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1.6 M SOLAR TELESCOPE IN BIG BEAR – THE NST

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ABSTRACT

New Jersey Institute of Technology (NJIT), in collaboration with the University of Hawaii (UH), is upgrading Big Bear Solar Observatory (BBSO) by replacing its principal, 65 cm aperture telescope with a modern, off-axis 1.6 m clear aperture instrument from a 1.7 m blank. The new telescope offers a significant incremental improvement in ground-based infrared and 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) will use the existing BBSO pedestal, pier and observatory building, which will be modified to accept the larger open telescope structure. It will be operated together with our 10 inch (for larger field-of-view vector magnetograms, Ca II K and Hα observations) and Singer-Link (full disk Hα, Ca II K and white light) synoptic telescopes. The NST optical and software control design will be similar to the existing SOLARC (UH) and the planned Advanced Technology Solar Telescope (ATST) facility led by the National Solar Observatory (NSO) – all three are off-axis designs. The NST will be available to guest observers and will continue BBSO's open data policy. The polishing of the primary will be done in partnership with the University of Arizona Mirror Lab, where their proof-of-concept for figuring 8 m pieces of 20 m nighttime telescopes will be the NST's primary mirror. We plan for the NST's first light in late 2005. This new telescope will be the largest aperture solar telescope, and the largest aperture off-axis telescope, located in one of the best observing sites. It will enable new, cutting edge science. The scientific results will be extremely important to space weather and global climate change research.

Key words : Sun: instrumentation

I. INTRODUCTION

The highest resolution solar telescopes currently operating are in the sub-meter class, and have diffraction limits which allow them to resolve features larger than 100 km in size on the sun. They are often photon-starved in the study of dynamic events because of the competing need for diffraction limited spatial resolution, short exposure times to minimize seeing effects, and high spectral resolution to resolve line profiles. Thus, understanding many significant and dynamic solar phenomena remains tantalizingly close, but just beyond our grasp.

We will replace the 65 cm vacuum telescope at Big Bear Solar Observatory (BBSO) with a modern, open, off-axis, 1.6 m clear aperture solar telescope – the NST (New Solar Telescope) of which a schematic view is shown in Figure 1. The NST will use the pedestal of the 65 cm instrument. First light will be in late 2005, with full operation early in 2006. The NST will utilize the current and planned complement of BBSO instrumentation. This includes visible and infrared (IR) Fabry-Pérot-based polarimeters and real-time phase-diversity speckle imaging instrumentation. A high-order Adaptive Optics (AO) system, which is now under development, will deliver light to each of these instruments. The NST will utilize our instrumentation that is being developed 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.

The total base cost of the replacement telescope is comparable to the cost of the planned 1.5 m German GREGOR telescope (the German 1.5 m on-axis telescope now under development and scheduled for first light in 2006, see gregor.kis.uni-freiburg.de). One significant cost driver would be expected to be the polishing of the primary mirror. However, it will be polished in partnership with the University of Arizona Mirror Lab. As part of their 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 twin 21 m telescopes). The end-product of the proof-of-concept will be the primary mirror for the NST.

The NST project is a collaboration of BBSO/NJIT and the University of Hawaii (UH). Both operate ground-based solar observatories and are leaders in space weather studies. The NST project will also benefit from a close

