a week, or so, at a time. In addition to being a risk mitigator for the technical issues in bringing the ATST to fruition, the NST will sharpen many of the scientific issues that the ATST is being built to address concerning the fundamental nature of our dynamic star.

The observed magnetic field of the sun is generally regarded as being composed of conglomerations of individual fibers (or “fluxtubes”, as they are also known) of the field. Although, Nordlund (?) has used his simulations to question the existence of fluxtubes, arguing that fields exist at smaller and smaller scales. Now, individual fluxtubes are generally thought to have cross sections of order 100 km. With the 1.6-m NST, we could probe the tubes with a resolution of about 50 km, and the interfaces between the tubes when they are bundled, and sharpen our knowledge on the size distribution of the fibers (or field). Understanding small-scale solar activity is at the heart of understanding large-scale solar activity. As for the dynamics, it is critical to resolve the structures within emerging active regions, small-scale motions around the fibers. Further, what is the nature of ephemeral regions? Why do sunspots form, and what

is their structure and dynamical nature? What are umbral bright points? What is the character of the penumbral magnetic layers and the flows of adjacent fluids? What is the fine structure of flares and their relation to coronal mass ejections (CMEs)? How do flares and CMEs, and the areas around them, evolve? Why are there so many kinds of flares? How do all these phenomena vary with the solar cycle? With these, and other unsolved problems in mind, we propose to replace BBSO's 65-cm telescope with the NST. We emphasize that before the replacement, we will test the instrumentation for the NST on the 65-cm telescope. The primary instrumentation for the NST will be adaptive optics, two Fabry-Pérot based vector polarimeters (one in the visible and the other in the near infrared), and real-time image reconstruction in the visible. The NST will have 2.5 times the aperture of the our current high resolution telescope, and 2.5 times the light gathering power of the new Swedish Solar Telescope (SST) in La Palma. The NST will keep ground-based US solar astronomy on a par with that Europe until the ATST arrives.

Until recently, high resolution studies of the sun were limited because adaptive optics systems were unavailable for solar telescopes. At the heart of the problem in studying the sun, which is an extended source, was the apparent lack of a guide star, as used in night time astronomy. Even using the granular field of the sun as a "guide star" was not possible because of the lack of fast and sensitive deformable mirrors, wavefront sensors and cameras. Recently, a low order system has been built at the National Solar Observatory (NSO), Rimmele et al. (1999). Formerly, Rimmele was a postdoc in the NJIT group. In collaboration with Rimmele, we are currently building two high order adaptive optics systems – one for BBSO and one for NSO. This work is funded by NSF-AST-MRI (Rimmele, PI as an NJIT Research Professor). According to our current schedule we plan to "close-the-loop" of the BBSO system in the Spring of 2003. The BBSO high order system will be used on the planned 1.6-m telescope. As part of the BBSO effort in adaptive optics, we have assembled here in Big Bear a team of experts with long experience building instrumentation. This team will also comprise the core of our effort to implement our 1.6-m telescope and feed its light to our state-of-the-art instrumentation. The NSO adaptive optics system is also meant to be a prototype for a still higher order system for the 4.0 m ATST, which has been strongly supported in the NAS/NRC Decadal Survey (Astronomy and Astrophysics in the New Decade, 2001). Further, NSF-AST and NSF-ATM have funded the design and development phase for the ATST. NSO is just beginning the site survey process, while they lead the effort to identify what instrumentation would be needed for the ATST. In the event that BBSO were chosen as the ATST site, the NST would continue to operate and the ATST would probably be built slightly to the north and west of the NST dome. This would give the ATST an unobstructed view. Locating the ATST in Big Bear has the tacit approval of the local authorities who own and control the lake. During the construction phase, one assumes that the NSO staff would locate to the Big Bear area, vacating its sites in Arizona and New Mexico. It easy to envision that the NST would then become a primary telescope for the university community served by NSO. This would provide continuity until the ATST is on-line, and would still be valuable afterwards. In fact, independent of the siting of the ATST the data from the NST will be publicly available, which would be especially valuable to the solar community during the construction and testing phase of the ATST. One would be quite optimistic in assuming 2010 as the time of first light. It could well be that this was part of the reason that an earlier NAS/NRC study (Ground-Based Solar Research: An Assessment and Strategy for the Future, 1998), the so-called "Parker Report", urged building an intermediate aperture solar telescope first, like the one we propose. Such a telescope would be a risk mitigator of the technologies and could be done much more quickly. We plan for first light early in 2006 for the NST. Of course, this telescope would be of great scientific benefit and would likely dominate ground-based solar astronomy in the US for several years. Further, as mentioned such a telescope meant to be well-positioned to complement and provide context for NASA solar missions, such as SDO, STEREO and SOLAR-B, all of which end their planned lifetime by about 2010. Among all the current and future missions, only Solar-B will provide high resolution observations. However, the aperture of Solar-B is only 50 cm. Its diffraction limit is only one-third that of our proposed telescope. Our IR capability is also unique. For the STEREO mission, the major objective is to provide a 3-D view of CMEs. Our observations will provide valuable magnetograms and images to understand the magnetic evolution of CMEs. SDO will provide large scale, lower resolution

magnetic field observations. Our new telescope will provide complementary high resolution observations.

