

Title of Investigation: 1.6 Meter 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), proposes to upgrade Big Bear Solar Observatory (BBSO) by replacing its principal telescope, of aperture 65 cm, with a modern off-axis, 1.6 m clear aperture instrument. 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, which is broadly called space weather that impacts human technologies and life on earth. This New Solar Telescope (NST) uses the existing BBSO equatorial mount and observatory building, which will be 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 lead by the National Solar Observatory (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 completing the NST. Although the NST is a PI-class instrument, it will be open to guest observers and will offer the US ground-based solar community instrumentation, which is competitive with contemporaneous advances in solar telescopes in other parts of the world. The MRI/NSF investment in the NST will be highly leveraged with 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 \$4 M project is \$2580 K including \$1800 K from the NSF, and a \$780 K BBSO/NJIT match, which includes support for two students who will earn Ph.D.'s from the project. 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

A. 1 Results from Prior NSF Support

Goode is the PI on a current grant from NSF-ATM (00-86999) "TITLE???", 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.

Kuhn is the PI on a recently funded NSF grant (AST01-23390) "Polarimetric Infrared Circumstellar Imaging." The bulk of Kuhn's solar and instrumentation research at Haleakala is funded by NASA and the Air Force.

A. 2 Overview of the Project

The highest resolution solar telescopes currently operating are in the sub-meter class having 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 and dynamic solar phenomena remains tantalizingly close, but just beyond our grasp.

We propose to replace the 65 cm vacuum telescope at Big Bear Solar Observatory (BBSO) by 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 and fork of the 65 cm instrument. First light will be in early 2006, with full operation by the Summer of 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 speckle image reconstruction 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 developed at 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.*

The total cost of the replacement telescope is about \$4 M, 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). *Our proposal for \$1.8 M will fund the design and construction of the mirror cell mechanical/thermal systems, the active alignment system and the telescope control system. The New Jersey Institute of Technology (NJIT), which operates BBSO, is investing \$1.3 M of its own funds in the NST – \$500 K above required match. The remainder will come from non-NSF sources.* The detailed budget and timelines are presented in the Project Management section (A.8).

The NST project is a collaboration between BBSO/NJIT and the University of Hawaii (UH), which both operate ground-based solar observatories and are leaders in space weather studies. The NST project will benefit from a close working relationship with the National Solar Observatory (NSO) team which is currently designing the Advanced Technology Solar Telescope (ATST). We also maintain collaborative discussions with the GREGOR group, and will share design information both way, especially related to thermal modelling of NST and GREGOR).

Through multi-wavelength spectroscopic and filter-based magnetic field measurements BBSO (and the UH) operates sustained observing campaigns. These 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 iron lines (0.2'') and enhanced temporal sensitivity and resolution (0.07'') at shorter visible spectral diagnostic wavelengths.

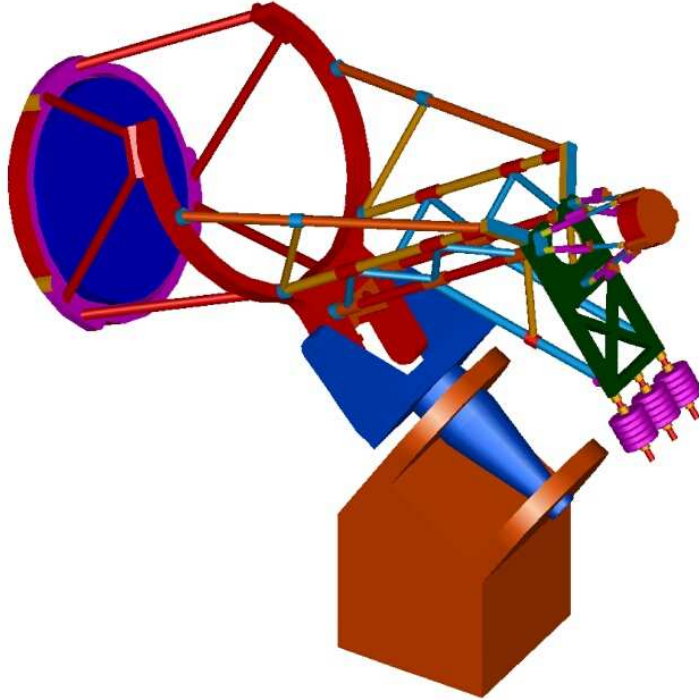


Figure 1: Schematic of the 1.6 m off-axis, open NST

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 several years later. Even then, the NST will have a critical role in space weather studies, since it will generate and provide synoptic space-weather data.

