

**Title of Investigation:** MRI: Development of Cooled Infrared Spectrograph for the 1.6 Meter Solar Telescope in Big Bear

**Principal Investigator:** Roy Coulter (BBSO/NJIT)

**Co-Principal Investigators:** Matt Penn (NSO/T), Tom Ayres (CU) and Philip Goode (BBSO/NJIT)

# Proposal Summary

Early in 2009 at Big Bear Solar Observatory (BBSO), first light observations were made with our 1.6 m clear aperture, off-axis telescope - the NST (New Solar Telescope). The NST will be the most capable, largest aperture solar telescope in the US until the 4 m off-axis ATST (Advance Technology Solar Telescope) comes on-line in the middle of the next decade. Here we propose, in collaboration with the Matt Penn of the National Solar Observatory (NSO) and Thomas Ayres of the University of Colorado (CU), to build the Cooled InfraRed Spectrograph (CIRS) spanning 1.0 to 5.0  $\mu\text{m}$  for the NST. This system is essential for the NST to achieve its scientific potential of probing for the first time the fundamental scale of the Sun's dynamic magnetic field, the origin of space weather, while providing valuable experience and risk reduction for the ATST project.

???SUMMARY TEXT FOR SCIENCE AND SPECTROGRAPH???

The principal scientific objectives for CIRS equipped NST are ???FINISH THIS???

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

(1) Intellectual merit: CIRS will enable the NST to provide the community unique (???HOW UNIQUE COMPARE TO WHAT CAN BE DONE AT THE MCMATH???) data on the solar magnetic field illuminating the fundamental character of our dynamic star, while probing the origins of space weather. Over the next decade, NSO will build and begin operating the ATST, the flagship telescope for the solar community. CIRS will be a significant testbed for the more complicated IR spectrograph planned for the ATST. After the ATST is on-line, the NST will continue to be an essential telescope in making campaign-style observations.

(2) Broader Impact: The development of the proposed CIRS system continues our decade long tradition of training the next generation of scientists who build instruments. The resulting data will be used in many PhD theses. Our data will be open to the scientific community, and a substantial portion of observing time on the NST will be open to the community.

## A. Project Description

### A.1 Overview

Spectral observations of the photosphere and chromosphere utilizing the largely unexplored near-infrared (NIR) are crucial for solving many outstanding problems in solar astronomy. In particular, high spatial resolution polarimetry at NIR wavelengths is essential and requires large aperture telescopes. Here, we propose for funding to implement a cryogenically Cooled IR Spectrograph (CIRS) operating from 1 to 5  $\mu\text{m}$  for the New Solar Telescope (NST) for observations at the Gregorian Focal Plane. Firstlight observations were made in January 2009 at Big Bear Solar Observatory (BBSO) with the new 1.6 m clear aperture, off-axis telescope - the NST. The NST will be the largest aperture solar telescope in the US, and perhaps the world, until the 4 m off-axis ATST (Advanced Technology Solar Telescope) comes on-line in the middle of the next decade. In addition to its tremendous scientific potential, the NST will be the testbed for many essential components and technologies of the ATST including CIRS. *Primarily we propose here, in collaboration with Matt Penn of the National Solar Observatory (NSO) and Thomas Ayres of the University of Colorado (CU), to build, which is essential for the NST to reach its scientific potential.*\*\*\*\*\*FIX THIS SENTENCE\*\*\*

\*\*\*\*\* MRI PROPOSAL GUIDELINES SAY THE FOLLOWING SUBSECTIONS MUST BE INCLUDED \*\*\*\*\*

### A.2 Research Activities

\*\*\*\* THIS SECTION WOULD INCLUDE THE NST DESCRIPTION \*\*\*\*\* \*\*\*\* SUGGESTED LENGTH FOR SUB-SECTION IS 4 PAGES \*\*\*\*\*

### A.3 Description of Research Instrumentation and Needs

\*\*\*\* THIS WOULD BE THE TEXT WE HAVE ALREADY WRITTEN \*\*\*\*\* \*\*\*\*\* SUGGESTED 6 PAGES \*\*\*\*\*

## A.4 Impact on Research and Training Infrastructure

\*\*\*\*\* SUGGESTED 2 PAGES \*\*\*\*\*

## A.5 Management Plan

\*\*\*\* SEE nsf09502MRI Guidelines.pdf FOR DETAILS ON SECTION REQUIREMENTS \*\*\*\*  
\*\*\*\*\* SUGGESTED 3 PAGES \*\*\*\*\*

## A.6 Schematic of the NST

BBSO has removed its old 0.6 m aperture telescope (donated to the Los Angeles Amateur Astronomy Society) and the alignment of the modern, off-axis 1.6 m clear aperture instrument (Goode et al., 2003) has been finished and first light has been attained at the Nasmyth focus, which will be the primary location for the IR spectrograph proposed here. The new telescope offers a significant improvement in ground-based high angular resolution capabilities, and will substantially enhance our efforts to understand (???WHAT EVER WILL BE PROPOSED IN NEXT SECTION???), as sketched in Section A.5. The NST project is described in detail in <http://www.bbsso.njit.edu/newtelescope>.

