

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 65 cm aperture telescope 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. 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 equatorial mount and observatory building, which will be modified to accept the 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 led by the National Solar Observatory (NSO) – all three are off-axis designs.

Given the strong background experience of the NST team, this collaboration is ideally suited for efficiently completing the NST. This is a PI-class instrument, but it will continue BBSO's open data policy, as well as being available to guest observers. In this capacity it offers the US solar community instrumentation that is competitive with contemporaneous advances in solar telescopes in other parts of the world. This MRI/NSF investment in the NST will be highly leveraged with support from private and other non-NSF funding sources. Here, we are asking for resources to complete the designs and to implement the mechanical, thermal, and control systems. The total cost to finish the \$4 M NST project is \$2580 K including \$1800 K from the NSF, and a \$780 K BBSO/NJIT match. Two students will earn experimental Ph.D.'s during the project. Additional funds from private sources have already been applied to the costs of the primary and secondary mirror blanks and polishing. We plan for first light in 2005.

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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) "Studies of Solar Atmosphere and Magnetic Fields", 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 graduated 6 Ph.D. students and 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 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 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 2005, with full operation late in 2005. 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 external 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 the required match. The remainder will come from non-NSF sources.* Additional NST resources come in the form of salary support for key observatory personnel who will be involved in the NST construction, but who are primarily supported by NJIT or BBSO.

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 also benefit from a close 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 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

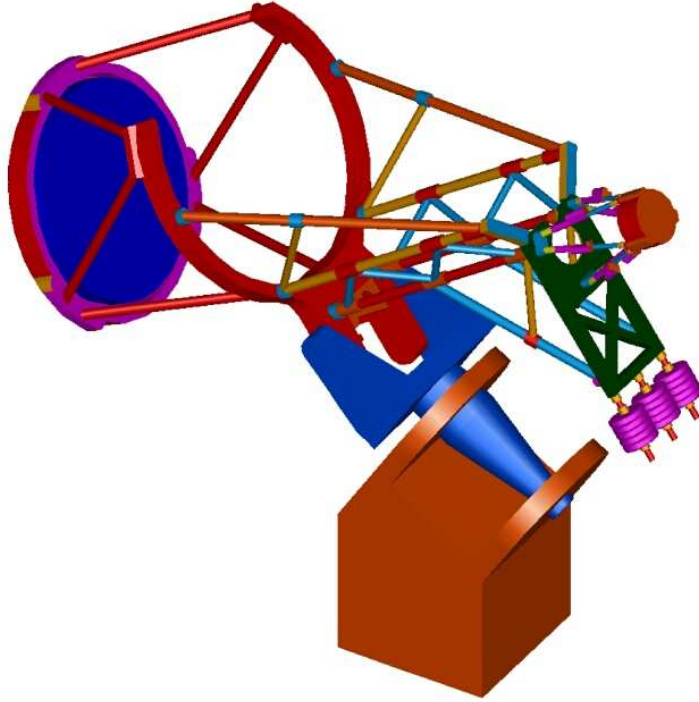


Figure 1: Schematic of the 1.6 m off-axis, open NST

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, 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 note that this proposal will support two experimental Ph.D students. We emphasize that beyond the required match to this proposal, NJIT will contribute \$500 K to the NST, which is matching money it has already agreed to provide for equipment for our existing NASA and NSF backbone grants now supporting BBSO.

A. 2.2 Heritage and Goals of the NST

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.

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.

First light for NST will come before the presently scheduled critical design review of the ATST. We plan to provide NSO with full access to the NST for ATST development tests or demonstrations, if needed. While the NST is more than an order 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 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 it comes on-line the ATST, 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 that the ATST is being built to address. Even after the advent of the ATST, the NST will be essential in campaign-style observations.

A. 2.3 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.

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.

The NST is a logical successor to SOLARC and the 0.5 m 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.

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. This will 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 stars (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. 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). While the fluxtube model has been disputed (Nordlund ???) establishing the utility of the model depends on critical magnetic observations with higher spatial resolution. Many believe that individual fluxtubes 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. 3.1 High Resolution, High Cadence Studies of Solar Flares

The improved resolution we achieve from BBSO’s NST allows flare imagery and spectroscopy which 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 (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 measurements of vector magnetic fields. A lot 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, 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 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 intra-network fields and their interaction with network fields. Therefore, we will be able to accurately measure the energy released during the reconnection of these fields. (2) Parker (1988) proposed that the X-ray corona is due to a continuous nanoflaring process. The energy source of these nanoflares is from the random motion of footpoints. So the observations of footpoint motions associated with all the above events is essential. We know that such footpoint motion is hard to observe and characterize in lower resolution observations with the current system. We plan to detect and characterize such footpoint motions with $0.1''$ spatial resolution, using real-time speckle constructed images. As G-band images show fluxtubes very well, we will use our G-band filter to observe for this part of the research. We expect to learn the correlation between footpoint motions and brightness of overlying EUV/X-ray loops.