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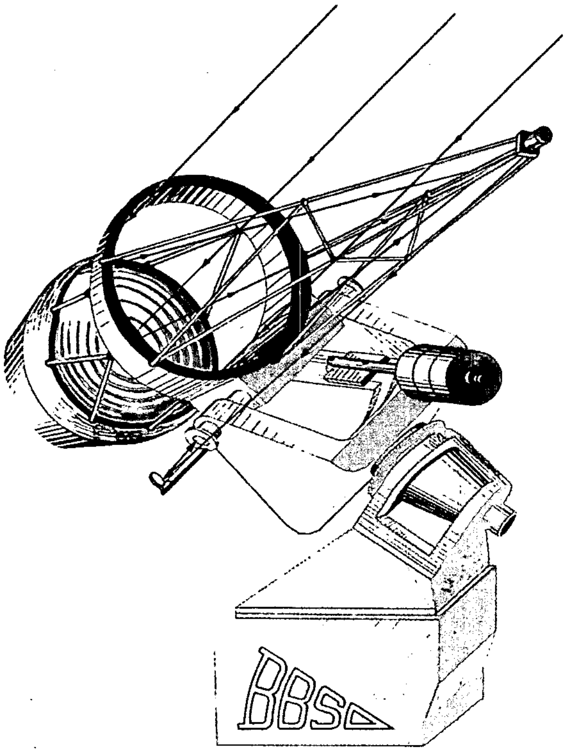

Fig. 1.— Schematic of the 1.6 m off-axis, open NST for which the primary mirror is as close to the declination axis as possible. The optical path is indicated. There is a Nasmyth-focus along the declination axis, where we can put instrumentation. In this design, the coudé mirror is simply a flip mirror to re-direct light from the declination axis to the floor below, where the AO and principal instrumentation reside.

working relationship with the National Solar Observatory (NSO) team that is currently designing the Advanced Technology Solar Telescope (ATST). In addition, we maintain collaborative discussions with the GREGOR group, and will share design information, especially that related to thermal modelling of the NST and GREGOR.

BBSO and UH operate in sustained observing campaigns using multi-wavelength spectroscopic and filter-based magnetic field measurements. These campaigns have been a key to understanding the mechanisms of space weather. The NST will deliver significantly higher angular resolution in the magnetically sensitive FeI 1.56 μm infrared lines (0.2″) and enhanced temporal sensitivity and resolution (0.07″) at shorter visible spectral diagnostic wavelengths.

The NST will provide leading-edge capabilities to the NSF community and will be the world's largest aperture solar telescope until the ATST comes to fruition. Even then, the NST will have a critical role in space weather studies by generating and providing synoptic space weather data.

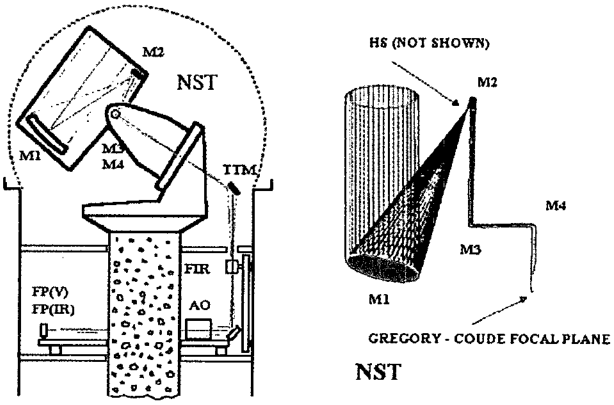

Fig. 2.— (Left) Schematic of the new open telescope and its retractable dome (not to scale). Typically, the light goes to the Fabry-Pérot-based scientific channels in the visible and near-IR, labelled FP(V) and FP(IR), which reside on the horizontal optical tables. The optical tables are installed on the floor beneath the telescope. Future Far-IR (FIR) instrumentation would require only a tip/tilt mirror (TTM) to get diffraction-limited images. The visible and near-IR channels would be operating downstream of the high-order AO system. We anticipate placing the polarizing optics between M2 and M3, 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, flat folding mirrors M3 and M4 (coudé mirror). M3 is a fixed folding mirror. The off-axis primary has an f-ratio 2.4 (parent's f-ratio is about 0.73). The telescope's effective focal length is about 80 m with a final f-ratio of 50, which is close to that of the current 65 cm telescope. The image scale in the Gregory-coudé focal plane is 2.6″/mm. TTM redirects light to the floor below to get diffraction-limited images for far-IR instrumentation.

