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The SOAR Telescope Project
Southern Observatory for Astronomical Research (SOAR)

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Final Report

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14. ABSTRACT
This final report describes work done over the life of the grant on the SOAR Telescope project. SOAR will be a 4.2 meter aperture telescope employing state-of-the-art technologies to deliver high-resolution images that are limited only by the excellent seeing conditions of this site on Cerro Pachon in northern Chile. SOAR is a joint project of the University of North Carolina at Chapel Hill, Michigan State University (MSU), the Conselho Nacional de Pesquisas Cientificas e Tecnologicas (CNPq) of Brazil, ant the Association of Universities for Research in Astronomy (AURA) (acting on behalf of the National Optical Astronomy Observatories). Most major subsystems have been completed, and progress on remaining tasks now indicates an October 2003 date for first light. The polishing of the primary mirror, and subsequent delivery of the active optical system, remains as the final pacing element.

15. SUBJECT TERMS
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I. SOAR Telescope Construction Overview

This document is the final report on progress in constructing the SOAR telescope. SOAR has been built with partial support from an AFRL grant (F29601-98-1-0032) to the University of North Carolina. This report is intended to provide the Air Force Research Laboratory (AFRL) with both an overview of the work done in the past 12 months (from March 2002 through March 2003) and an overall summary of the status of the telescope and facility at the completion of the grant.

SOAR is a 4.2-meter aperture telescope employing state-of-the-art technologies to deliver high-resolution images, which are limited only by the excellent seeing conditions of its site on Cerro Pachon in northern Chile. It is designed to operate from the near-ultraviolet through the near-infrared ($\lambda\lambda 0.33 – 2.5\mu m$). SOAR is a joint project of the University of North Carolina at Chapel Hill, Michigan State University (MSU), the Conselho Nacional de Pesquisas Cientificas e Tecnologicas (CNPq) of Brazil, and the Association of Universities for Research in Astronomy (AURA) (acting on behalf of the National Optical Astronomy Observatories).

In aggregate the bulk of the telescope, its systems, and the facility are complete. The building, dome, and mount are finished and have been subjected to months of commissioning and test. Over the next several months, culminating in about August 2003, the active optical system will be delivered in Chile and integrated with the telescope, as well as several of the first generation instruments. The remaining pacing elements in this schedule are the last stages of polishing of the primary mirror, its test, shipping, and aluminizing. Consider delay has occurred in the primary mirror polishing. This loss of schedule became of sufficient concern that the SOAR project invited an outside panel of experts to review the progress to date and the processes being applied by the contractor, to thereby advise the board on the likelihood of the contract being successfully completed. We discuss extensively the active optical system in this report and also attach a copy of the report of the independent review committee. In brief, it now appears that the polishing of the primary mirror is converging within a (probably) acceptable aperture. Based on this progress, the project currently expects integration of the active optical system in about August 2003 with the potential of first light in October 2003.

In what follows we provide a more detailed overview of progress, broken down by WBS element.