BBSO is an ideal site for ground-based campaign-style observations because it is characterized by excellent “seeing” conditions all day long. The atmospheric turbulence that degrades images (“poor-seeing”) comes primarily from two atmospheric layers – near the ground and at the level of the jet stream. BBSO is situated high (7,000 ft) in a mountain lake in the cloudless mountains of southern California. It is an ideal site for daytime astronomy. BBSO’s dome is located at the end of a 1000 ft long causeway jutting into the lake. The lake, with its cool waters, provides a natural inversion, and the dome has two miles of open water to its west. Since the prevailing winds are from the west, the ground-seeing problem is largely eliminated, Goode et al. (2000), and the wind comes to us in a nearly laminar flow. Another factor for the good seeing might be the east-west orientation of the Big Bear Valley acting as a wind channel. Further, since we are relatively close to the ocean, turbulence from the jet stream layer is reduced because the jet stream is calmest over the oceans.

The support at NJIT for our program remains strong. In the last year, NJIT has supported the expansion of our group to include a fourth, regular tenure-track faculty member; Carsten Denker became an assistant professor starting with the Fall 2001 semester. We have our team in place to do the work that we propose, especially with UH and NSO team members. The team includes optical, mechanical and electronics engineers. Further, this team includes students who are the future of our scientific and instrument building program. We believe that building and implementing our 1.6-m telescope will be a bridge to the future of solar astronomy in the US. The telescope, and its attendant instrumentation, will provide many new and unexpected scientific results. This will help to draw the best students into the field, and keep the field alive and vital. These students will be the true beneficiaries of the ATST, and vice versa.

BBSO highly prizes its special role in the education of the next generation of scientists who build instruments. We graduated 6 Ph.D. students between 2000 and 2002. We currently have 11 Ph.D. students (8 men and 3 women). Generally, each student builds the additional instrumentation necessary for his/her Ph.D. work. This broadens the education of the student, while strengthening the observatory. The typical new instrument needed by a solar observatory constitutes a small enough project, so that one graduate student can handle all aspects of its development. Our typical student will receive a Ph.D. in Applied Physics, Electrical and Computer Engineering or Computer Science. Such training prepares our students for a scientific career, while ensuring broader career opportunities. Our most recent graduate is now leading an infrared (IR) optics group in a New Jersey company, and he is consulting with us on the design of IR instrumentation for the ATST.

To appreciate the resolution that our 1.6-m telescope would provide, in Figure 2, we show a high resolution image of a sunspot taken on August 27, 1999 with our 65-cm telescope. In the figure, one can easily identify the dark umbra of the sunspot and the daisy petal-like penumbral fibers. In the inset on the lower right the transition from the penumbral structure to the granular field is apparent. In the lower right panel, one can see the granular field, and an occasional bright point in the lanes. The bright points are at the diffraction limit of the 65-cm telescope. These points are regarded as the fundamental fibers of the field (fluxtubes), or aggregates thereof, and with the NST we should be able to resolve them, and gain clarity on the fundamental nature of the solar magnetic field. A 1.6-m telescope in combination with AO enables us to do spectroscopy/polarimetry with essentially diffraction limited resolution!

A. 3 The 1.6-m NST

A. 3.1 Technical Overview

The NST will have an off-axis, open design (see Figure 3, which shows the layout of the open telescope including its retractable dome). We chose an off-axis design primarily because of the reduction of stray light and there is no central obscuration, which reduces the telescope’s MTF (Modulation Transfer Function) at high spatial frequencies. Further, by having the heat stop mirror outside of the optical path of the incoming light and placing an appropriate diaphragm in the path, we can expect to obtain high-contrast