A. 4 The 1.6 m NST

A. 4.1 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 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).

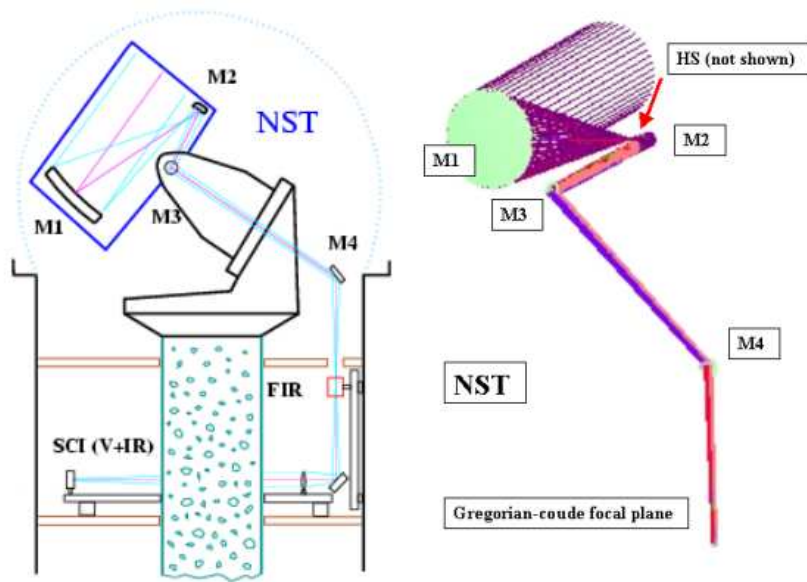


Figure 2: (Left) Schematic of the new open telescope and its retractable dome (not to scale), including the light path to the Far-IR (FIR) instrumentation (at the Gregory-Coudé focal plane) on the vertical optical table. Typically, however, the light goes to the Fabry-Pérot-based scientific channels in the visible and near-IR, labelled FP(V) and FP(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 downstream of 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"/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.

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 2). 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. 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. 4.2 Telescope Optics

The telescope will use a four mirror, off-axis Gregorian configuration, see Figure 2, 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. 4.3 Mechanical Structure

The current 65 cm 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. 4.4 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. Some of the details of the mechanical performance are:

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

A. 5 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 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 ,

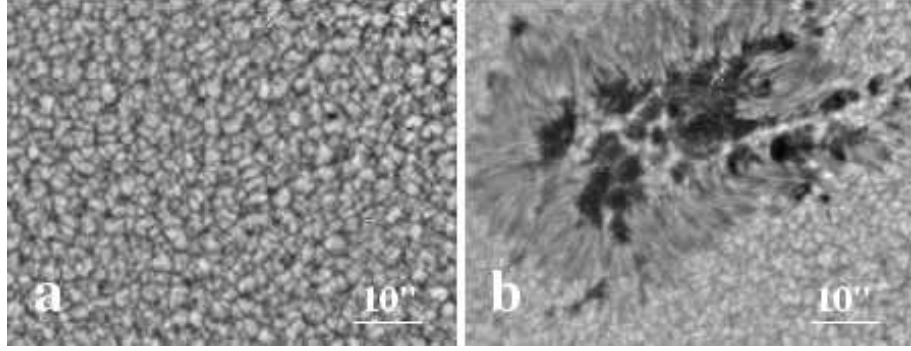


Figure 3: Unprocessed, single exposure (0.13 ms) IR images of the quiet sun and a sunspot region, demonstrating our excellent image quality.

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 3. 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, see Figure 2. 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. 6 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. 6.1 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 $1\text{K} \times 1\text{K}$ 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 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.

A. 6.2 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 μm , giving us a 0.25 nm wide prefilter (narrower than the 0.5 nm free spectral range of the IR Fabry-Pérot). This will solve the longstanding problem of constructing a filter-based IR magnetograph, while avoiding the complications of using a double (or even triple) etalon system. At this time, regularly operating, stable dual etalon IR systems do not exist. We expect the first generation of the IRIM to be on-line shortly after the VIM. We have purchased a large format, high frame rate IR CMOS camera ($\sim 1\text{K} \times 1\text{K}$, 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 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.

A. 6.3 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, 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. 7 Project Organization and Management

The NST project is more than an order of magnitude smaller than most facility astronomical telescope projects (e.g. ATST is likely to be an 80-100M\$ program). Nevertheless the NST scale is comparable to many current astronomical instrument construction activities, and dedicated project management and systems engineering talent are essential for its success. Project design and implementation will be led by the BBSO group with help from the UH/IfA group and outside contracts and consultants.