The NST is configured as an off-axis Gregorian system consisting of a parabolic primary, prime focus field stop and heat reflector (heat-stop), elliptical secondary and diagonal flats, see Figure 1. The primary mirror (PM) is 1.7 m with a clear aperture of 1.6 m. The PM was figured to a final figure residual error of 16 nm rms by Steward Observatory Mirror Lab. The focal ratio of the PM is  $f/2.4$ , and the final ratio is  $f/50$ . The 180" circular opening in the field stop defines a 120"  $\times$  120" maximal square field of view (FOV) of the NST. The working wavelength range will cover 0.4 to 1.7  $\mu\text{m}$  in the Coudé Laboratory one floor beneath the telescope, and all wavelengths including far infrared at the Nasmyth focus on an optical bench attached to the side of the telescope structure. Here we are proposing for a spectrograph at the fed from the Gregorian focal plane along the path to the Coudé Laboratory. An off-axis design was chosen principally because of its vastly reduced stray light, since there is no central obscuration, which reduces the telescope's MTF (Modulation Transfer Function) at high spatial frequency.

We have designed an open telescope structure with

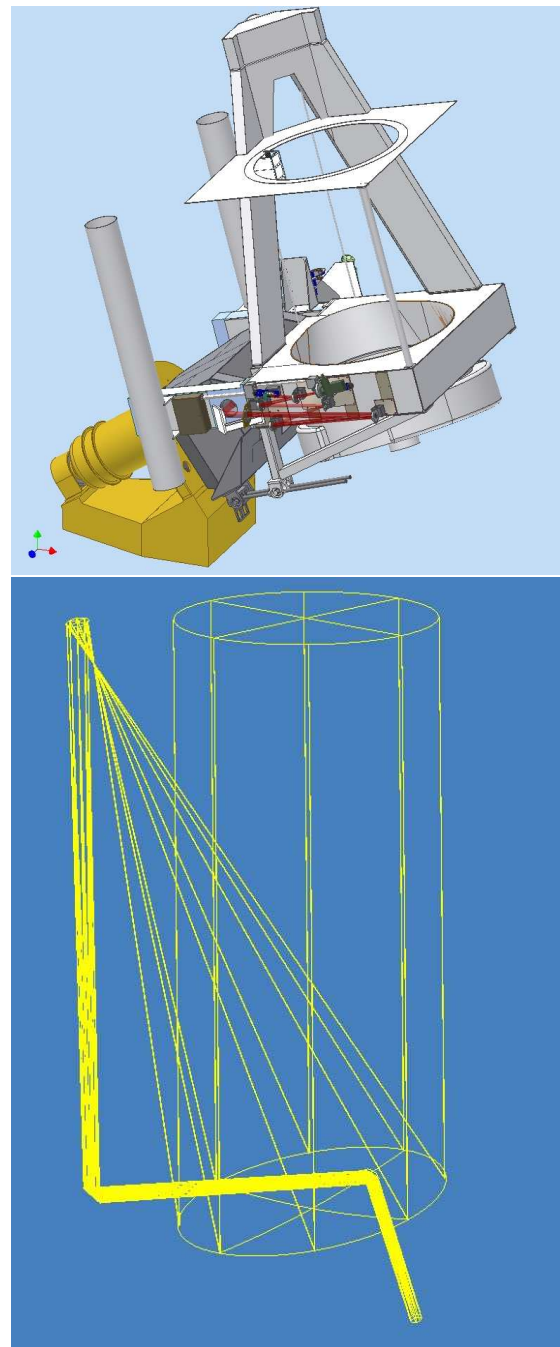


Figure 1: Schematic of the 1.6 m off-axis, open NST (top) and its optical layout (bottom). On the top part, the heat stop (HS) resides at the prime focus with the SM mounted on a PI hexapod. The wavefront sensing system (WFS) resides immediately before M3 (along with the polarization optics for magnetic field measurements). M4 sends the light to the Coudé Room below. The HS, SM, M3 and M4 are not apparent in the figure. If M4 is flipped the light goes to the Nasmyth Bench where the spectrograph will reside (???REPLACE UPPER DRAWING WITH ONE HAVE A SCHEMATIC SPECTROGRAPH ON THE NASMYTH???) for which the light path is shown in red. This is where the first light observations occurred. The design was driven by competing needs for rigidity near the SM and an open light path. For more details, see <http://www.bbsso.njit.edu/newtelescope>.