The 65 cm telescope remains a potent scientific instrument and will be donated, along with the dome, to Prairie View A&M, which has an active observational solar physics research program with its 35 cm telescope (see <http://www.pvamu.edu/cps/solar.html>). Prairie View A&M is the second largest university in the Texas A&M system and is an historically black college. We will work with Prof. Huang, who is the Director of the Prairie View Solar Observatory, to design and implement their observatory around the 65 cm telescope.

A. 2.1 NJIT Support for BBSO Programs

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 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.

We emphasize that this proposal budgets for two students who will earn their Ph.D.'s from the NST project. We note that beyond the required match to this proposal, NJIT will contribute \$500 K to the NST, which is money it has already agreed to fund equipment matches to our existing NASA and NSF backbone grants supporting BBSO.

A. 2.2 Heritage and Goals of the NST

Currently the largest coronagraph and infrared solar telescope is the NASA and AF-funded UH SOLARC instrument on Haleakala (Kuhn et al. SPIE ref.). 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.

Just as NST benefits from the SOLARC experience and there are common technical issues (mirror cell support technologies, thermal design, active optic alignment, control and software) with which ATST will be engaged. We expect that our informal collaboration with NSO and ATST engineers will benefit both projects.

First light for NST will come at about the same time as the presently scheduled critical design review of the ATST (early in 2006). We expect to provide NSO with full access to the NST for ATST development tests or demonstrations, if needed. While the NST is nearly two orders of magnitude less expensive than the ATST its intermediate aperture may be a useful risk mitigator for a 4 m solar telescope. We note that the NAS/NRC study (Ground-Based Solar Research: An Assessment and Strategy for the Future, 1998), the so-called "Parker Report", suggested building such an intermediate aperture solar telescope like the 1.6 m 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 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 which are near the end of their planned lifetimes by about 2010, which is 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 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 it comes on-line the ATST, in contrast to the NST, will be a real facility, formally responsive to the national and international research communities. Nevertheless, the NST has an important role as it sharpens some of the scientific issues that the ATST is being built to address concerning the fundamental nature of our dynamic star. Even after the advent of the ATST, the NST will be essential in campaign-style observations.

A. 3 Science Drivers for the NST

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 and the origin of space weather.

A. 3.1 High Resolution, High Cadence Studies of Solar Flares

With observations of greatly improved 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 (sub-second) fine structure 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. 3.2 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 mea-

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. 3.3 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. 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? 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.

A. 3.4 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-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 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.