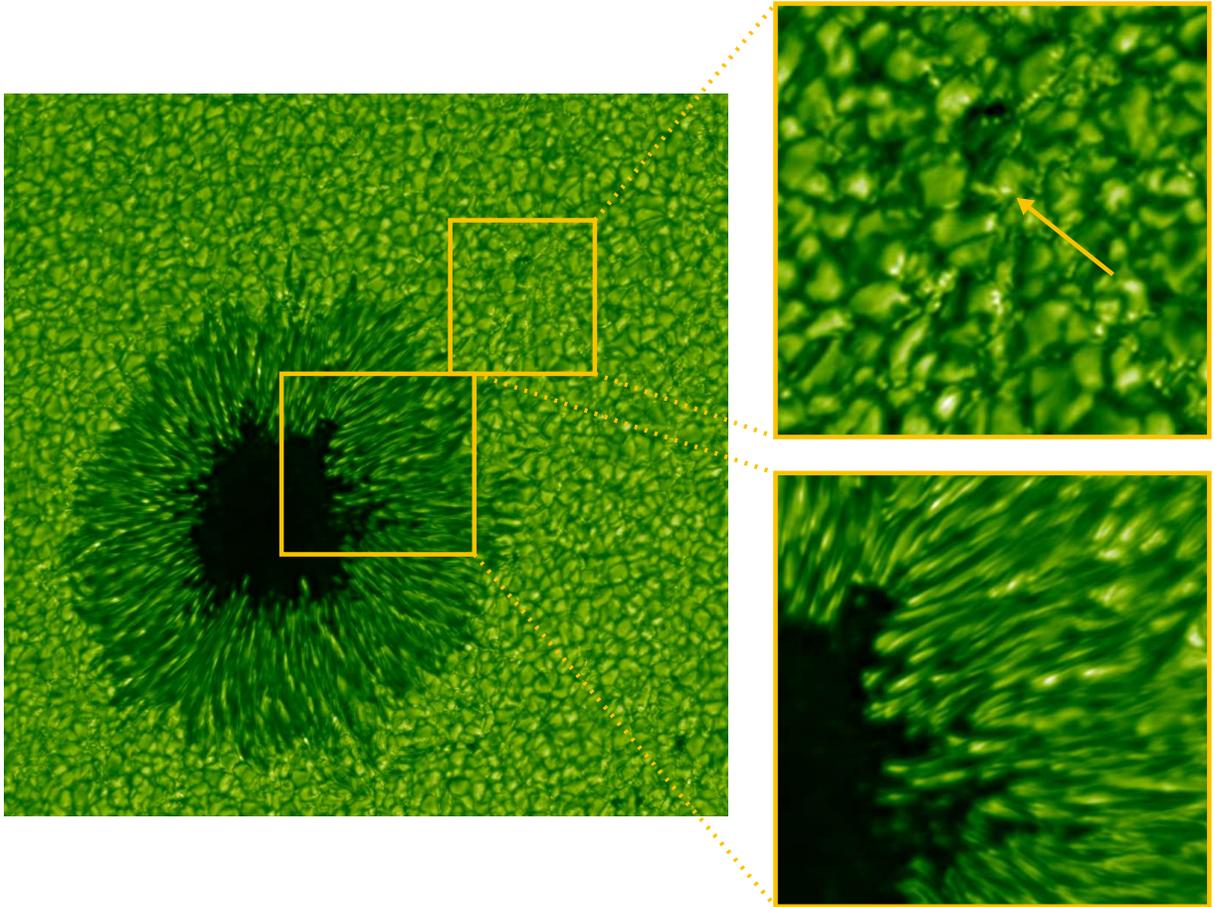


Figure 2: Image of a sunspot (NOAA 8673) taken on August 27, 1999 (520 nm with a $76'' \times 76''$ field-of-view) with the characteristic black umbral center and the penumbral fibers. Also shown are parts of the granular field as an inset. The bright points in the intergranular lane, like the one indicated by the arrow in the upper right panel, are at the diffraction limit of the telescope.

images, as if the telescope were a refractor. The telescope will utilize the current pedestal and fork of BBSO's 65-cm telescope. This is possible, in part, because the mass of the NST is comparable to that of the 65-cm telescope. However, the dome will be removed and replaced by a retractable one. We list the main features of the telescope below:

- 1.6-m aperture
- Off-axis Gregorian configuration (four mirrors – parabolic primary (M1), heat stop, elliptical secondary (M2) and diagonal flat) with cooling systems
- Figuring of M1 to $\lambda/30$ and M2 to $\lambda/15$
- 10-15 Å finishing of M1 and M2
- Open telescope structure with equatorial mount, fully retractable dome
- Real-time systems for maintaining telescope alignment
- Computer controlled pointing and tracking
- Active optics

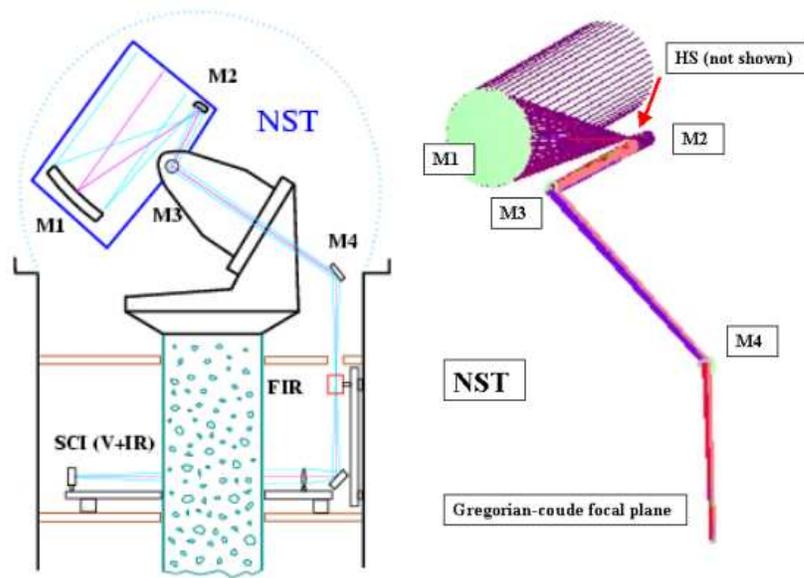


Figure 3: (Left) Schematic of the new open telescope and its retractable dome (not to scale), including the light path to the Far-IR (FIR) instrumentation (at the Gregory-Coudé focal plane) on the vertical optical table. Typically, however, the light goes to the scientific channels in the visible and near-IR, labelled SCI(V+IR), that reside on the horizontal optical tables. The optical tables are installed on the floor beneath the telescope. Far-IR instrumentation would require only a tip/tilt mirror to get diffraction-limited images. The visible and near-IR channels would be operating under the high-order AO system. We anticipate placing the polarizing optics between M3 and M4 (close to M4), where the light is nearly parallel. (Right) The optical layout of the NST with a true relative scale (a Zemax created model). The NST is an off-axis section of a conventional Gregory telescope with parabolic primary mirror M1, elliptical secondary M2, removable (for access to the primary focal plane, with a wide FOV) heat-stop mirror HS, and a flat folding mirror M3. The off-axis primary has f-ratio 2.5 (parent's f-ratio is about 0.76). The telescope's effective focal length is about 90 m with a final f-ratio of 56, which is close to that of current 65-cm telescope. The image scale in the Gregory-Coudé focal plane is $2.3''/\text{mm}$. M4, which redirects light to the floor below, and may be replaced by a tip/tilt mirror to get diffraction-limited images for far-IR instrumentation, installed on the vertical optical table.