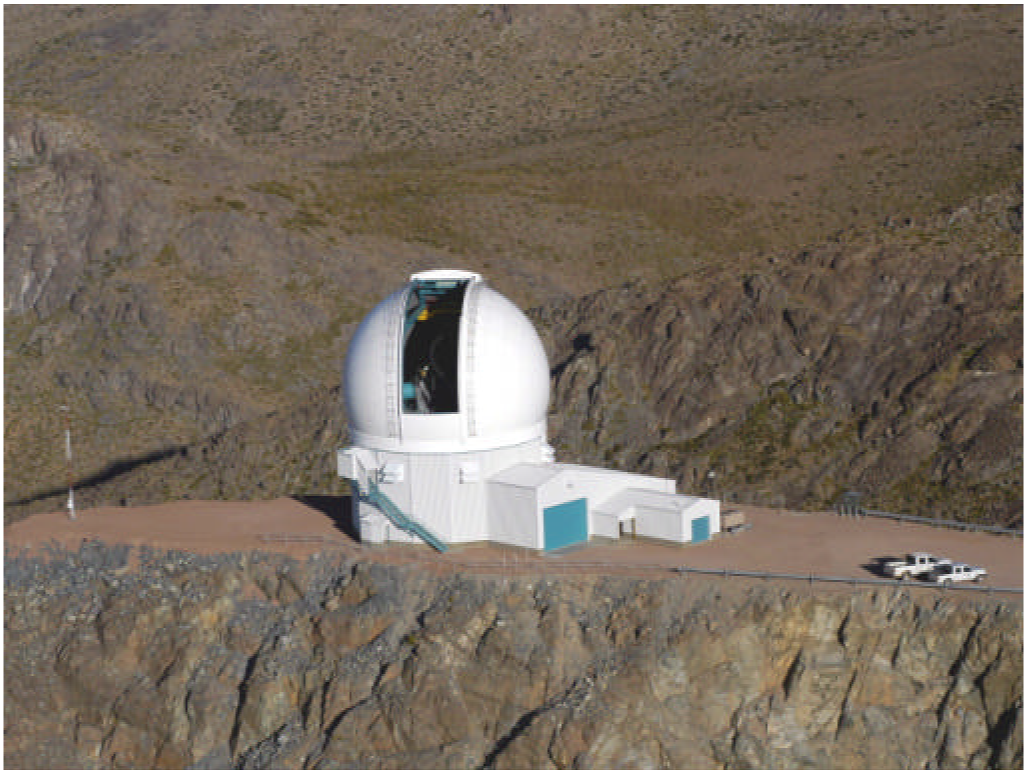

Figure 1: The SOAR telescope on Cerro Pachon in Chile.

II. Present Status by SOAR Project System Element

Figure 2. The SOAR facility on Cerro Pachon in northern Chile prior to installation of the dome in March 2002

1. Facility and Site

Aura Observatory Support Services (AOSS) managed the construction of the facility in Chile. The general contractor was Puga Majuica S.A. (PUMA), a Chilean firm. Initial design was provided by M3 Engineering (US). Geotecnica (Chile) provided additional design and construction support. PUMA's work was accepted in May 2001, with remaining, smaller-scale tasks being handled on a continuing basis by AOSS and SOAR. While the facility was completed in May 2001, this past winter (May through September 2002) was the first since being mated with the dome. Prior to the installation of the dome, the facility had been capped with a temporary plywood roof (see figure 2 above), placed there to accommodate the slip in scheduled delivery of the dome. Most of the project team transferred to Chile in May 2001 which accelerated the completion of interior work such as installation of furniture and tools, certification of the manlifts, installation of a protective cage for the elevator, establishment of a high-speed data link to the Gemini building, work on the electrical, HVAC, plumbing, and fire alarm systems, etc.

Last May through September (2002) the combined SOAR facility and dome passed through their first winter. The severe weather revealed some weaknesses in the original design, materials and systems. A silicone seal is now being added to the exterior panel system. In addition, foyers are being added at each of the exterior doors. To provide a computer network backup, a radio link is being added. Similar remediation was necessary with the dome (see below).

In the past twelve months additional infrastructure improvements have been made. The facility compressor was installed. Some residual steps in developing the site have been taken, including installation of perimeter and equipment protection, access to the water plant, and installation of a temporary sky seeing monitor.

Integration of the dome and telescope mount was hard on the interior of the facility. In the aftermath of this activity the observing room floor has had to be restored. The entire interior has been inspected and repainted as necessary, and some concrete and guardrail repair was necessary. The present thrust of activity (March 2003) is on protection against winter weather. Fan louvers and vent shutters are of particular concern. A few subsystem installations remain: The instrument chiller is being installed in March 2003; the compressed gas system in April; and intra-facility air and light seals are being improved.

The original budget for the site and facility was $3,860,873. Total expenditure was $3,256,852. The *facility and site* WBS element was closed out and additional work is assigned to *integration*.

Figure 3. The SOAR site. View of SOAR from access road; installation of guardrail.

Figure 4. Aerial view of completed SOAR dome and facility.