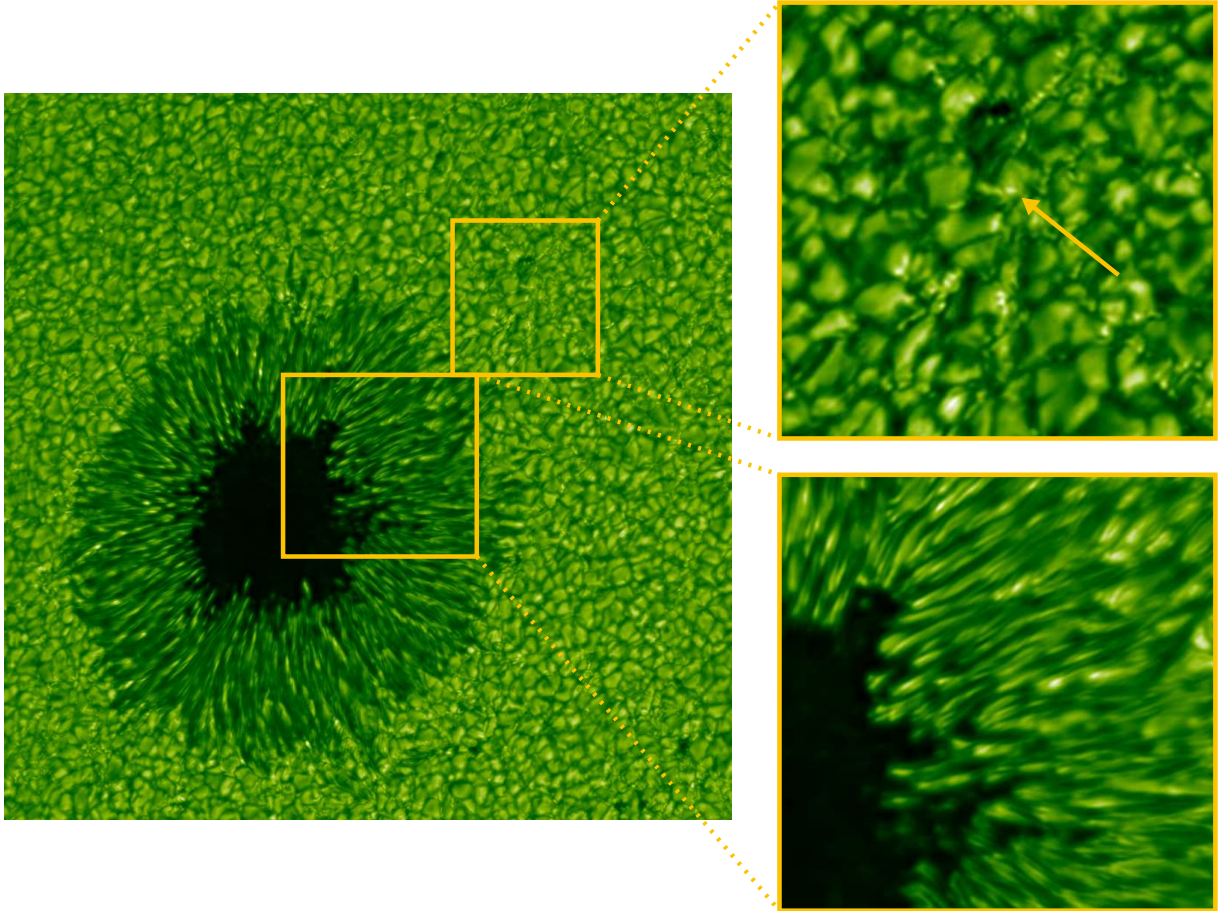


Figure 2: Image of a sunspot (NOAA 8673) taken on August 27, 1999 (520 nm with a $76'' \times 76''$ field-of-view) with the characteristic black umbral center and the penumbral fibers. Also shown are parts of the granular field as an inset. The bright points in the intergranular lane, like the one indicated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

A. 4 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, turbulence from the jet stream layer is reduced because the jet stream is calmest over the oceans.

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! 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. In some ways, the NST is a logical successor to SOLARC and the 0.5 m Dutch Open Telescope in La Palma. 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 is comparable in many ways to the on-axis 1.5 m GREGOR telescope. The NST will keep ground-based US solar astronomy on a par with that Europe until the ATST arrives, and we will have the opportunity to make network observations with the new facilities on the Canary Islands.

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. One could speculate that the NST could partially re-focus its mission in the interim, and become a primary telescope for the university community served by NSO. This would provide continuity until the ATST is on-line, and the NST would still be valuable afterwards.

We emphasize that 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. The open data policy is already in force at BBSO, as well our telescopes are available and potential users can apply on our website, www.bbso.njit.edu. Even after the advent of the ATST, the NST data would be central in studies of the origin of space weather.

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 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 (24 actuators) 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 (97 actuators) 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).