The 65 cm telescope remains a potent scientific instrument and will be donated to Prairie View A&M, which has an active observational solar physics research program with its 35 cm telescope (for details see www.pvamu.edu/cps/solar.html). Prairie View A&M is the second largest, and an historically black university in the Texas A&M system.

II. HERITAGE AND GOALS OF THE NST

The largest coronagraph and infrared solar telescope is the NASA and AFOSR-funded UH SOLARC instrument on Haleakala (Kuhn et al. 2002). Although its small aperture makes it unsuitable for high resolution photospheric observations, its optical performance has been important in establishing that a relatively fast, off-axis configuration can be successfully extrapolated and implemented in the NST. SOLARC has established that the collimation, alignment, and scattered light performance we expect from NST can be achieved with the off-axis design.

NST benefits from the SOLARC experience and their common technical issues (mirror cell support technologies, thermal design, active optical alignment, control and software). Similarly, the ATST project has common technical hurdles. Our informal collaboration with NSO and ATST engineers will benefit both projects.

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 on solar dynamics and the origin of space weather, from upcoming space missions, like SDO (Solar Dynamics Observatory, launch 2007), STEREO (Solar TErrestrial RElations Observatory, launch 2006) and SOLAR-B (launch 2006). All of these are near the end of their planned lifetimes by about 2010, which is the currently scheduled first light for the ATST. Among all the current and future missions, only Solar-B will provide high resolution observations. The aperture of Solar-B is 50 cm, which is about 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 vector 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.

In contrast, the ATST achieves a resolution that reaches the photospheric density scale length with a light-gathering power an order of magnitude greater than NST. The ATST coronagraphic capabilities for detecting coronal magnetic fields are fundamental and unique and, unfortunately, beyond the capabilities of the NST. When the ATST comes on-line, in contrast to the NST, will be a facility, formally responsive to the national and international research communities. Nevertheless, the NST has an important role as it sharpens some of the questions concerning the fundamental nature of our dynamic star, which the ATST is being built to address; and even after the advent of the ATST, the NST will be essential in campaign-style observations, which are at the heart of studies to determine the character and origin of space weather.

III. NST, BBSO AND OTHER SOLAR OBSERVATORIES

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, jet stream turbulence is reduced because the jet stream is calmest over the oceans.

A 1.6 m telescope in combination with AO will enable us to do spectroscopy/polarimetry with essentially diffraction limited resolution! We emphasize that before the replacement, we will test the instrumentation for the NST using 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 is a logical successor to 0.5 m SOLARC and the comparable aperture Dutch Open Telescope in La Palma. It will have 2.5 times the aperture of 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 also improve on the optical performance of the future conventional (on-axis) 1.5 m GREGOR telescope.

BBSO has an open data policy, and our telescopes are available to users by application to our website, www.bbso.njit.edu. We generate about 10 GB of data per day and that is dominated by our synoptic data from our small telescopes. We expect that dominance to continue with the NST, so making the NST data publicly available does not present a data storage problem.

Until recently, high resolution studies of the sun were limited because adaptive optics systems were unavailable for solar telescopes. At the heart of the solar AO problem is that the sun is an extended source, with an apparent lack of a guide star (as used in nighttime astronomy). Even the use of 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 (24 actuators) has been built at the National Solar Observatory (NSO), Rimmele et al. (1999). In collaboration with Rimmele, we are currently building two high order (97 actuators) adaptive optics systems – one for BBSO and one for NSO. According to our current schedule we plan to "close-the-loop" of the BBSO system in the Summer 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).

IV. SCIENCE DRIVERS FOR THE NST

The observed magnetic field of the sun is generally regarded as being composed of conglomerations of individual fibers (or "flux tubes"), and establishing the nature of the individual fibers depends on critical magnetic observations with higher spatial resolution. Many believe that individual flux tubes have cross sections of order 100 km. With the 1.6 m NST, we can explore spatial scales as small as 50 km and test flux models of fibers and tubes. Understanding this small-scale solar activity is at the heart of understanding large-scale solar activity and the origins of space weather.