Figure 2: The NST equatorial mount, mirror cell, counterweights (for right ascension balance), and tower to secondary.???UPDATE???

an equatorial mount, as illustrated in Figure 1. A key design issue for a large aperture, solar telescope is the thermal control system to keep the temperature of the mirrors very close to, or even slightly below that of the ambient air. The dome employs a wind-gate and exhaust system to control the airflow from the wind helping to maintain the same temperature inside and outside the dome, and remove concentrations of heat in and around the optical paths. In fact, we have measured the temperatures along the optical path from the telescope to the Coudé Laboratory (which is thermally controlled to 0.5 C). When the vent gates and exhaust system are turned on, the temperature all along the optical path becomes precisely uniform. In addition, we have implemented a closed cycle, chilled air system as part of the OSS (Optical Support Structure) to limit so-called “mirror seeing” by sweeping away turbulent cells and directly cooling the PM. What matters for CIRS is the feed to the Nasmyth bench, which also has an isothermal light path. The OSS and active support mirror cell were built and tested by DFM, Engineering in Longmont, CO. The PM is supported by 36 actuators that can bend out low-order aberrations,

such as those due to gravity and/or thermal effects. Its shape will be controlled by a wavefront sensing system (<http://www.wavefrontsciences.com>), which resides immediately before M3. First light observations of the Sun have been made at the Nasmyth focus, and image is shown in Figure 3.

The new, larger dome, required to house the NST, is fully operational and the installed telescope is shown in Figure 2. The elliptical secondary mirror (SM) was silvered, and was been tested by both SORL (Space Optics Research, which figured the SM) and Steward before its installation on the NST PI hexapod. The latest version of the BBSO telescope headquarters control system software has been written in BBSO and tested at DFM. While this software is not essential for early observations, it would make them somewhat less cumbersome. \*\*\*\*ADJUST FORMAT? – THIS SECTION(ABOVE) PERTAINS TO THE REQUIRED PREVIOUS MRI REPORT\*\*\*\*

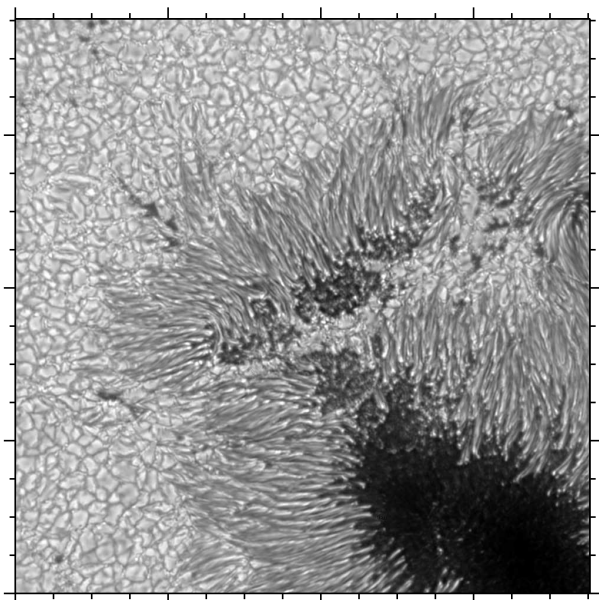


Figure 3: A diffraction-limited image obtained on the NST at the Nasmyth focus (???NEED REAL FIGURE WITH  $r_0$  TO DEMONSTRATE KOLMOGOROV SEEING, ETC???).

### A.7 Strehl Ratio of the Beam Feeding the Spectrograph

\*\*\*\*\*SHOULD THIS GO IN THE PERFORMANCE PREDICTION SECTION?\*\*\*\*\*

Ideally, we would like the Nasmyth Bench spectrograph to be fed with diffraction limited light over the entire 1.0-5.0  $\mu\text{m}$  range of operation. This spectral range does not require full adaptive optics correction because the terrestrial atmosphere is less turbulent in the IR than in the visible, so tip-tilt corrections alone are sufficient for most observations. Given the seeing at BBSO and the limitations of tip-tilt corrections, the diffraction limit will almost never be achieved at 1.0  $\mu\text{m}$ , while for wavelengths beyond 2.5  $\mu\text{m}$ , diffraction limited observations will be the norm.

The Strehl, generally used to quantify the performance of an adaptive optics (AO) system, is the ratio of the maximum intensity in the corrected image in the detector plane to that from a theoretical, perfect imaging system operating at the diffraction limit. Experience, at the National Solar Observatory at Sacramento Peak (NSO/SP) and elsewhere, from existing solar AO systems as well as detailed performance modeling of corrected observations using MHD simulations of solar magnetic fields show that a Strehl of  $S \geq 0.3$  is

required to perform the desired quantitative analysis of the small-scale magnetic elements. So, under what circumstances will this Strehl be achieved for light fed to our planned spectrograph by a tip-tilt system?