A. 5 The 1.6 m NST

A. 5.1 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

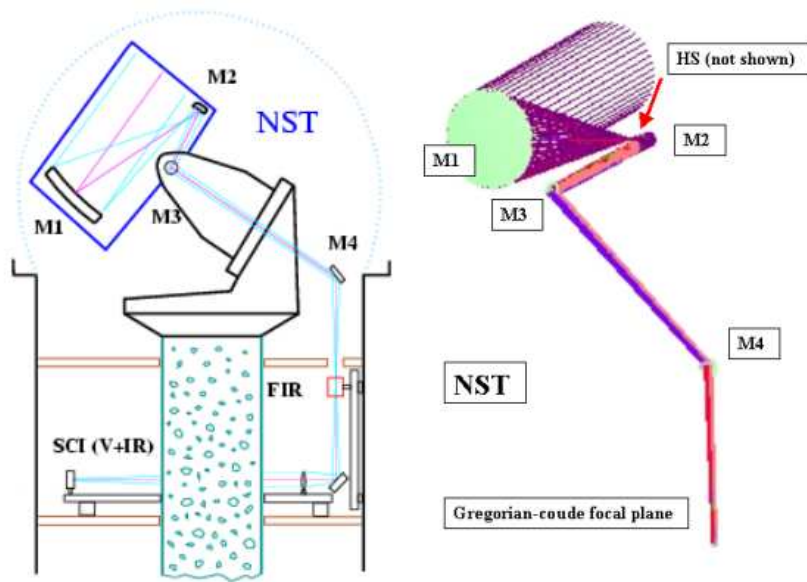


Figure 3: (Left) Schematic of the new open telescope and its retractable dome (not to scale), including the light path to the Far-IR (FIR) instrumentation (at the Gregory-Coudé focal plane) on the vertical optical table. Typically, however, the light goes to the scientific channels in the visible and 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.

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 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 clear aperture
- Off-axis Gregorian configuration (four mirrors – parabolic primary (M1), heat stop (HS), 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 (4.4 m long) with equatorial mount, fully retractable dome
- Real-time systems for maintaining telescope alignment
- Computer controlled pointing and tracking
- Active optics
- 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 0.39-1.6 μm 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 $0.20''$ 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 Astrosital (CO-115m). Astrosital 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 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 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. 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 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. 5.2 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. 5.3 Mechanical Structure

The current 0.65m telescope uses an equatorial mount which we will adapt for the NST. Because the existing 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 that includes a heavy vacuum tank. The existing small telescopes on the fork will be remounted on NST and also 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 20 micron alignment tolerances over the length of the OSS using commercial interferometric metrology and lead-screw actuated control loops on a relatively lightweight structure.

A. 5.4 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 will be three systems for detecting and correcting improper tilt, de-center and de-focussing the NST. There will be four high-precision, temperature controlled systems for the four mirrors (M1, HS, M2 and M3) with precision temperature control. There will be 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)

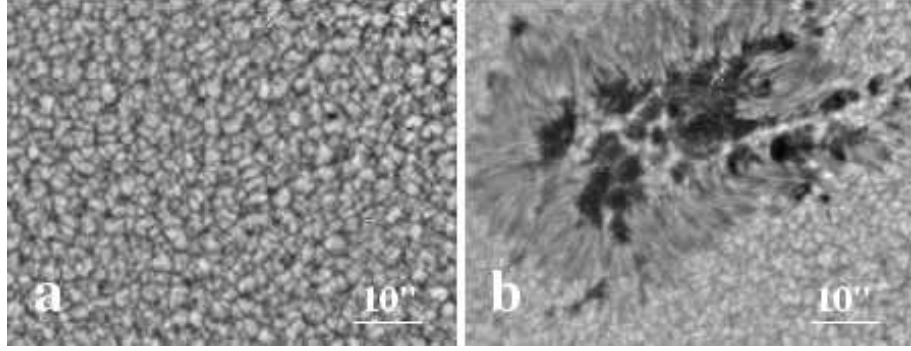


Figure 4: Unprocessed, single exposure (0.13 ms) IR images of the quiet sun and a sunspot region, demonstrating our excellent image quality.