2. Dome

The preliminary design of the dome was handled by M3 (US). A Brazilian firm, Equatorial Sistemas led the construction, with a major subcontract to Ratech Industries (US) for the fiberglass panels. The dome was not delivered prior to the start of the 2001 Chilean winter as the contract stipulated. Instead, acceptance testing was finally conducted on 24 July 2001. The dome was declared sufficiently acceptable and Equatorial was told to proceed with disassembly and shipping. The dome was to have been shipped prior to the revised delivery date of 15 September 2001. Instead, shipping did not actually begin until 9 November 2001. Further delay subsequently occurred when one of the six trucks was involved in a highway accident in Brazil. The remaining five trucks continued on and reached Cerro Pachon on 26 November 2001. Some of the components from the truck that was involved in the accident were damaged. Indeed, several large beams, including both crane beams and cross beams for the shutter assemblies were damaged beyond repair. Salvaged parts arrived on Cerro Pachon on 9 January 2002. SOAR elected to have components remanufactured in Chile.

The project also had to cope with the bankruptcy of the subcontractor, Ratech Industries, which had been contracted to supply the dome panels. Ratech filed for Chapter 11 on 11 May 2001. The SOAR project reached an agreement with Equatorial to allow SOAR to take over direct management of the contract with Ratech. Over the next several months the SOAR project team worked closely with Ratech management and managed to get all of the remaining dome panels fabricated and delivered.

Construction of the dome was accomplished between February and May 2002. A number of shortcomings were found in manufactured dome components and these elements were re-machined or replaced by the on-site SOAR team. Substantial reassembly of the dome electronics was required.

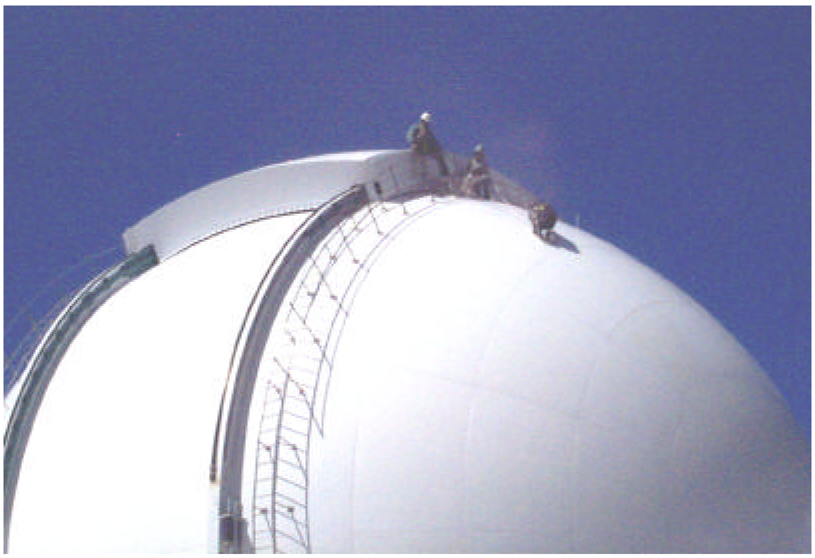

Figure 5. Exterior of the SOAR dome being painted.

The 2002 winter revealed some shortcomings in the dome design and in what was actually delivered by the contractor. The panel system has recently been subjected to a program to seal all of the panel joints. The shutter seals have also required work. An effort is underway presently to fabricate steel parts for the shutter seals, which were missing when the dome was assembled last year. Additionally, work remains to be done on installing contact brushes/rubber seals at the joint between the base of the dome and the building. Finally, with the panel joints sealed, the entire interior and exterior of the dome has been painted.

The installation of the lightning protection system and the wind screen remain to be done and are scheduled for April 2003.