A simple way of quantifying the image quality after tip-tilt correction is by computing the residual wavefront error variance,  $\sigma^2 = 0.134(D/r_0)^{\frac{5}{3}}$ . From, this we can calculate the Strehl of a long exposure image in the usual Marechal approximation (for more detailed discussion see Christou et al, 2006, and references therein), where  $S = e^{-\sigma^2}$ . Further,  $D$  and  $r_0$  are the telescope aperture diameter and  $r_0$  is the Fried parameter. Often, the Fried parameter,  $r_0$ , is used to quantify the seeing conditions at a site.  $r_0$  is the coherence length of the atmospheric turbulence. Without image correction, for telescope apertures larger than  $r_0$ , resolution is seeing limited. The Fried parameter is wavelength dependent ( $r_0 \propto \lambda^{\frac{6}{5}}$  for the generally-assumed Kolmogorov turbulence). The BBSO site has been well-studied within the ATST site survey (see <http://atst.nso.edu/site> for details). Over the two years of seeing measurements, BBSO has been shown to be characterized by steady seeing all day long with an average of Fried parameter of about 6.5 cm for light of  $\lambda=0.5\mu\text{m}$ . About one-quarter of the time,  $r_0 \geq 10$  cm all day long. The origin for the steady, good seeing is the well-documented lack of ground-level atmospheric turbulence, which is the result of the NST dome being located in the middle of Big Bear Lake. The lake is almost always cooler than the air and, thus, provides a natural inversion that suppresses the turbulence during our typical observing conditions in which a constant wind comes from the west over two miles of open lake water.

Using the Marechal approximation and assuming  $r_0 \sim 10$  cm at  $\lambda=0.5\mu\text{m}$  in all cases in this paragraph, we calculate that at 1  $\mu\text{m}$   $r_0 \sim 25$  cm, and we have  $S=0.03$ , which means we are seeing limited with a seeing disk of about  $0''.5$ . At 1.6  $\mu\text{m}$ , where the Sun has its opacity minimum and there are strong magnetic lines, we have  $r_0 \sim 40$  cm and a tip-tilt corrected  $S=0.26$ , which is close to the 0.3 that experience has taught us is sufficient for diffraction limited imaging that would be  $0''.20$  at 1.6  $\mu\text{m}$  for the spectrograph. At 2.5  $\mu\text{m}$ ,  $r_0 \sim 70$  cm and  $S \sim 0.7$ . For all wavelengths red of 2.5  $\mu\text{m}$ , even the everyday seeing, after tip-tilt correction, is sufficient to feed diffraction limited light to the spectrograph. In general, we plan to

use our real-time speckle reconstruction system as a daily guide on the wavelengths feeding the spectrograph. Some particular wavelengths of interest in the 1-5  $\mu\text{m}$  band are listed in Table 1, along with their significant properties and the science tasks that can be attacked with the spectrograph. Another advantage at longer-than-visible wavelengths is the appreciably greater Zeeman splitting, which enables us to separate the true magnetic field strength and filling factor from the magnetic flux that is measured in the visible.

## A.8 Zeeman Splitting in the NIR

Observations in the NIR have advantages associated with the relatively larger Zeeman splitting (Zeeman splitting increases quadratically with wavelength) in that regime and are vital for measurements of weak magnetic field strengths. In that way, visible and NIR observations complement each other.\*\*\*WHAT DOES THIS MEAN?\*\*\*

The Zeeman splitting,  $\delta\lambda$ , is given by  $\delta\lambda \propto gB\lambda^2$ , or more typically the fractional Zeeman splitting  $\delta\lambda/\lambda \propto gB\lambda = \lambda(gB)$ , where  $\lambda$  is the wavelength,  $g$  is the Landé  $g$ -factor and  $B$  is the magnetic field strength. Further,  $(gB)$  is called the “Magnetic Sensitivity” for purposes of comparing the utility of various IR lines.

## A.9 Scientific Motivation: Photospheric and Chromospheric Magnetic Fields

Many fundamental properties of our dynamic star will finally come within our grasp with the tip-tilt corrected IR light feeding the NST Cooled IR Spectrograph.

Observations of weak magnetic fields in the solar photosphere using absorption lines in the visible spectrum suggest that kilo-Gauss magnetic fields exist in the quiet Sun, and the observed weak flux is a result of the low spatial filling-factor that characterize these fields (e.g. Stenflo 1992). However, when measurements of these fields were made with the more sensitive 1565 nm Fe I ( $g=3$ ) absorption line, a different picture emerged. A distribution of weak magnetic field strengths was seen (Rabin, 1992; Lin 1995) which contradicted the observations made at visible wavelengths. It has been suggested that thermal effects in some visible lines combined with their weaker

Zeeman splitting have produced erroneous measurements, and that the field strength distribution measured by the infrared lines are more representative of the true solar magnetic fields (Collados, 2005).

New observations using more sensitive spectral probes of the weak solar magnetic field can help to resolve this problem. A set of Fe I and Si I lines are seen in the photosphere in the reference atlas from Wallace and Livingston (2003) between 3695 and 4150 nm. An Si I and a Fe I line near 4060 nm both have  $g_{\text{eff}}=1.25$ ; this makes them slightly more magnetically sensitive than the 1565 nm Fe I line (an 8% advantage), see Table 1. Alan Clark has observed the intensity spectra of several spectral lines from Si I near 4137nm, which do not have their transitions listed by Kurucz (Kurucz and Bell, 1995); from intensity spectra he sees these lines showing large Zeeman splitting, suggesting that they are much more sensitive than the 1565 nm line (by more than 50%). Han Uitenbroek lists only two possible transitions for the Si I line at 4142.5 nm, and the line should have  $g_{\text{eff}}=1.625$  or  $g_{\text{eff}}=2.25$ . This means that this line is either 40% or 98% more magnetically sensitive (see Table 1) than the 1565 nm line, and will provide a sensitive measurement of weak solar magnetic fields. Within sunspot umbra, currently the most sensitive line known is the Ti 2231 nm line. Some initial work has been done with this line (Ruedi et al., 1998, Penn et al., 2003) and the  $g_{\text{eff}}=2.5$  value makes this line 18% more sensitive than the Fe I 1565 nm line. This Si I line at 4142.5 nm will provide an even more sensitive probe of sunspot magnetic fields.