- 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 $\pm 50 \mu\text{m}$)

A. 6 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

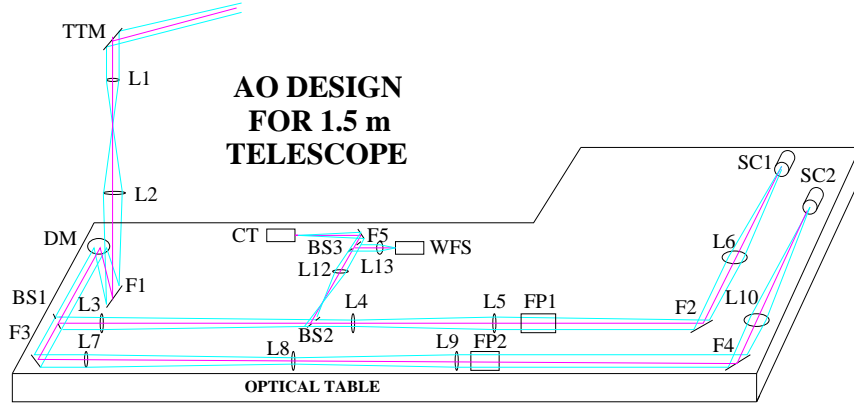


Figure 5: The optical layout of the BBSO adaptive optics system for the 1.6 m telescope (not to scale). TTM guides the light from the telescope to the optics laboratory on the floor beneath. “DM”, “F”, “BS”, “CT”, “WFS”, “PFI” and “SC” mean deformable mirror, folding mirror, beam splitter, correlation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

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 A.6.3. 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 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 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, 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 $0.2''/\text{pixel}$ 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. 7 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. 7.1 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 $1K \times 1K$ 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 (for details, see Denker et al. 2003). 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. 7.2 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), for details see Denker et al. (2003). 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 $1.56 \mu\text{m}$, 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 (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. 7.3 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 we look at the data.

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. 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.

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 in existence 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 visualize and interpret large data sets effectively.

A. 8 Project Management

Goode is the PI on the project and has overall responsibility. 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. Figure 6 is a Gantt chart of the parts of the NST project proposed for herein. The chart also includes the remaining parts of the NST project and related BBSO instrumentation projects.

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. Each key person will have people reporting to him.

The mirrors, the retractible dome, and the final optical design of the telescope are not part of this proposal. To ensure an on-time finish, the mirrors must be purchased and optical design completed before this project begins. The retractible dome will be purchased in 2004 (GREGOR/DOT VENDOR ???) and delivered early 2005 and installed in mid-2005.

Dr. Leonid Didkovsky (BBSO/NJIT) will be responsible for the final optical design of the telescope. This design is nearly finished and is being reviewed by Prof. Jeff Kuhn (co-PI) and will have contributions from our partners at Steward Observatory, who will figure the primary mirror. 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 generation of M1 will be done by Space Optics (???) at a cost of \$100 K (???). The primary mirror will be polished in partnership with the University of Arizona Mirror Lab (ONGOING DISCUSSIONS???). 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 (figured to $\sim \lambda/30$ with a micro-roughness of $\sim 10 \text{ \AA}$). In the partnership, they figure the mirror as a proof-of-concept, and the NST uses polished 1.6 m. The MRI financial contribution will be the cost of using our astrositall blank instead of their boro-silicate blank (\$50 K ???). After their testing, the delivery date for the polished primary is mid-2004. We are contracting for the polishing of the secondary mirror, and from several vendors we have quotes of about \$100 K.

The mirror cell mechanical and thermal design will be done by Doug Neill of Goodrich at a cost of \$100 K ??? under consultation with Jeff Kuhn (is mirror too thick???). That design will be built by M3 at a cost of \$ 500 K ???. Active optics???

The optical support system will be designed by Jeff Kuhn, Roy Coulter (UH) and Leonid Didkovsky, with Leonid (???) taking the lead. Leonid 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. We will hire another experienced mechanical engineer, Dr. Adolf Yelizarov to help in this part of the project. Much of the mechanical and thermal manufacturing can be done at NJIT manufacturing facility under the direction of Dr. Joe Molnar. PLACE HOLDING TEXT.

Dr. Varsik (half-time) will be in charge of the control system (hardware cost ???) and telescope control system software with NSO consulting.

The budget for the proposal includes full support for Didkovsky, Varsik and Yelizarov, and... As well as \$850 K ??? in hardware.