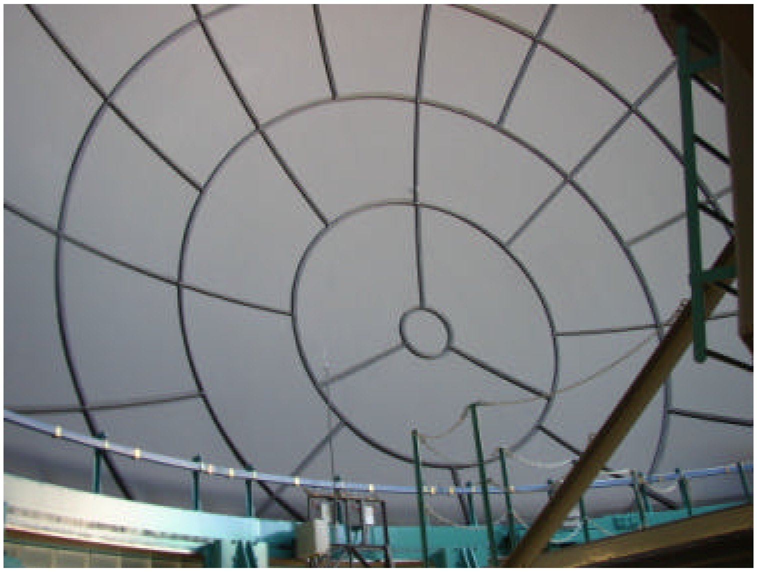

Figure 6. Interior view of the SOAR dome and panel system.

One area of concern is the performance in azimuthal rotation of the dome and in the movement of the shutter. The maximum azimuth speed is 1.5 degrees per second, while the specification called for 2.5 degrees per second. Full rotation requires 4 minutes. For comparison, the mount is able to slew at a rate of 2.0 degrees per second. The shutter is limited to 0.38 degrees per second, compared to a specification of 2.5 degrees per second. Shutter motor remounting and shutter realignment may mitigate some of the shutter performance loss. SOAR is making a detailed review of these issues and collaborating with SEW Brazil, the original subcontractor. An increase in performance would require a major overhaul, including new motors and gearbox assemblies, new variable frequency drives, and new power rails for the shutter.

The original budget for the dome was $1,923,972. Total expenditure ended up being $1,892,507. The *enclosure dome* WBS element was closed out and additional work has been assigned to *integration*.

3. Active Optical System (AOS):

Goodrich Aerospace is the prime contractor for the active optical system (AOS). The substrates were fabricated by Corning Glass and delivered to Goodrich in April 2000. The design and development of the active optical system has suffered considerable slippage in schedule, with the polishing of the primary mirror controlling the critical path. The original delivery date of the AOS was set at 2 August 2001. The current date projected by Goodrich for shipping is 11 June 2003.

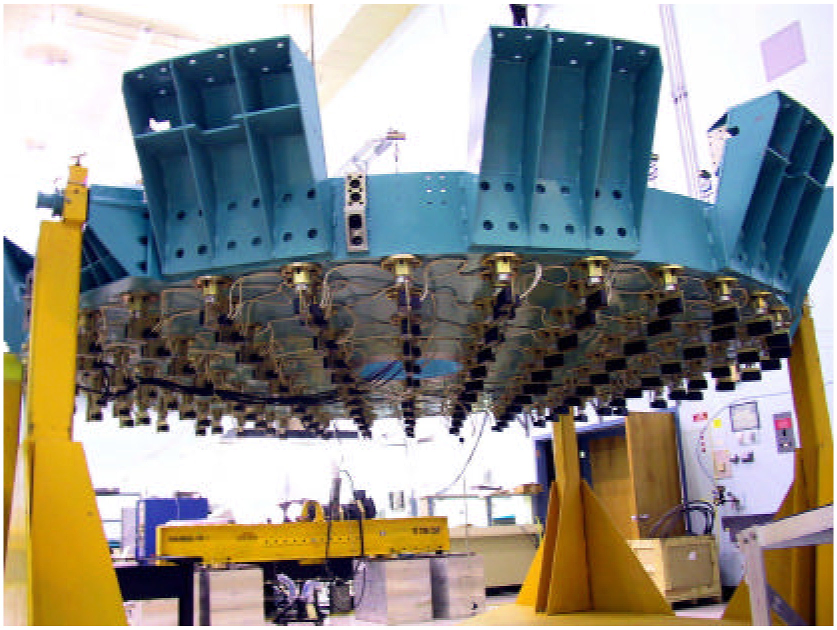

Figure 7. Active primary mirror cell on test stand at Goodrich Aerospace.