Not only will new measurements of this 4142 nm Si I line address the measurements of weak fields in the solar photosphere, but they will provide the most accurate photospheric measurements possible to use as inputs for magnetic field extrapolation models.

Recent work measuring the magnetic fields in the solar chromosphere using the 854.2 nm Ca I line have produced intriguing results regarding the magnetic canopy, and also show interesting effects in filament channels (Harvey et al., 2003). A promising chromospheric line in this spectral region is the Mg I line at 3681.6 nm. With a  $g_{\text{eff}}=1.17$ , this line is 5 times more sensitive to Zeeman splitting than the 854.2 nm line. With the gain in magnetic sensitivity provided at these longer wavelengths, a new realm of sensitive chromospheric magnetic measurements will be possible when

Table 1: IR Bands of Interest for the Nasmyth Spectrograph.

Region	Species	$\lambda$ [nm]	$g_{\text{eff}}$	Mag Sensitivity $\lambda g_{\text{eff}}$
Photosphere	Fe I	1565	3	4695
	Ti I (spots only)	2231	2.5	5578
	Fe I	4063.7	1.25	5080
	Si I	4142.5	(1.625 or 2.25)	(6732 or 9321)
Chromosphere	Ca I	854.2	1.0	854
	Ca I	3697.4	1.1	4067
	Mg I	3681.6	1.17	4307

these lines are used. Again, in addition to addressing several unique chromospheric magnetic questions, these measurements will produce new and better 3-D extrapolations of the solar magnetic field as they will provide a much more accurate boundary condition for these models.

???IT NEEDS TO BE CLEAR WHY THE INSTRUMENT AND NST WILL PRODUCE UNIQUE SCIENCE THAT CANNOT/COULD NOT BE DONE AT THE MCMATH WITH ITS NIR INSTRUMENTATION. ALSO, WHAT ARE ATST PLANS???

## B. Proposed Work

### B.1 Overview

CIRS will be located at Big Bear Solar Observatory on Big Bear Lake in the San Bernardino mountains of California. \*\*\*MOVE THIS REQUIRED SENTENCE FORWARD???\* The CIRS is a complex cryostat, construction of the dewar and the incorporated camera system will be handled by an outside vendor specializing the cryogenic instrumentation. BBSO personnel will be responsible for initial design and specification of the dewar and construction of the optical interfaces outside the dewar. These will include the image stabilization hardware (correlation tracker), image control and positioning systems (image rotator and scanner), and the overall optomechanical interfaces that interrupt the Coudé light path and feed light to CIRS. BBSO will perform the final integration of CIRS and will develop the control systems and data acquisition hardware and software.

### B.2 The CIRS Development Plan

Design of the CIRS and its support optics will be finalized within the first 6 months of the project. Once the Critical Design Review is completed the work will be able to proceed on 3 fronts.

IR Labs Inc. of Tucson AZ will be contracted to assist with design, fabricate the dewar, build and install the various cryo-mechanisms, and provide a turn-key IR camera system with the sensor integrated in the dewar. This is part of the standard instrument development that they offer. The integrated camera system is a unique product that will save a lot of design and development at BBSO, trimming about 1 year off the project.

BBSO will proceed with development of the optical path to CIRS and integrate the support structures required into the standard optical path to the Coudé Laboratory. The interface to CIRS will be installed as a place holder during the refurbishing of the Coudé Lab's Adaptive Optics system. This will allow Coudé observations to proceed with minimal interruption during the installation and 'static' testing of CIRS.

At the same time BBSO will proceed with CIRS control system development along with the fabrication and testing of the various moving systems that require machine control in the optical path external to the dewar.

Once these tasks are completed and the dewar system has been delivered the BBSO team will integrate the external optical bench and dewar, install internal optical elements and proceed with testing of the overall system. The initial work will be done in our on-shore laboratories and all but final testing can be accomplished with a warm dewar. This will minimize

the testing required once CIRS is installed at the telescope.

After bench tests are complete and the instrument is certified as operational CIRS will be transported to the telescope and installed on the 3rd floor along with its control system and cryo-compressor. This move will require a crane to lift the dewar and bench into position and will likely mean that most of the optics will have to be disassembled for safety and reinstalled at the telescope.