(a) High Resolution, High Cadence Studies of Solar Flares

The improved resolution we achieve from BBSO's NST allows flare imagery and spectroscopy that would otherwise be beyond our reach. High cadence X-ray and microwave observations have revealed a temporal (sub-second) fine structure in solar flares, called elementary flare bursts. 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 Hα with a cadence between 10 ms to 33 ms and an image scale of $0.5''$. In particular, Wang et al. (2000) found the Hα source of sub-second hard X-ray bursts. Qiu et al. (2002) studied the footpoint shifts of flare kernels and derived the DC component of the 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 He D_3 and off-band Hα. 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 Sprectroscopic 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. Currently, our resolution is only about 300 km under excellent seeing conditions and without image correction. With 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 flux tubes (see Schüssler 2001).

(b) 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 and 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. Many of the questions 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 in 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.

(c) 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 flux tubes 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 flux tubes, 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. How are flux tubes formed and how do they evolve? What is the lifetime of a flux tube? How do the flux tubes interact with turbulent flows in the photosphere? 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 flux tubes into the higher atmosphere.

(d) Heating of the 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-sight 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″ pixel^{-1} – we estimate a sensitivity of 1 G for the line-of-sight component and 5 G for the transverse component of the magnetic field in the IR. Either way, we will be able to detect more intranetwork 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.

V. THE 1.6 M NST

(a) Technical Overview

The NST will have an off-axis, open design (see Figure 2, 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, since 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 images, as if the telescope were a refractor. The telescope will utilize the current pedestal 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. To make the telescope open, the current dome will be removed and replaced by a retractable one. We list the main features of the telescope below:

- 1.6 m clear aperture (1.7 m primary)
- Off-axis Gregorian configuration (four mirrors – parabolic primary (M1), heat-stop (HS), elliptical secondary (M2) and two diagonal flats) with cooling systems
- Figuring of M1 to $\lambda/30$ and M2 to $\lambda/15$
- 10-15 Å finishing of M1 and M2, where the precision of M1, within our budget, is only possible because of the partnership with the UA Mirror Lab
- Open telescope structure (4.1 m long) with equatorial mount, fully retractable dome
- Real-time systems for maintaining telescope alignment
- Computer controlled pointing and tracking
- Adaptive optics and active 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
- 80 m effective focal length with a final ratio of f/50 (close to f/52 of the 65 cm telescope)
- Wavelength range from 0.39-1.6 μm with AO
- All wavelengths >0.39 μm on additional optical bench without AO
- Diffraction limited resolution of 0.07″ at 500 nm and 0.20″ at 1,565 nm (with AO)
- 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 made of Astrositall (CO-115m), which has an extremely low coefficient of thermal expansion (1.5×10^{-7} per °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 the thermal control system including 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, for 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 factors cause the image to shiver and become blurred. To control the temperature of the mirrors, the mirrors will have a high reflectivity coating, and we will use five high-precision cooling systems for M1, HS (heat stop), M2, M3 (see Figure 2), and between the dome floor and the floor beneath. The back of the HS mirror will be cooled using circulating alcohol, while the front of M1 and M2 will be cooled by airknives that push (mounted 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 to be used on the UH/IfA SOLARC and 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 has a 1 m aperture, Scharmer et al. (2002). Our 1.6 m telescope has been designed to be a completely open telescope with a retractable dome, to limit internal seeing.

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

i) telescope optics

The telescope will use an off-axis Gregorian configuration (with two flat mirrors), see Figure 2, with a parabolic f/2.4 primary mirror (M1). 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 flat mirror M3 to the declination 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) will be the tip-tilt mirror for infrared observations on the Nasymth bench. The Gregory-coudé focal plane is relayed to 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 set up on one optical table in the future.

ii) mechanical structure

The 65 cm telescope has a large vacuum chamber, the new, open off-axis optical support structure has a comparable mass, even though its aperture is nearly three times larger. Its total weight will be about 5 tons – equalling the telescope weight presently supported by the pedestal. The existing small, synoptic telescopes on the current fork will be remounted on new NST fork, where they will help to counterbalance the NST.