The overall project responsibility rests with PI Goode who benefits from advice from co-I Kuhn. Systems and project management will be done by Dr. John Varsik, a broadly experienced scientist at BBSO. Technical oversight for the optical and mechanical systems design and implementation will be provided by Dr. Leonid Didkovsky (BBSO), a senior scientist recently from the Crimean Astrophysical Observatory with significant and broad astronomical project experience. Kuhn and the UH/IfA science and technical group will provide additional general NST support. Specific technical services will be provided by external consultants and collaborators. The aforementioned four principals will be in regular contact with face-to-face meetings being scheduled as needed, but at least twice a year. Figure 4 summarizes our development and implementation timelines/milestones for many of the NST systems. Varsik, Didkovsky, Guo Yang and V. Yelizarov are the only BBSO employees who will be paid from the MRI funds. Major system responsibilities, and associated hardware costs from MRI and the NJIT match are summarized below:

- NST systems engineering is Varsik’s responsibility but he will have help from Marquette (BBSO), UH (Coulter) and possibly NSO/ATST (Oschmann).
- The NST optical design and its implementation will be Didkovsky’s responsibility, although the optics design group will consist of Kuhn and possibly Moretto (as a consultant from the NSO).
- The OSS mechanical systems design group will include Didkovsky, Yelizarov (also from the Crimean, to be hired at BBSO), Marquette (BBSO), Nenow (BBSO), Coulter (UH), and a consultant with significant telescope mechanical design experience in academe and industry. Responsibility for pieces of the OSS and mirror cell design will be distributed amongst this team (for example the mirror cell and finite element trials of the telescope OSS will be designed by the consultant, the prime-focus heat stop will be the responsibility of UH, etc.). A contract for designing the M1 skeletal cell (for support

during polishing), active M1 cell (if necessary) and optical support structure is being finalized, so that the design will be ready for implementation at the start date of the work proposed here.

- The primary mirror (10cm thick Astrocital) has been purchased from LZOS (Moscow, Russia). Contracts for mirror generation have not been fixed. The University of Arizona (Mirror Lab) has agreed to polish M1 as a demonstration of their off-axis optics capabilities in preparation for larger 30m-class astronomical telescopes. Secondary optics contracts have not been fixed but are likely to be carried by Space Optics Research Laboratories Inc (Massachussets) and Rayleigh Optics (Tucson) at a cost of \$100 K.
- Fabrication contracts for mirror cell and the OSS have not been fixed but are likely to involve Goodrich Inc. (Connecticut), Agracoast (Canada), or M3 (Tucson). Additional fabrication work may be done at the UH/IfA and NJIT machine and instrumentation shops. NJIT has a degree program in manufacturing engineering, which has a large, associated fabrication facility that has built a 2.0 m radio telescope including the control systems. The integration of the mirror cell and OSS systems will be the responsibility of the OSS mechanical system design group. The fabrication costs are estimated to be \$600 K (with a \$100 K contingency from non-MRI sources).
- The retractible dome contract has not been fixed, but is virtually certain to engage the Dutch DOT design group (Hammarlag). We have a quote from them for \$400 K for an installed, retractible dome like that for the GREGOR. This part of the project will be led by Denker (NJIT) and Wang (NJIT).
- Thermal design work will be led by Denker (BBSO) with help from UH (Coulter and Kuhn), and the German GREGOR project. The cost for the associated hardware is \$200 K, but will not be borne by the MRI.
- Controls and software design and implementation will be under the direction of Wang (BBSO) with primary effort by Guo Yang (BBSO) and Varsik with help from UH and (possibly) NSO/ATST technical personnel. Yang wrote the control software for the real-time speckle/phase diversity system at BBSO. The associated hardware costs for the control systems is \$100 K.
- Integration of the focal plane instrumentation, including modified AO, with the new telescope will be the responsibility of Wang and Didkovsky with help from Wenda Cao (BBSO) who is expert in instrumentation and is currently active in the IRIM project. Didkovsky has taken the lead in the AO effort at BBSO, and will take the lead in modifying the AO optics to accommodate the NST. The required optics cost \$100 K.

We note that the project is organized around an optics, mechanical, and a controls and software team of scientists and engineers. The technical shops at UH/IfA and NJIT will provide services as needed to support this design effort. Depending on vendor pricing and delivery schedule the UH/IfA and NJIT instrument fabrication shops may be used for some of the telescope assemblies. In addition, to the NJIT match to the MRI, NJIT is investing \$500 K in this project. Of the \$500 K, \$200 K remains uncommitted, but represents the contingency for the fabrication of the NST. The project budget is presented and discussed in detail the Detailed Budget section.