Look for Gantt Chart after references.

A. 8.1 Active alignment system and collimation procedure

Contractor and UH consulting

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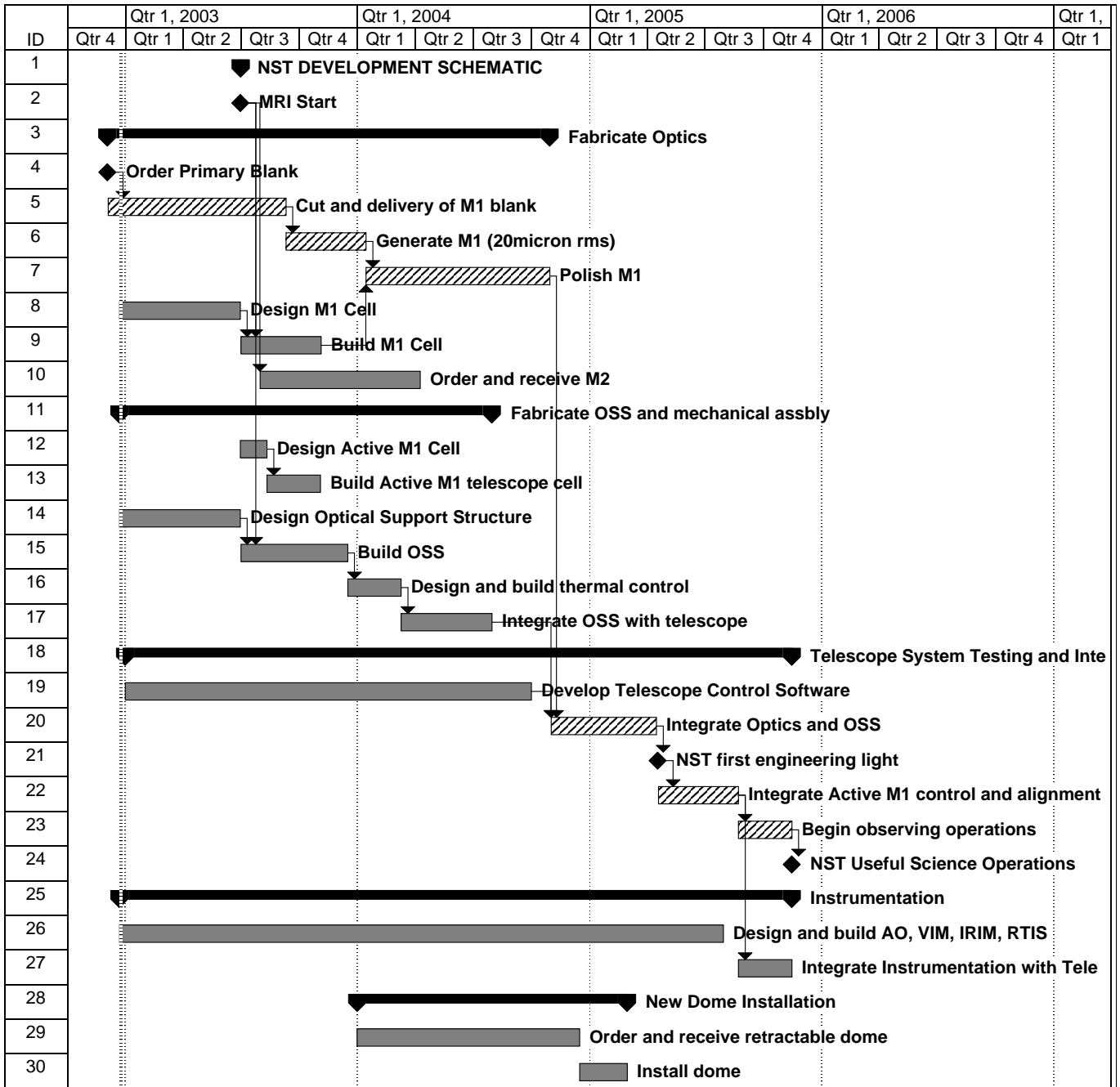


Figure 6: Gantt Chart for the Project.