- Adaptive optics
- Multiple focus locations that serve a variety of focal-plane instrumentation.
- 30 arcmin field-of-view (FOV) in prime focus (removing heat-stop mirror enables nighttime observations with a wide FOV).
- 3 arcmin FOV in Gregory-Coudé focus.
- 90 m effective focal length with a final ratio of $f/56$ (close to $f/52$ of the 65-cm telescope)
- Wavelength range from $0.39\text{-}1.6\ \mu\text{m}$ with AO

- All wavelengths $>0.39 \mu\text{m}$ on additional optical bench without AO
- Diffraction limited resolution of $0.07''$ at 500 nm and $0.21''$ at 1,565 nm (with adaptive optics)
- Fiber optic spectrograph for observing the earthshine spectra into the IR for determining the large-scale content of the terrestrial atmosphere
- Temperature monitoring at many points on the telescope
- Telescope optics will be made of Astrositall (CO-115m). Astrositall has an extremely low coefficient of thermal expansion (1.5×10^{-7} per $^{\circ}\text{C}$ in the temperature range -60°C to 60°C).

There are two key design issues for a large diameter open solar telescope; the first is polishing the primary and secondary to high optical quality, and the second is keeping the temperature of the mirrors the same as the air. The success of the Dutch Open Telescope has been lauded in the Parker Report; in particular, relying on the wind to limit so-called “mirror seeing”. We plan to add airknife technology to further reduce mirror seeing, because in addition to the effects of atmospheric turbulence, solar telescopes suffer from the heating of the optics by sunlight. These cause the image to shiver and become blurred. For controlling the temperature of the mirrors, the mirrors will have a high reflectivity coating, and we will use four high-precision cooling systems for M1, HS (heat stop), M2, M3 (see Figure 3). The back of the HS mirror will be cooled using circulating alcohol, while the front of the mirrors will be cooled by airknives that push (mount on the edge of half the mirror) and pull (mounted on the edge of the other half of the mirror) air above the mirrors. Airknives are used on the 4-meter SOAR (SOuthern Astrophysical Research) telescope to push/pull air from the edge of the mirror to the central hole.

Modern solar telescopes are either vacuum telescopes (like BBSO’s 65-cm telescope), and/or use careful control of the temperature of the optical elements to reduce heating of the air in the telescope. Vacuum telescopes cannot be built with large apertures because such a design requires a vacuum window of extremely high optical homogeneity, one that is as large as its aperture. In particular, a host of problems arise because of the thickness needed to withstand the enormous difference in pressure between the air and the inside of the vacuum window. In detail, it is difficult to design a vacuum telescope, if the aperture is larger than 1 m. This is the fundamental reason why the new Swedish Solar Telescope will have a 1 m aperture. Our 1.6-m telescope has been designed to be a completely open telescope with a retractable dome, to limit internal seeing. The ATST will also have an off-axis, open design, so that project will benefit from our experience.

The open design requires a stiff construction. Care will to be taken to protect the telescope from dust, and to enable it to withstand strong winds. Our typical winds are westerly at 10 km/h, and this is the condition under which we have the best seeing.

ADD SOMETHING HERE ABOUT ACTIVE OPTICS AND CONTROL SOFTWARE

A. 3.2 Telescope Optics

The telescope will use a four mirror, off-axis Gregorian configuration, see Figure 3, with an $f/2.5$ primary mirror (M1), whose shape will be parabolic. A tilted, cooled heat stop mirror (HS) at the primary focus will reject 98% of the light out of the telescope. HS will have a 3 arcmin diameter hole to pass light to M2. There is a focal plane between M1 and M2. For nighttime observations, like earthshine or searching for exo-solar planets, HS is removable. M2 will be a concave ellipsoidal secondary mirror. Next, the light from M2 will be reflected out of the telescope axis by a flat mirror M3 to the polar axis. There is a pupil plane between M2 and M3, where we can put a Lyot diaphragm to reduce stray light. A folding mirror (M3) could be the tip-tilt mirror for infrared observations. The Gregory-Coudé focal plane is along the vertical optical bench fed by M4. Relay optics feed this light to the adaptive optics system. Since the Gregory-Coudé focal plane is produced by all-reflecting optics, far infrared instrumentation may be setup on one optical table.

A. 3.3 Mechanical Structure

We will use an equatorial mount for the NST, because it allows an optical design with only two or three mirrors to bring the light to the TIP-TILT MIRROR. Equatorial-type telescopes can be lightweight and well-balanced. Its total weight will be about 5 tons, which is equal to the telescope weight presently supported by the pedestal, which includes a heavy vacuum tank. The current small telescopes on the fork will be used as counterweights for the NST. The main problems for the mechanical structure of the NST would arise from insufficient stiffness, and deformation by temperature changes. We have considered these problem seriously, and will use special systems to control and to maintain the the alignment of the NST. Also, we will use cooling systems to maintain fixed temperatures in key parts that face the sun during observations.

A. 3.4 Control Systems

We will use a Linux-based PC to control the telescope, and use a DC motor to drive the telescope and guider for tracking. The absolute encoder will be adapted for precise pointing. There are three systems for detecting and correcting improper tilt, de-center and de-focussing the NST. There are four high-precision, temperature controlled systems for the four mirrors (M1, HS, M2 and M3) with precision temperature control. There are three delicate temperature control systems for the other components of the telescope, which are needed to reduce thermal effects, with a temperature control precision that will be $\pm 0.3^\circ$ C. More than sixty temperature monitoring points will be utilized in the telescope to estimate the performance degradation by temperature fluctuations. The main control computer can exchange data with both its serial and parallel ports. Some of the details of the mechanical performance are:

- Range of Motion:
 - RA axis $\pm 180^\circ$ (south is origin)
 - DEC axis $+10^\circ$ to $+80^\circ$
- Speed range:
 - RA axis $1''/s$ to $1^\circ/s$
 - DEC axis $1''/s$ to $1^\circ/s$
- Pointing accuracy:
 - $5''$
- Tracking accuracy:
 - $1''/5$ min (without sun guiding)
 - $1''/10$ min (with sun guiding)
- Characteristics of special systems to maintain the alignment of the NST:
 - M2 tilting (detecting and correcting to better than $\pm 5''$)
 - M2 de-centering correction (to better than $\pm 20 \mu\text{m}$)
 - M2 shifting (to better than $\pm 50 \mu\text{m}$)

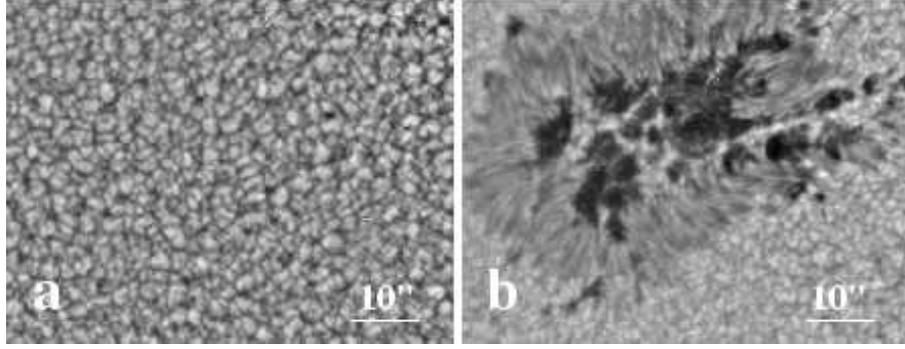


Figure 4: Unprocessed, single exposure (0.13 ms) IR images of the quiet sun and a sunspot region, demonstrating our excellent image quality.

A. 4 Adaptive Optics

The proposed 1.6-m telescope will enable us to solve many of the outstanding problems in solar physics, especially those requiring higher resolution studies of the sun than are currently possible. As well, the telescope will occasionally function as a “light-bucket” collecting photons for higher temporal cadence, lower spatial resolution observations. However, the key to many of the most intriguing questions lies in observations with the highest possible spatial resolution. Not only does one require a large aperture telescope and a site, like BBSO, where adaptive optics can correct images to the diffraction limit, but we also need a high order adaptive optics system. NSF-ATI has funded the construction and implementation of two high order systems (97 actuators) – one at BBSO and one at the DST of NSO. The BBSO system will be used for the 1.6-m telescope after upgrading the deformable mirror system, if necessary.

The need for adaptive optics is made clear by considering the Fried parameter (roughly speaking, the largest aperture telescope that would be diffraction limited) at even an excellent daytime site, like BBSO. A good site has a Fried parameter of about 10 cm in visible light (500 nm). At BBSO, we sometimes have upwards of 20 cm. As good as this might be, it is small compared to a 1.6-m aperture. This problem can be partly solved by post-facto image reconstruction, as discussed here in Section D.3. We estimate that under our typical good seeing, we will correct to a Strehl ratio (intensity ratio of corrected image to the true diffraction limited image) of about a steady 0.4-0.5 in the middle of the visible spectrum, which bodes well for the adaptive optics system maintaining “lock”, so that we will have steady diffraction limited observations. Once the upgraded AO system is working in the visible, the IR performance should be even better since the Fried-parameter r_0 , the isoplanatic angle θ_0 , and the Greenwood time delay τ_0 scale with $\lambda^{6/5}$ and the number of control parameters of the AO system even scales with $\lambda^{-12/5}$, implying that a visible light Fried-parameter of about 10 cm translates to one of order $r_0 = 40$ cm at 1,565 nm, and the Strehl ratio is significantly higher than in the visible. Further, we have evidence in short-exposure, frame selected NIR images that the isoplanatic angle can exceed $80''$, see Figure 4. In summary, with the AO system working, we might be able to correct the full FOV of $180''$ of the 1.6-m telescope in the NIR at 1,565 nm without upgrading the current AO system and without the need for multi-conjugate AO. For studies in the far infrared, we note that for a wavelength of $5\mu\text{m}$, the anticipated Fried parameter is comparable to the telescope aperture, so one needs only a tip-tilt correction.

At BBSO, we have completed the design of our AO system and are implementing it (Didkovsky et al., 2002), and expect it to close-the-loop in the Spring of 2003. For the 1.6-m telescope, we will have to only slightly modify the light feed, and possibly upgrade the deformable mirror (DM) system. We estimate this downstream cost to be about \$300 K. The light from the telescope is fed to the optical laboratory on the floor beneath the telescope. Here, we give some details of the system, and show its optical layout in Figure 5. As designed, the system uses a small, elliptically shaped ($a = 45$ mm, $b = 25$ mm) Tip/Tilt mirror installed at the end of the existing Coudé optical path, and a DM with a sufficient number of subapertures

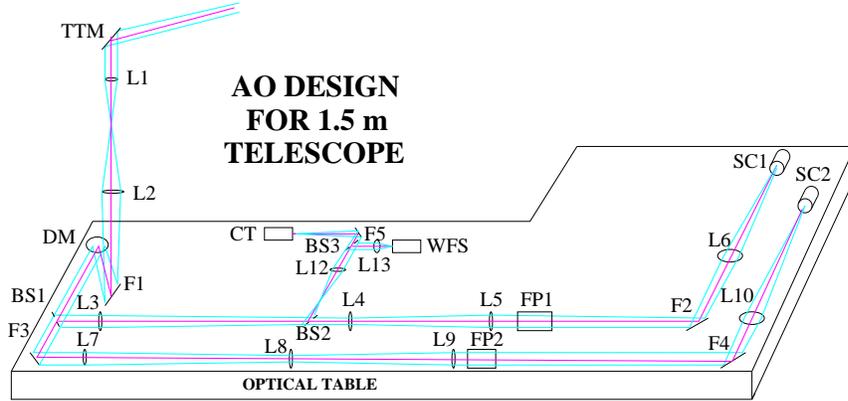


Figure 5: The optical layout of the BBSO adaptive optics system for the 1.6-m telescope (not to scale). TTM guides the light from the telescope to the optics laboratory on the floor beneath. “DM”, “F”, “BS”, “CT”, “WFS”, “PFI” and “SC” mean deformable mirror, folding mirror, beam splitter, correlation tracker, wavefront sensor and science cameras, respectively.