Given the significant delay, SOAR assembled an Independent Review Committee (IRC) of outside experts to review Goodrich's progress and to advise the board of directors on the likelihood of successful completion of the active optical system, on remaining risks, and on probable schedule. The committee was comprised of

- Wolfgang Bauer, Chair, Physics and Astronomy Department, Michigan State University
- Wayne van Citters, Program Director of Astronomical Sciences at the NSF
- Harry Feinstein, AURA legal counsel
- Jerry Nelson, Project Scientist for the Keck Telescope during design and construction
- Jim Oschmann (Chair), Deputy Director for the Gemini Telescope during construction, now Project Manager at the National Solar Observatory
- Robert Shelton, Provost of the University on North Carolina at Chapel Hill
- Bill Smith, President of AURA

The specific charge to the committee was: (1) Determine and state the underlying reasons for schedule loss in the program. This is to include all components and subsystems. (2) Identify remaining critical risk areas and potential approaches to mitigation in completion of the contract. (3) Assess the probability of Goodrich's successful completion of the contract and the likely completion date based upon the information provided.

In response to its first charge, the IRC noted that the pacing element has been the primary mirror. The most critical piece of equipment is the Arboga grinding and polishing machine, which was previously used at ITEK and had not been used extensively by Goodrich in Danbury until the SOAR primary mirror work began. The committee found that the following list of issues impacted the schedule:

- Equipment characteristics were not adequately understood
- Equipment reliability was not included in schedule planning
- A few specific grinding and polishing errors led to significant delays. These were based on surface metrology errors
- Initial scheduling was overly optimistic on convergence rate and other efficiencies
- Insufficient management attention to the program early on may have contributed
- Recent conflicts with other government programs (minor impact so far)

The IRC found that more recently the equipment risks had been significantly reduced, that the project was now receiving good management and technical staff attention, and that Goodrich was knowledgeable about their processes and problems.

Figure 8. Primary mirror cell showing the actuators ready for bonding and the laminar airflow system (dark ring).

On the second charge to the committee, of identifying remaining critical risk areas and potential approaches to mitigation, the committee focused on three areas of particular concern. The first of these dealt with the rate of convergence in polishing and the removal goals of each polishing run. The IRC felt that Goodrich now had a better handle on the convergence rate. Previously the predicted and actual convergence rates had differed by roughly a factor of two. The committee was concerned about Goodrich's plans to make default use of a high number of the actuators to correct for polishing aberrations. The IRC preferred that Goodrich plan on only removing low-order aberrations. They advised that each remaining polishing run be used to attack the uncorrected figure, using the actuator corrections as a final step only to determine the overall quality. The second issue highlighted by the IRC was the integration and test phase at Goodrich. They stressed that the integration and test schedule is optimistic and that delays can be expected. Additional concern was expressed about the potential for cross talk between different actuator modes and the likelihood of actuator performance degradation and calibration drift over time. Again, the IRC urged that the polishing effort work toward *a priori* use of the active supports only to correct lowest order modes. The third risk area the IRC highlighted was the integration, test and commissioning phase in Chile. The IRC concluded that other SOAR telescope subsystems are in exceptional shape but that experience on other large active telescopes argues for caution in believing that a three-month commissioning phase is feasible or that early science use will be productive.