### **B.2.1 The Opto-mechanical Design of CIRS**

A baseline concept has been developed for CIRS with sufficient detail to confirm good optical performance across the desired wavelength band of 1 to 5  $\mu\text{m}$  and identify feasible locations for the dewar and fore-optics. CIRS is configured as an out-of-plane Ebert design using a 79 line/mm grating at an F# of 2340. The grating is a custom length to allow clearance for light paths within the dewar but is readily available from Newport Optics. Light enters CIRS through a side window in the dewar, is folded to run lengthwise and intercepted by the slit. There will be a series of 8 slit-filter combinations housed in a rotating wheel. The image formed at the slit is 100 arc-seconds in diameter and the slit height will be 20mm. The slit structures and filters will be a standard 25mm diameter. Each slit will be sized to 1/2 the diffraction limit at the wavelength of interest and paired with the appropriate order blocking filter in the wheel. All moving elements within the dewar will be power by external motors via standard vacuum feedthroughs. There will be no slit viewing camera but context images can be obtained from the Correlation Tracker camera in the fore-optics module.

Beyond the slit the light will be folded back, passing by the slit mechanism to reach the collimator. The collimator is a standard parabola tilted slightly to move the beam out-of-plane and onto the grating. This allows space for the grating rotation mechanism outside the crossing light paths. In the Ebert design the same parabola is used as the collimator and the focusing element for the detector. This simplifies the spectrograph alignment but presents a challenge for masking the unused portions of the parabola and requires careful attention to scattered light control. The more general Czerny-Turner design which uses 2 off-axis parabolic elements would also be suitable for the

CIRS configuration. Early design work should examine the trades between these 2 designs. In either case the light emerging from the grating is folded again to run lengthwise through the dewar and to shift the beam to the open area opposite the filter wheel where the detector will be mounted on a focus stage. The detector is an InSb 1024x1024 array produced by Ratheon California. IR Labs produces a standard turn-key system that can operate this array at 30 frames/second. The camera will be integrated into the dewar by IR Labs. Light from the 1.6 meter telescope can be directed down the polar axle and transfer optics send the light to the Coude Lab 2 floors below the telescope. The CIRS fore-optics will intercept the light as it exits the polar axle and redirect it to the spectrograph. Since the gregorian focus occurs inside the axle, a set of transfer optics ( a pair of parabolic mirrors ) will be required to place the image in range of the correlation tracker (CT) subsystem. These transfer optics will be moved in and out of the light path on a linear motion stage mounted at the back of the telescope pedestal. A collimating mirror will form a small pupil image on an active mirror that corrects tilt in the incoming wavefront. This is identical to the system already developed for the NST's nasmyth focus. The two systems will be able to share the CT camera and active mirror systems to reduce development cost, if needed. The CIRS dewar and its detector will be maintained at 70-50 Kelvin by means of closed cycle cryo-coolers reducing the thermal background emitted by the spectrograph's optical elements. The slit wheel and slit substrate will provide a good cold mask to eliminate most scatter from the warm elements upstream of the dewar. This will be a substantial improvement over current solar IR spectrographs operating at the National Solar Observatory and Institute for Astronomy which are based on warm optics except for the detectors and order sorting filters. This will be a significant advantage particularly for observations of dimmer targets such as sunspot umbrae and off-limb features.

### **B.2.2 Control Systems**

CIRS will have a number of moving sub-systems and will require sophisticated machine control. The NST project has standardized on Galil motion controllers for all ancillary telescope instrumentation and we will continue that tradition with CIRS. Each Galil motor controller is capable of running control sequences



with onboard firmware. Programming is written in an easy to learn mnemonic language and downloaded to the controller. Standard library functions as well as custom code can be executed via the ethernet. The team is already quite familiar with this control method and can quickly bring the systems on-line. We will use at least 2 motion controllers, likely having one dedicated to the dewar systems and one the Fore-Optics module.

### B.3 Performance Predictions

### B.4 Education and Research Training

???"I THINK THIS SECTION IS MOSTLY OK"???

NJIT has a diverse student body in an urban environment, with a large minority student population. BBSO highly prizes its special role in the education of the next generation of scientists who build instruments. We currently have six PhD students, including 2 US citizens, who will receive PhD's from NJIT in various fields: applied physics, electrical and computer engineering, and computer science. The very best NJIT students are attracted to the BBSO program. The typical student designs and builds the instruments used to make his/her PhD measurements in BBSO, although this is not possible for the CIRS Project.

A PhD student will be involved in this project. However, he/she will be funded by BBSO's five-year NSF-ATM backbone grant. We believe that this project will be a strong draw for talented NJIT students who are already interested in instrument development. The graduate student will be trained in spectrograph design, and will also assist with the set-up, observation and data analysis. In addition, BBSO typically has 1-2 undergraduates who spend the summer at BBSO, as well as working on BBSO projects during the school year. The NST will also become a teaching tool for optics, mechanics, computer control and solar physics.

### B.5 Data and Telescope Time

???"THIS SECTION IS PROBABLY OK, TOO?"

Since NJIT began operating BBSO, its telescope time and data have been open to the community. Many scientists have had observing time. Further, several PhD students from around the world have used BBSO data as a central part of their work on their theses.