installed together with wavefront sensors (combined fast correlation tracker and Shack-Hartman sensors) with scientific channels (visible and IR, called SC1 and SC2 in Figure 5) on the optical tables. The two-axis Tip/Tilt platform has a resonant frequency around 3.3 kHz and tilting range of about 2 mrad, which corresponds to about 25'' in the sky. With 32×32 pixel frames, the correlation tracker sensor can detect 2 kHz differences between a reference frame and real-time frames. The WFS channel will use either a 260×260 pixel Dalsa camera, or a 1280×1024 Photobit camera (2 by 2 binning), with a frame rate of more than 2000 frames/s for detecting high-order atmospheric aberrations of the wavefront. Both scientific channels will utilize Fabry-Pérot etalons (FP1 and FP2) in telecentric configurations for imaging polarimetry (magnetographs). The optical design for these channels allows using small aperture prefilters (interference or Lyot) and 70 mm diameter Fabry-Pérot etalons with field-of-views about 180'' (IR) and 170'' (visible), respectively. The visible and IR imaging magnetograph channels with spatial resolution of about 0.2''/pixel may work simultaneously with a signal-to-noise ratio of about 400 and 600 for a 0.25 sec integration time. This performance is nominal and quite satisfactory for our needs. Thus, the adaptive optics system will feed the downstream scientific instrumentation.

A. 5 New Scientific Instrumentation for the NST

There are several on-going instrumentation projects at BBSO. Here, we sketch the ones that will benefit the most from the adaptive optics, while making optimal use of the larger aperture of the 1.6-m telescope.

A. 5.1 Visible Light Vector Magnetographs

Our project to make a new Digital Vector MagnetoGraph (DVMG) system has been completed (Spirock et al., 2001). The DVMG uses a 1K×1K pixel CCD camera (12-bit, 15-30 frames/s), and has no moving parts. The DVMG has markedly increased the sensitivity and accuracy of our magnetograms – representing a significant improvement over the old, supplanted videomagnetograph. The operational DVMG system serves as the basic model for the first of our two new Fabry-Pérot filter-based magnetograph systems, which will yield absolutely calibrated vector magnetograms. The approach here reflects our approach to instrumentation in general – each new system builds on its predecessor. The DVMG was built on an earlier version that could not measure vector fields. The Visible light Imaging vector Magnetograph (VIM) – which will use a Fabry-Pérot etalon – will utilize the DVMG experience. The DVMG is part of the Ph.D.

thesis work of Tom Spirock. With the VIM, we will be able to make much more accurate and higher resolution measurements of the evolving magnetic fields in flare-producing active regions. The VIM will reside on the optical bench, as indicated in Figure 5 by FP1 and FP2, while its polarizing optics will lie on the 1.6-m telescope to minimize polarization problems arising from the downstream mirrors. The VIM will use its Fabry-Pérot filter to provide the spectral line profile and the full Stokes vector when observing photospheric magnetic fields. This improvement will preclude Zeeman saturation where the fields are strong (in sunspots), and it will also provide filling factors for weaker fields. We have all the necessary hardware in hand, and expect to complete the VIM by the end of 2003.

A. 5.2 Infrared Vector Magnetograph

We have developed a narrow bandpass filter system, which combines a Lyot filter and an IR Fabry-Pérot filter – the Infra-Red Imaging vector Magnetograph (IRIM). A recent NJIT Ph.D. graduate, Jingshan Wang designed and developed the IR Lyot filter. We have our operational IR Fabry-Pérot in hand. Our one-of-a-kind Lyot filter has a bandpass of 0.25 nm at 1.56 μm , giving us a 0.25 nm wide prefilter (narrower than the 0.5 nm free spectral range of the IR Fabry-Pérot). This will solve the longstanding problem of constructing a filter-based IR magnetograph, while avoiding the complications of using a double (or even triple) etalon system. At this time, regularly operating, stable dual etalon IR systems do not exist. We expect the first generation of the IRIM to be on-line shortly after the VIM. We have purchased a large format, high frame rate IR CMOS camera ($\sim 1\text{K}\times 1\text{K}$, 30 frames/s ???) from Rockwell Scientific Imaging and expect delivery early in 2003.

The VIM and IRIM will be able to operate simultaneously, which means we can obtain high resolution observations of the sun’s structure at different altitudes in the solar atmosphere. The VIM and the subsequent IRIM (FP2 and SC2 in Figure 5) systems will be located in the Coudé Room one floor beneath the telescope, but like the VIM the polarization optics will reside on the 1.6-m telescope. We expect the IRIM to be ready a year after the VIM. The optical design for this project is coordinated with the one for the adaptive optics project and the NST. The VIM, IRIM, and the real-time image reconstruction system have all been designed for diffraction limited observations, i. e., the photon flux per diffraction limited resolution element is constant. Therefore, only the transfer optics have to be modified to accommodate the NST.

