

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

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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 μm 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 μm for the New Solar Telescope (NST) for observations at the Nasmyth bench. Firstlight observations were made in January 2008 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.*

A.2 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 location of the thermal 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.bbso.njit.edu/newtelescope>.

The NST is configured as an off-axis Gregorian system consisting of a parabolic primary, prime fo-



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

cus 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 with a final figure residual error of 16 nm rms. The PM was figured 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 Nasmyth. 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 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 (A. Coulter, 2008, private communication). In addition, we have implemented a closed cycle, chilled air knife 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

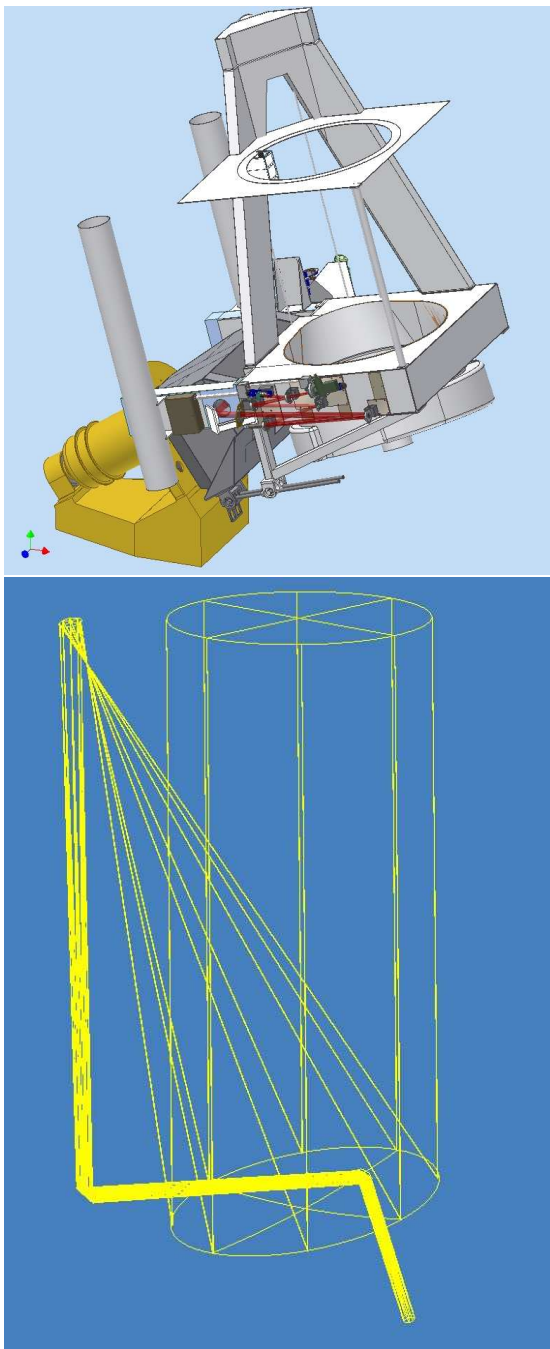


Figure 1: Schematic of the 1.6 m off-axis, open NST (top) and its optical layout (bottom). On the top part, the heat stop (HS) resides at the Gregorian focus with the SM mounted on a PI hexapod. The wavefront sensing system (WFS) resides immediately before M3 (along with the polarization optics for magnetic 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>.

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.

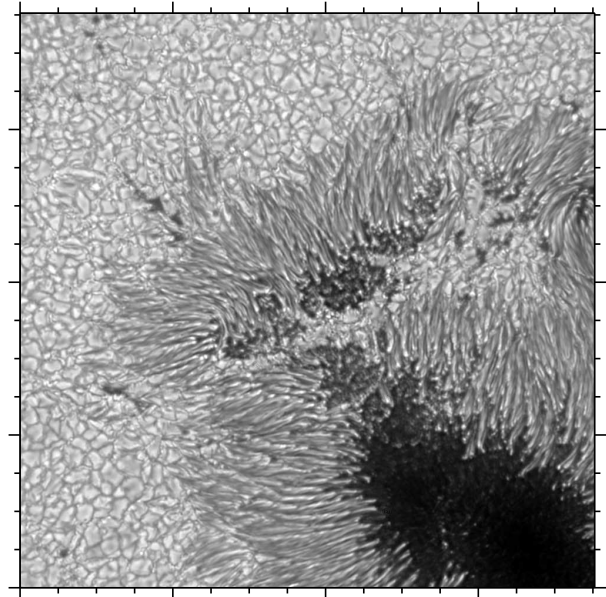


Figure 3: A diffraction-limited image obtained on the NST at the Nasmyth focus (???NEED REAL FIGURE WITH R0 TO DEMONSTRATE KOLMOGOROV SEEING, ETC???)