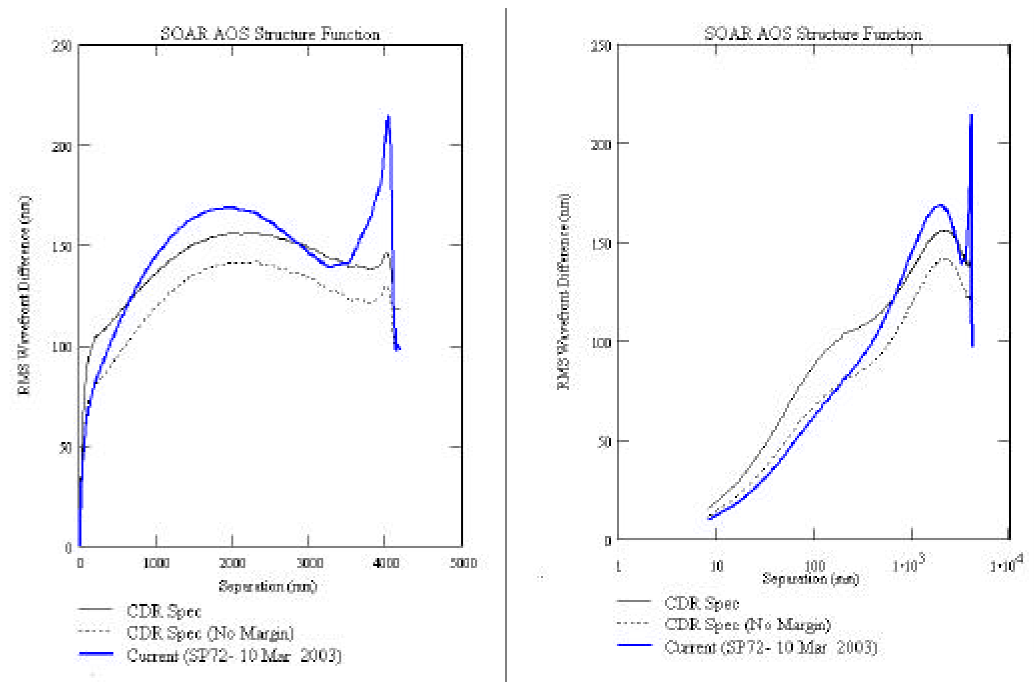

Figure 9. Present AOS structure function following polishing run SP72, compared to requirement.

The committee concluded that Goodrich is likely to complete the contract (i.e., the primary mirror), though their scheduled ship date of early June 2003 is optimistic. Key to this estimate, and any other, is a pending decision on whether the primary mirror meets specifications, whether the specifications will be relaxed in favor of avoiding additional polishing time, or whether the project will push to obtain specified figure over the entire clear aperture. Only a two-week period is set aside for optical testing once the polishing concludes and there is the potential that other government-sponsored projects may compete for and take priority over the use of the grinding and polishing facilities.

At this writing, the latest tests indicate that the primary mirror is near to meeting the specified figure over an aperture diameter of 4.1 meters, but that a series of grooves lie within the outermost 7.5 cm of the edge. These features may be as deep as 5 microns. If so, their removal to meet the specified clear aperture of 4.2 meters would require at least an extra three months of polishing. By the end of March 2003 the SOAR Scientific Advisory Committee (SAC) and project team are expected to consider the latest optical test and simulation data, to consider the trade-offs, and to make a recommendation to the SOAR Board as to how to proceed.

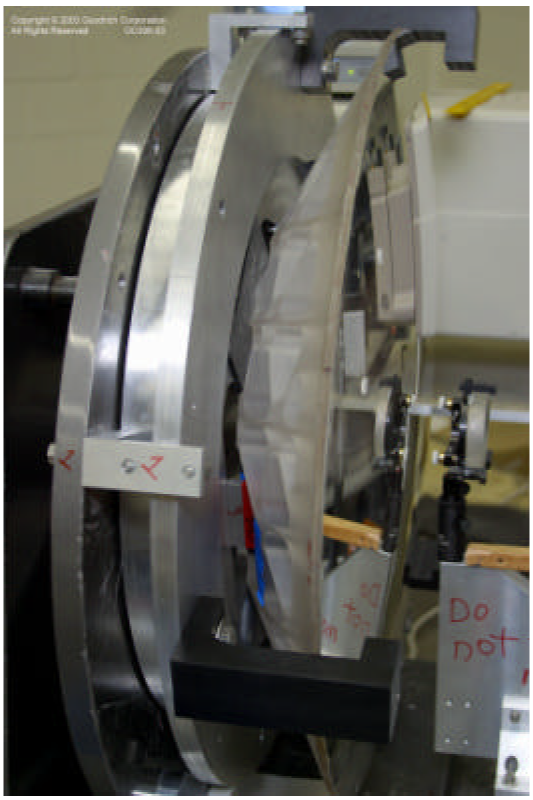

Figure 10. SOAR secondary mirror in test stand at Goodrich Aerospace.

Also as of this writing, the secondary mirror (M2) is nearly complete. The surface error is at 11 nm when the full allowable 10 lbs of actuator range is committed to compensate for residual errors. Another polishing run (S2-17) is underway, targeted to maintain at least the 11 nm residual but with only 6 pounds of force applied. Immediately following, a super polish will be made to achieve the desired degree of micro roughness. This surface will be better than specified, allowing some margin for shifts that may occur once the part is trimmed to the final outer diameter. Thus, M2 is very near to being accepted.