Maintaining the critical alignment of the NST requires a stiff and thermally stable optical support structure (OSS). A careful truss design and active alignment control system will allow us to achieve 10 micron alignment tolerances over the length of the OSS, using commercial interferometic metrology and lead-screw actuated control loops on a relatively lightweight structure.

The telescope mirror cell will have active support, for which we will initially utilize a look-up table to compensate for changing gravity and thermal conditions. We expect the system to have about 20 actuators. Ultimately, we will have a closed loop system with a wavefront sensor operating at about 0.1 Hz; before that time there will be an additional burden on the AO system. M2 will be mounted in a hexapod for ease of alignment, and the alignment is maintained by computer control systems.

iii) control systems

A supervisor (master) computer (operator control station) will be connected by a dedicated Ethernet to individual control computers for the various subsystems: mount, offset guider, M1 and M2 figure and alignment, thermal control, and so forth. Each major subsystem will have its own control computer. The mount control computer, for example, will control the RA and DEC axis motors and read the encoders. It will communicate with the supervisor computer. The solar offset guider, for example, may ask for motions to adjust the offset pointing. These requests would be relayed by the supervisor computer to the mount controller. There will be four high-precision, temperature controlled systems for the four mirrors (M1, HS, M2, M3) with precision temperature control. There will be three additional 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 ±0.3° C. More than sixty temperature monitoring points will be utilized in the telescope to estimate the performance degradation by temperature fluctuations. Some of the details of the mechanical performance include the range of motion (RA axis from horizon to horizon and DEC axis from -29° to $+29^\circ$), speed range (RA axis, $1''$/s to 1°/s and DEC axis, $1''$/s to 1°/s), pointing accuracy ($5''$), and tracking accuracy ($1''$/5 min without sun guiding and $1''$/10 min with sun guiding). Characteristics of M2 behavior to maintain alignment include M2 tilting (detecting and correcting to better than $\pm 5''$), M2 decentering correction (to better than ±10 μm), and M2 shifting (to better than ±20 μm).

VI. ADAPTIVE OPTICS

The proposed 1.6 m telescope will enable us to address 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-MRI has funded the construction and implementation of two high order systems (97 actuators) – one at BBSO and one at the Dunn Solar Telescope 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 have had upwards of 40 cm, with some steady periods of 20 cm (from ATST site survey telescope). 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 VIIc. 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 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. In addition, the Strehl ratio is significantly higher than in the visible. Further, we have seen that in short-exposure, frame selected NIR images, the isoplanatic angle can exceed $80''$. 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 μm, 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 we are implementing it (Didkovsky et al., 2002), and expect it to close-the-loop in the Summer of 2003. For the 1.6 m telescope, we will have to modify some optics, and possibly upgrade the deformable mirror (DM) system. The light from the telescope is fed to the optical laboratory on the floor beneath the telescope, see Figure 2. Both scientific channels will utilize Fabry-Pérot etalons (FP(V) and FP2(IR)) 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 fields-of-view 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 1000 and 1500 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.

VII. 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. Each is directly related to determining the origin and variation of space weather.

(a) 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. 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 (for details, see Denker et al. 2003). The VIM will reside on the optical bench, as indicated in Figure 2 by FP(V) and FP(IR), 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.

(b) 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), for details see Denker et al. (2003). 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$1K$\times$1K, 12-bit, 50 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 (FP(V) and FP(IR) in Figure 2) 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.