A. 7.1 Budget

How about defining a budget for each design group (optics, mechanical, controls and software) which is subdivided into personnel costs by group (BBSO, IfA), subcontract costs, etc. So if we sum the UH contributions over each of these activities I imagine we'll want to pay one design person full time for three years (with overheads this is 120K\$/yr). I'm guessing we might also want to use as much as 50K\$ /yr (total) from our machine, software, and electronics shops. Add travel to this: 5 person trips/yr CA-HI

(30 person days). Perhaps the budget should include a separate category then for the "integration" phase of the NST, which could also be subdivided. Maybe the subcontracts below can be summarized in such a budget table. I'd add another table that summarizes the BBSO personnel to be supported by the MRI and the free salary support for Goode, Kuhn (5%), Denker, etc. that NST profits from. I hope this is helpful.

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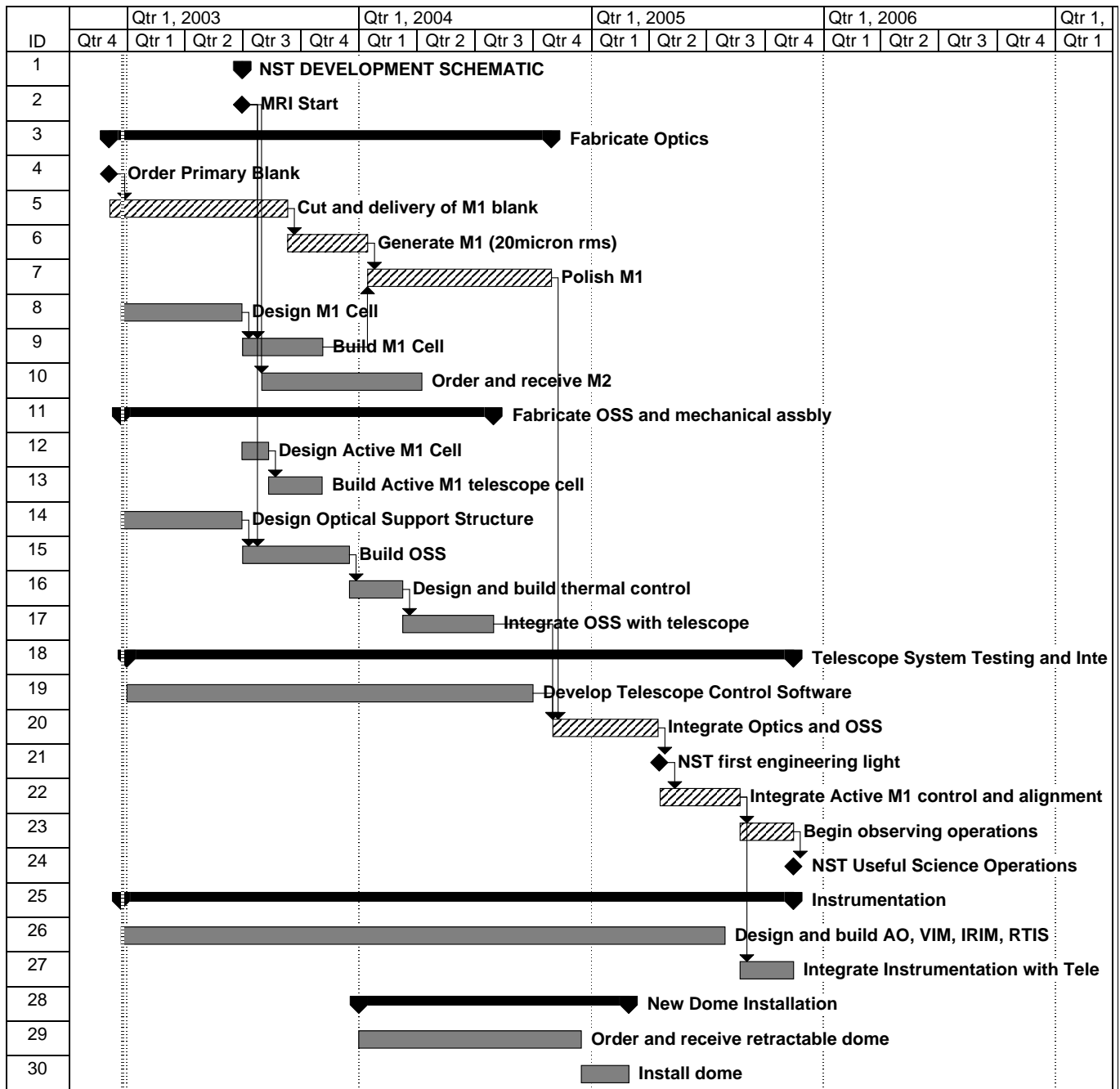


Figure 4: This Gantt chart summarizes the NST development and implementation timeline. The critical path (cross-hatched) for the NST is determined by the primary mirror fabrication, polishing, and NST integration phases of the project.