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.

A.3 Strehl Ratio of the Beam Feeding the Spectrograph

Ideally, we would like the Nasmyth Bench spectrograph to be fed with diffraction limited light over the entire 1.0-5.0 μm 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 see-

ing 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 modelling 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 $1\text{-}5 \mu\text{m}$ 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.4 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.

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 λ 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.5 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 Thermal IR Spectrograph, CIRS.

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

Region	Species	λ [nm]	g_{eff}	Mag Sensitivity λg_{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

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 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

B.2 The CIRS Development Plan

???THESE SECTION HEADS ARE LEFT IN FOR GUIDANCE AND USE, IF LOGICAL???

B.2.1 The Optical Design of CIRS

B.2.2 Electronic, Computational and Mechanical Systems

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

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.

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 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. As a part of this phase, some members of the NST team will be partly shifted to the CIRS project. The implementation of CIRS is, in fact, part of the commissioning phase. Thus, we already have our team in place to do the proposed work and we risk losing

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

Year	Task	Person In Charge
Year 1	Overall Management and Coordination	Rimmele
	Interface with NST	Goode, Gorceix and Cao
	Optio-mechanical Design	Rimmele and Gorceix
	DSP Control Software	Richards and Varsik
	NST Wavefront Data Analysis for AO-76*	Gorceix and Cao
	VIM and IRIM on NST with AO-76*	Cao and Graduate Student
Year 2	Overall Management and Coordination	Rimmele
	Interface with NST	Goode, Gorceix and Cao
	Optical Design Implementation	Gorceix
	DSP Software	Richards and Varsik
	DSP Hardware Integration	Varsik and Richards
	Reconstruction Matrices	Rimmele and Marino
	Wavefront Data Analysis for AO-308	Gorceix and Cao
	VIM and IRIM testing with AO-308 on NST	Cao and Graduate Student
Image Reconstruction with AO-308	Andic	
Year 3	Overall Management and Coordination	Rimmele
	Interface with NST	Goode, Gorceix and Cao
	Performance Testing of AO-308	Rimmele, Gorceix and Cao
	Software and Electronics	Varsik and Richards
	Wavefront Data Analysis for AO-308	Gorceix and Cao
	Regular Observations with AO-308*	Team

essential BBSO staff and our momentum by delaying the start of the CIRS Project.

In the Gantt chart in Figure 4 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 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. The NST is now beginning its commissioning phase. The main tasks in the first year of the AO-308 Project will be the PDR followed by a careful consideration of alternative hardware, which is followed by the final, external design review. Then comes the immediate purchase of the CIRS hardware. With the hardware in hand, the optical, electronic and mechanical designs of the CIRS system will be implemented, along with its interface to the NST and the focal plane instrumentation in the second year. This timing will leave the BBSO staff in a good position to undertake CIRS. The main tasks in the second year will be... The tasks for the

third year are ...

???DUTIES THAT YOU WILL HAVE TO SPELL OUT. I LEFT IN THE AO STUFF??? PI Coulter will manage and coordinate the diverse elements of the project. Co-PI Goode is in BBSO about 50% of the time, so he will provide hands-on leadership, and coordinate the joint efforts between NSO and BBSO. Rimmele will oversee the optical and interface designs of the system, which is the most difficult part of the project. Nicolas Gorceix, the BBSO optical engineer, has completed the optical AO-308 design, which has been reviewed by Rimmele. As mentioned above, more formal review processes will occur when the project is funded. Goode will oversee the integration of the AO system and the NST, as well as the work of Jeff Nenow (mechanical engineer) and Vlad Abramenko (electronics engineer) in this integration process. Rimmele will closely work with Kit Richards on the interfacing of the WFS camera, the DSP’s and DM control. Kit Richards at NSO and John Varsik at BBSO will be in charge of the software development, which is primarily DSP control with Varsik helping to

test and implement Richards' code in BBSO. A key component in the AO development is to convert from wavefront information to the movements of the actuators (reconstruction matrices). Rimmele will lead José Marino in this wavefront analysis, as Rimmele has significant experience in handling wavefront analysis for AO-76. Marino did such work when he was Rimmele's Ph.D. student at NJIT. Co-PI and NJIT Assistant Professor, Wenda Cao, is well-experienced in the BBSO AO-76 system and was a key developer of the IRIM and VIM. He will be responsible for integrating these instruments into AO-308. Aleksandra Andic, a new postdoc in BBSO, is an expert in image reconstruction, and she will see that speckle and phase diversity software is implemented into the data stream. BBSO had NSF-ITR funding in which this software was developed. Rimmele, Goode and Cao will also ensure that the AO-308 design will match the scientific requirements as sketched in Section A.2.

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