(c) Real–Time Image Reconstruction (RTIR)

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. This is sufficient to resolve the evolution of solar surface phenomena, such as granulation, pores, and sunspots, including the fine-structure of sunspot umbrae and penumbrae (Denker et al., 2001). 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 ($\sim$ 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 we look at the 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 pre-processing the data concern the standard average dark current and flat field image corrections. Diffraction limited images will be obtained at a one-minute cadence. 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. Furthermore, we are collaborating with Drs. Mats Löfdahl and Christopher Keller to implement phase-diversity speckle imaging, which will improve the image resolution even further.

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 only 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 at this time.

Parallel processing of solar data will literally provide a new window through which we can observe the sun, and the origin of space weather, 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 effectively visualize and interpret large data sets.

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REFERENCES

Denker, C., Didkovsky, L.I., Ma, J., Shumko, S., Varsik, J., Varsik, J., Wang, H., & Goode, P.R. 2003, Imaging Magnetographs for High Resolution Solar Observations in the Visible and Near Infrared Wavelength Region, Astron.Nachr., in press

Denker, C., Yang, G., & Wang, H. 2001, Near Real-Time Image Reconstruction, Sol. Phys., 202, 63–70

Didkovsky, L.V., Dolgushyn, A.I., Marquette, W.H., Nenow, J., Varsik, J.R., Hegwer, S., Ren, D., Fletcher, S., Richards, K., Rimmele, T.R., Denker, C., Wang, H., & Goode, P.R. 2002, High-Order Adaptive Optics System for Big Bear Solar Observatory, Proc. SPIE, 4853-75

Goode, P. R, Wang, H., Marquette, W. H., & Denker, C. 2000, Measuring Seeing from Solar Scintillometry and the Spectral Ratio Technique, Sol. Phys., 195, 421–431

Kuhn, J. R., Coulter, R. Lin H., & Mickey, D.L. 2003, The SOLARC Off-Axis Coronagraph, 2003 SPIE, Kona, HI, in press

Parker, E. N. 1988, Nanoflares and the solar X-ray corona, ApJ, 330, 474–479

Qiu, J., Ding, M. D., Wang, H., Denker, C., & Goode, P. R. 2000, Ultraviolet and $H\alpha$ Emission in Ellerman Bombs, ApJL, 544, L157-L161

Qiu, J., Ding, M. D., Wang, H., Gallagher, P. T., Sato, J., Denker, C., & Goode, P. R. 2001, Asymmetric Behavior of $H\alpha$ Footpoint Emission during the Early Phase of an Impulsive Flare, ApJ, 554, 445–450

Qiu, J., Lee, J. W., Gary, D. E., & Wang, H. 2002, Motion of Flare Footpoint Emission and Inferred Electric Field in Reconnecting Current Sheets, ApJ, 565, 1335–1347

Rimmele, T. R., Radick, R. R., Richards, K., & Dunn, R. B. 1999, The NSO Solar Adaptive Optics Program: First Results, AAS Spring Meeting, 5/99

Scharmer, G., Gudiksen, B. V., Kiselman, D., Löfdahl, M. G., & Rouppe van der Voort, L. H. M. 2002, Dark Cores in Sunspot Penumbral Filaments, Nature, 420, 151

Schüssler, M. 2001, Numerical Simulation of Solar Magneto-Convection In Advanced Solar Polarimetry, M. Sigwarth (ed.), ASP Conference Series, 236, 343–354

Spirock, T., Denker, C., Chen, H., Chae, J., Qiu, J., Varsik, J., Wang, H., Goode, P. R., & Marquette, W. 2001, The Big Bear Solar Observatory's Digital Vector Magnetograph In ASP Conf. Ser. 236, Advanced Solar Polarimetry Theory: Observation and Instrumentation, ed. M. Sigwarth (San Francisco: ASP), 65

Wang, H., Qiu, J., Denker, C., Spirock, T., Chen, H., and Goode, P. R. 2000, High-Cadence Observations of an Impulsive Flare, ApJ, 542, 1080-1087