A. 5.3 Real-Time Image Reconstruction

In recent years, post-facto image processing algorithms have been developed to achieve diffraction limited observations of the solar surface. We are about to use the speckle masking imaging technique, in combination with a parallel computer built of 32 1.8 GHz AMD Athlon processors, to yield near real-time time-series with a cadence of approximately 1 min, which is sufficient to resolve the evolution of solar surface phenomena, such as granulation, pores, sunspots and including the fine-structure of sunspot umbrae and penumbrae. We emphasize that there is no such system in existence at any observatory. Our first observations are scheduled early in 2003. Without the parallel computer, the processing time for each data set ranges between one-half to 16 hours, depending on image size and truncation of the speckle masking bi-spectrum. This effectively limits us to a short observing day (~ 2 hours) because the controlling computer’s disk is filled by storing all the raw data, so the chances are slim of obtaining a sequence containing the long term evolution of an active region, and catching flares during the observations. Further, we will not know if we have been lucky until the next day.

Initially, we used a 4-node system to develop and test the needed software for the 32-node system (Denker et al., 2001). Recently, we adapted and applied that software to our 32-node system at NJIT, and the system is ready to ship to BBSO for use in taking real-time data. Speckle masking imaging requires a sequence of short-exposure images (less than 10 ms) to “freeze” the wavefront aberrations, which makes it possible to separate the object information from the information on atmospheric turbulence. The first

steps in preprocessing the data concern the usual corrections by means of the average dark and flat field image. Diffraction limited images will be obtained at a one minute cadence.

We note that when our adaptive optics system is in place, it will aid the reconstruction and provide a powerful test of it, but it will not replace the need for speckle reconstruction, because the adaptive optics system fully corrects on a single isoplanatic patch (of order a few arc seconds in extent at 500 nm) with decreasing correction for more distant patches. Only multi-conjugate adaptive optics would fully correct the entire field of view. There is no such system in existence at this time. Our new parallel computing system will only save reconstructed image data, and therefore, the disk will be big enough for several days of continuous observation.

Parallel processing of solar data will literally provide a new window through which we can observe the sun in exquisite detail, and study the evolution of granulation, sunspots, prominences, and flares. For highly dynamical features, such as flares, the parallel processing will be useful in determining, say, the evolution of the photospheric structures that trigger the dynamic phenomena. For parallel processing, the underlying data processing algorithms are understood, but the complexity is such that only parallel computing enables us to visualize and interpret large data sets effectively.

A. 6 New Science from the NST

The science planned for the NST is motivated by observations done using our current 65-cm telescope. Of course, these problems are of broad interest in solar astronomy.

A. 6.1 High Resolution, High Cadence Studies of Solar Flares

With observations of unparalleled resolution from BBSO's NST, we will make significant progress, which would otherwise be beyond our reach, in our on-going efforts to understand solar flares.

High cadence X-ray and microwave observations have revealed a temporal fine structure (sub-second) in solar flares, called elementary flare bursts (see the review paper by Sturrock, 1989). These may be attributed to the fine structure in coronal magnetic fields, which are related to the aggregation of photospheric magnetic fields into "magnetic knots". Very recently, the BBSO group has experimented with high cadence flare observations (Wang et al., 2000, Qiu et al., 2000, 2001, 2002), probing the far blue wing of $H\alpha$ with a cadence between 10 ms to 33 ms and an image scale of $0.5''$. In particular, Wang et al. (2000) found the $H\alpha$ source of sub-second hard X-ray bursts. Qiu et al. (2002) studied the footpoint shifts of flare kernels and derived the DC electric current as a function of time. This current was found to be coincident with the hard X-ray temporal profile, and therefore, clearly revealed the flare acceleration mechanism.

The 1.6-m telescope can obtain high resolution, high cadence images of flares in wavelengths such as HeD_3 and off-band $H\alpha$. These observations will provide details of electron precipitation on fine temporal and spatial scales. By combining high cadence optical imaging with hard X-ray imaging from missions (such as a future mission replacing the Ramaty High Energy Solar Spectroscopic Imager (RHESSI)), as well as with high resolution magnetograms, we expect to learn if and how, the individual sub-second peaks in the hard X-ray and microwave time profiles correspond with the rapid precipitation along various flux loops. Since the 1.6-m telescope will provide a spatial resolution of ≈ 50 km in the visible wavelength region, we will be able to determine whether the moving flare kernels have such a small scale. At this moment, our resolution is only about 300 km under excellent seeing conditions and without image correction. Including adaptive optics on our current 65-cm telescope, we anticipate 150 km resolution under most observing conditions. With the 1.6-m telescope, under better than average seeing conditions, we anticipate 50 km resolution. The 50 km scale is important, since many models predict this value for the cross section of fluxtubes, see Schüssler (2001).

A. 6.2 Structure and Evolution of Magnetic Fields in Flaring Active Regions

We plan to use the NST to answer the following questions: (a) What is the role of the evolution of the photospheric magnetic field in triggering solar flares, and what is the relationship between the magnetic configuration and the properties of flares? (b) How do electric currents evolve, and what is their relationship to particle precipitation?

It is generally accepted that the energy released in solar flares is stored in stressed magnetic fields. So, the study of magnetic fields is a very important component of flare science. This concept of energy release has motivated many attempts to detect flare-induced changes in the magnetic fields of active regions.