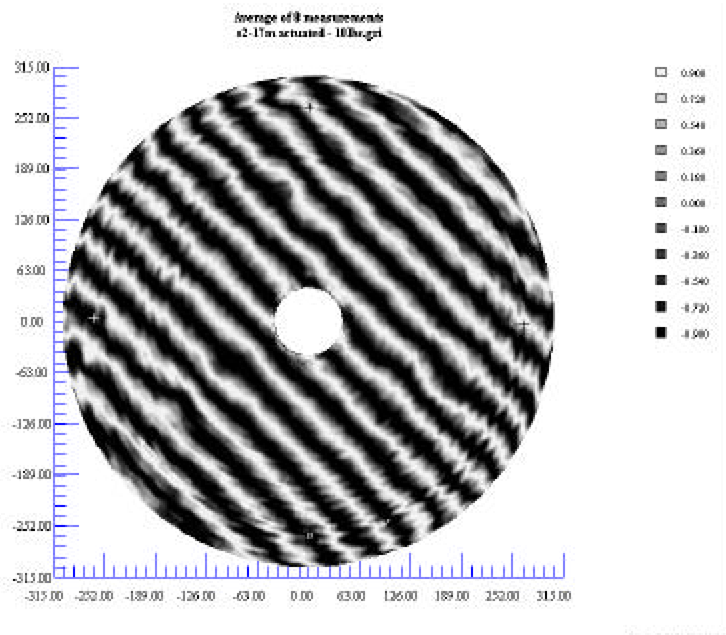

Figure 11. Simulated interferogram of the SOAR secondary mirror based on computed actuator inputs.

The tertiary mirror (M3) has been accepted. The astigmatism and power are 100 nm rms, as compared to the requirement of 70 nm rms. While these measures do not by themselves pass, they are correctable with the actuators on M1. The maximum force required on M1 to correct the 100 nm rms residual on M3 is 0.1 pound. Up to 1 pound had been budgeted to compensate for M3 fabrication errors. Hence the astigmatism and power are being regarded as acceptable. Instant aperture errors range over the mirror at the level of 12 to 18 nm rms. This compares to a requirement of 20 nm rms. M3 passes this measure. The structure functions meet the requirements. There is some print through of the mounting posts but the surface still meets the rms and structure function requirements.

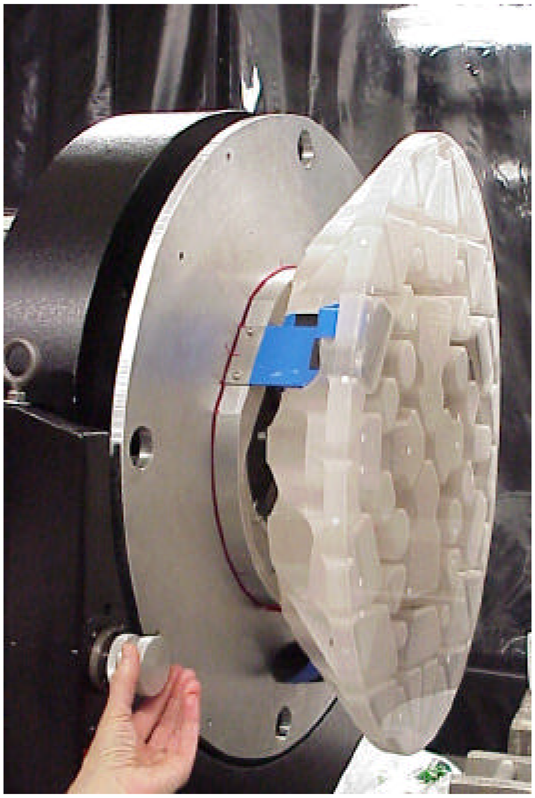

Figure 12. SOAR tertiary mirror in its active cell, prior to aluminizing.