Data requests come to BBSO on a daily basis from around the world. We are an active participant in the Virtual Solar Observatory (VSO). Users of our telescopes and data are only asked to acknowledge BBSO in their resulting publications. Many observers have used our data to help plan their observing campaigns.

The observing time of the first, next generation solar telescope in the US, the NST, will be oversubscribed because of its much improved scientific capability compared to the old 0.6 m telescope. We will continue our open observing time and open data policies. We plan to make a portion of observing time available to the community. The Telescope Allocation Committee will rank the proposals and allocate time.

### B.6 Hardware and Personnel Budget

???"LEFT IN THE AO BUDGET DISCUSSION FOR GUIDANCE"???

*The requested budget for the project is \$895 K. The budget is relatively low because the DM (\$275 K) and its controller (\$175 K) will be purchased with other funding that includes a \$100 K match from NJIT. In addition, about \$30 K of the hardware that we already have in hand for AO-76 that will be directly transferable to AO-308. Thus, of the \$780 K in hardware required for this project, only \$300 K will be charged to this grant, highly leveraging the NSF investment in AO-308. As well, NJIT/BBSO and NSO personnel will be working part-time on the AO-308 Project with no charge to the project. The contribution here is difficult to know exactly, but it amounts to about 1 FTE. Most of the key hardware items for AO-308 are shown in Figure ???. These include: 1) the Xinetics DM (\$275 K) and its Controller (\$175 K); 2) the Phantom V7.3 Camera System (\$95 K), which is the WFS camera; 3) three Bittware T26U-OU-445-306-1177 DSP boards (\$55 K); 4) integrated link from the WFS camera to the DSPs to the DM (and tip/tilt) provided by Bittware (\$120 K); 5) PI tip/tilt stage and mirror (\$15 K); 6) host computer (\$15 K); 7) lenslet array and miscellaneous hardware (\$15 K); and 8) one off-axis parabolic mirror (Optical Surfaces, \$15 K) in the AO-76 will have to be replaced. The total hardware cost for AO-308 is \$780 K. Subtracting from this items 1), 5), and 6), our equipment request is reduced to \$300 K.*

The remainder of the budget is dominated by personnel costs of about 2 FTE per year over the three

Figure 4: The Gantt Chart shows the AO-308 project schedule. The chart is “rolled-up” because it is so detailed and would be hard to read. A complete version showing the tasks with each summary unrolled appears in the “Supplementary Documents” section, along with a vertical flow version of the full Gantt chart that is shown there.

year project. The PhD student will be supported by BBSO’s backbone NSF grant. The effort of these personnel will be focussed on all aspects of implementing the AO-308 system.

The main NSO task is the development of DSP code with about 20% of the support for the development of optimized control matrices for AO-308. The travel budget is primarily for collaborating personnel travel between BBSO and NSO/SP.

## **B.7 Management Plan and Timelines**

???MODIFIED DISCUSSION SOME, BUT STILL WILL NEED WORK???

During the building of the NST, we have assembled

a strong instrumentation team at BBSO. The commissioning phase of the NST has just begun at this writing. If CIRS is funded several members of the NST team will be partly shifted to the CIRS project. The implementation of CIRS will, in fact, be part of the commissioning phase since mounting structures need to be integrated with the light feed to the Coudé Lab AO system. Thus, we already have our team in place to do the proposed work and we risk losing essential BBSO staff and our momentum by delaying the start of the CIRS Project.

In the Gantt chart in Figure ?? and in Table 2, we show the major proposed tasks of the CIRS project with timelines, as well as key personnel associated with the tasks. The Gantt chart sketches the CIRS

Table 2: Tasks and Assignments for the AO-308 Project.

Year	Task	Personnel
Year 1	Overall Management and Coordination	R. Coulter
	Interface with IR Labs	R. Coulter, Gorceix and A. Coulter
	Opto-mechanical Design	R. Coulter, Gorceix and A. Coulter
	Fore-Optics Fabrication	Nenow
	External Fabrication Contracts	A. Coulter
	Install Fore-Optics Mount	A. Coulter, Nenow
Year 2	Overall Management and Coordination	R. Coulter
	Interface with IR Labs	R. Coulter, Gorceix and A. Coulter
	Opto-mechanical Design	R. Coulter, Gorceix and A. Coulter
	Fore-Optics Fabrication	Nenow
	External Fabrication Contracts	A. Coulter
	Control Electronics	Abramenko, A. Coulter, and Shumko
	Control Software	Shumko, A. Coulter, and Abramenko
	Integration and testing Fore-Optics	R. Coulter, Gorceix, A. Coulter, Shumko and Graduate Student
Year 3	Overall Management and Coordination	R. Coulter
	Opto-mechanical Design	R. Coulter, Gorceix and A. Coulter
	Fore-Optics Fabrication	Nenow
	External Fabrication Contracts	A. Coulter
	Control Electronics	Abramenko, A. Coulter, and Shumko
	Control Software	Shumko, A. Coulter, and Abramenko
	Integration and testing of Dewar	R. Coulter, Gorceix, A. Coulter, Shumko and Graduate Student
Year 4	Overall Management and Coordination	R. Coulter
	Control Electronics	Abramenko, A. Coulter, and Shumko
	Control Software	Shumko, A. Coulter, and Abramenko
	Integration and testing of Dewar	R. Coulter, Gorceix, A. Coulter, Shumko and Graduate Student
	Installation of Dewar	R. Coulter, Gorceix, A. Coulter, Shumko and Graduate Student
	Testing of Overall System	R. Coulter, Gorceix, A. Coulter, Shumko and Graduate Student
	Routine Operation	Observing Staff