So far, no one has detected, in any consistent way, the changes in magnetic fields associated with solar flares. The inconsistency of the results is due to observational limitations. We cannot get high temporal and spatial resolution, as well as high polarization accuracy at the same time, with existing telescopes/instruments. Our new, large telescope will provide much more reliable and high quality measurements of vector magnetic fields. A lot of the ambiguities discussed above will be resolved with the new higher resolution, higher cadence data. In addition to the temporal and spatial resolution mentioned earlier, the precision of the polarimetry would be on the order of 10^{-4} . With the improved accuracy of our vector magnetograph system, studies of more examples of evolving magnetic fields, and active regions, and changes due to flares will provide the evidence needed to lead us to understanding the process of flare energy release, and the role of photospheric magnetic fields therein.

A. 6.3 Dynamics of Kilogauss Flux Tubes

One of the major breakthroughs in solar physics during the last 40 years has been the discovery that most photospheric magnetic flux that is measurable in visible light, via Zeeman polarization, appears outside of sunspots in the form of small scale flux concentrations with field strengths of typically 1 to 2 kG. Evolving from this discovery is the picture of small fluxtubes with typical sizes of a few tens to a few 100 kilometers, as building blocks of plage and network magnetic fields. Sophisticated Magneto-HydroDynamic (MHD) models now offer a variety of predictions that need to be tested. Also, precise measurements are necessary in order to define boundary conditions for these models.

The main questions about the dynamic behavior and structure of small scale kilo-Gauss fluxtubes, which need to be addressed with the 1.6-m telescope, concern the formation of photospheric flux concentrations with field strength above the equipartition field strength, and the dynamic interaction with the turbulent photospheric atmosphere. The observational verification of the process(es) that leads to kilo-Gauss flux concentration in the solar photosphere, where the equipartition field strength is only about 500 G, is a fundamental problem in solar and stellar physics that needs to be solved, and better than 100 km resolution is critical to resolve this problem.

Understanding the dynamic interaction of photospheric flux concentrations with turbulent granulation is essential in order to estimate the total energy flux that is transmitted/channelled by small-scale fluxtubes into the higher atmosphere.

Here we list basic science questions that can only be addressed with a 1.6-m telescope (as opposed to our current 65-cm telescope):

- How are fluxtubes formed and how do they evolve?
- What is the lifetime of a fluxtube?
- How do the fluxtubes interact with turbulent flows in the photosphere?

A. 6.4 Magneto-Convection in Sunspots

With the appreciably higher resolution of the NST, combined with powerful tools in visible and IR imaging, we will make substantial progress in answering the following questions:

- What are the origin and dynamics of umbral dots: oscillatory convection vs. field free plumes.
- What is oscillatory convection? – test model predictions.
- What is the sub-photospheric structure of sunspots – the 3-D structure of sunspots.
- What are the origin and dynamics of umbral and penumbral oscillations?
- What are the origin and dynamics of penumbral fine structures?.
- What is the size distribution of penumbral filaments?
- What are MHD waves in sunspots? – test model predictions.
- Are there oscillations in the umbral magnetic field strength?

A. 6.5 Heating of Upper Atmosphere

Recently, there have been some significant advances in the research on the origin of coronal heating. Our new telescope will provide breakthroughs in this area for two reasons:

(1) We will provide direct measurements of magnetic reconnection rates in the quiet sun with magnetograms that have 3 times better resolution or 10 times better sensitivity (or a compromise between the two) with the 1.6-m telescope than with our current telescopes. By keeping the same pixel resolution we have now, but using the 1.6-m telescope as a light bucket, we can obtain a sensitivity of about 0.1 G for the line-of-site component of the magnetic field. Alternatively, if we go for maximal spatial resolution – assuming a nominal circular FOV of $180''$ and an image scale of $0.17'' \text{ pixel}^{-1}$, we estimate that IRIM's sensitivity is 1 G for the line-of-sight component and 5 G for the transverse component of the magnetic field. Either way, we will be able to detect a lot more intra-network fields and their interaction with network fields. Therefore, we will be able to accurately measure the energy released during the reconnection of these fields.

(2) Parker (1988) proposed that the X-ray corona is due to a continuous nanoflaring process. The energy source of these nanoflares is from the random motion of footpoints. So the observations of footpoint motions associated with all the above events is essential. We know that such footpoint motion is hard to observe and characterize in lower resolution observations with the current system. We plan to detect and characterize such footpoint motions with $0.1''$ spatial resolution, using real-time speckle constructed images. As G-band images show fluxtubes very well, we will use our G-band filter to observe for this part of the research. We expect to learn the correlation between footpoint motions and brightness of overlying EUV/X-ray loops.

A. 7 Project Management

Goode is the PI on the project and has overall responsibility for the project. Dr. John Varsik (BBSO/NJIT) will be the Project Manager (half-time responsibility). He is an experienced astronomer with a thorough knowledge of instrumentation hardware and computer control software.

Each individual piece of the project will be the responsibility of one person who will coordinate with Goode and Varsik, as well as the leaders of the other pieces of the project. In detail, Dr. Leonid Didkovsky (BBSO/NJIT) will be responsible for the optics and mechanical structure and associated issues. Dr. Didkovsky was a key person in the construction of the Russian-Ukrainian-German-Italian 1.7 m SPECTRUM-UV Space Telescope (awaiting launch). Dr. Carsten Denker (BBSO/NJIT, co-PI) will be responsible for the thermal control. Much of the mechanical and thermal manufacturing can be done at NJIT manufacturing facility under the direction of Dr. Joe Molnar. Dr. Steve Keil (NSO, co-PI)/Thomas Rimmele (NSO, co-PI)/Dr. Jeff Kuhn (UH, co-PI) will be responsible for the heat stop mirror, computer control systems and thermal control of the primary. Dr. Varsik will be in charge of the computer control

systems (half-time). Each key person will have people reporting to him... OVERLAPPING RESPONSIBILITIES, BUT THEY ARE NOT YET DIVIDED.

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