tasks (the detailed chart and vertical flow versions are shown in the “Supplemental Documents” Section). Before CIRS, visible light and NIR NST observations at the Nasmyth focus will be on-going along with the afore mentioned AO construction. The first year of the CIRS Project will be used to refine designs, conduct the normal internal reviews and confirm those designs with IR Labs. Once the designs are finalized we will establish the construction contract for the dewar. The dewar and hardware for the Fore-Optics mount structure will be purchased during Year 1. In Year 2 the BBSO team will concentrate on producing the Fore-Optics hardware and software while the dewar and camera system are being built at IR Labs. Occasional visits to IR Labs will be used to track progress

and stay abreast of any interface issues. Year 3 will see the completion and installation of the Fore-Optics System along with software development and operational testing at the telescope. Once the dewar is delivered work will shift to installation of the optics in the dewar, initial alignment and operational testing of the dewar systems and camera controls. During Year 4 the project will culminate with final operational testing and installation at the telescope. Once test images are processed and approved the instrument will be brought online for observational use.

???DUTIES THAT YOU WILL HAVE TO SPELL OUT. I LEFT IN THE AO STUFF??? PI Roy Coulter will manage and coordinate the diverse elements of the project and oversee the optical and mechanical

design and operation of the system. Nicolas Gorceix, the BBSO optical engineer will complete the CIRS optical design, identify vendors, oversee purchasing and assist with integration and testing. Aaron Coulter will be responsible for mechanical design (with assistance from R. Coulter), outside fabrication contracts, machine control, along with integration and testing. Jeff Nenow (mechanical engineer) will be responsible for on-site fabrication and assist with assembly. Vlad Abramenko (electronics engineer) will design and build the electronic interfaces and control hardware. Sergiy Shumko will handle all high level software included interfacing CIRS to the NST Telescope Control System and participate in integration, testing and initial operations. R. Coulter will oversee training of observing staff and production of documentation, maintenance, and user manuals.

## C. References

- Cao, W., Denker, C., Wang, H, Ma, J., Qu, M., Wang, J., & Goode, P. R. 2004, *Characteristic Evaluation of a Near-Infrared Fabry-Perot Filter for the InfraRed Imaging Magnetograph (IRIM)*, SPIE, 5171, 307-315
- Cao, W., Jing, J., Ma, J., Xu, Y., Wang, H. and Goode, P.R., 2006, *Diffraction Limited Polarimetry from Infrared Imaging Magnetograph of Big Bear Solar Observatory*, PASP, 118, 838-844
- Collados, M., 2005, in Solar Polarization IV workshop, Boulder CO.
- Didkovsky, L, Dolgushyn, A., Marquette, W., Hegwer, S., Ren, D. Fletcher, S. Richards, K., Rimmele, T. R. Denker, C. and Wang, H. 2003, *High-order Adaptive Optical System for Big-Bear Solar Observatory*, Proc. SPIE, 4853, 630-639
- Goode, P. R., Denker, C. J., Didkovsky, L. I., Kuhn, J. R. and Wang, H., 2003, *1.6 M Solar Telescope in Big Bear – The NST*, JKAS, 36, 125-133
- Harvey, J.W. et al., 2003, AGU meeting #SH42B-0545
- Kurucz, R.L, Bell, B., 1995 Atomic Line Data, Kurucz CD-ROM No. 23. Cambridge, Mass.: SAO
- Lin, H., 1995, *On the Distribution of the Solar Magnetic Fields*, ApJ, 446, 421
- Madec, P.Y., 1999, in *Adaptive Optics for Astronomy*, F. Roddier ed., Cambridge University Press, 131
- Penn, M.J., Cao, W.D., Walton, S.R., Chapman, G.A. and Livingston, W., 2003, *Imaging Spectropolarimetry of Ti I 2231 nm in a Sunspot*, Sol. Phys., 215, 87
- Rabin, D., 1992, *A true-field magnetogram in a solar plage region*, ApJ, 390 L103
- Rüedi, I., Solanki, S. K., Keller, C. U., and Frutiger, C., 1998, *Infrared lines as probes of solar magnetic features. XIV. Ti I and the cool components of sunspots*, A&A 338, 1089

Stenflo, J.O., 1992, in IAU Symp. 141, ed. Zirin, Ai & Wang, 205

Sturrock, P. A., 1989, Proceedings of Max'91 Workshop, p. 1

Wallace, L. and Livingston, W., 2003, NSO Technical Report #03-001