Finally, the project plans to coat the primary mirror in the Gemini facility in Chile. The coating approach has been well defined through numerous meetings with the Gemini project's engineering staff. The present schedule for delivery of the SOAR optics in Chile is compatible with Gemini's schedule. However, because part of the aluminizing facility at Gemini South is shared with Gemini North in Hawaii, a schedule slip might involve the primary mirror arriving while the aluminizing facility is inoperative. This scenario would require that the magnetron be returned from Hawaii. In addition, given the first time use of new hardware, it is unlikely that the first coating will be optimized.

The original budget for the active optical system was $10,029,455. The current budget for the AOS is $10,149,784. The *active optical system* account remains open.

4. Telescope Mount

VertexRSI, Inc. of Texas built the SOAR telescope mount. V. Krabbendam within the SOAR project office served as the manager for the mount subsystem. The final acceptance testing for the mount was held on 5 October 2001. The mount met its specifications and was regarded by the project team as a fully successful subsystem. At the acceptance test, the system blind pointing was within 1 arc second and the tracking jitter was less than 0.08 arc seconds rms.

VertexRSI subsequently disassembled the mount and shipped it to Chile on 4 February 2002. The shipment arrived in La Serena in March 2002 and reached the summit of Pachon. Assembly of the mount followed close on the heels of the construction of the dome. Over the subsequent six months the project team has been able to refine the control over tracking and pointing and feels that the mount is fully commissioned.

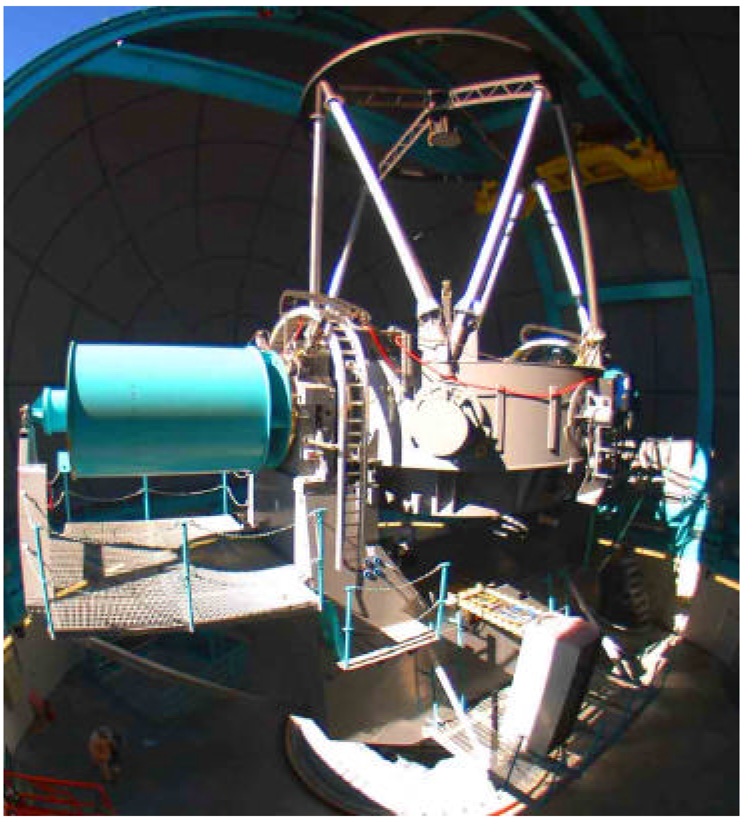

Figure 13. The SOAR telescope mount. Evident in the image is the dummy instrument load, several bent cassegrain ports, and the cable wrap.

The capabilities of the mount have now been fairly well demonstrated. The specification for maximum slewing rate is 3 degrees per second and the slew acceleration is 1 degree per second per second. The blind pointing accuracy was required to be less than 2 arc seconds, with less than 0.5 arc seconds as a goal. When the offset is less than one degree, the pointing accuracy was specified to be less than 0.2 arc seconds rms. The following table gives the measured slew rate and slew acceleration.

	Azimuth	Elevation	Nasmvth
Velocity deg/sec	2	2	5
Accel deg/sec2	1.2	1.1	2.6

Table 1. Measured slew and acceleration rates of the SOAR telescope mount.

The measured pointing accuracy, both blind and offset, is given in the next table.

Arcsec Peak	Azimuth	Elevation	Nasmyth
Blind, all Sky	1.3	2.2	6.4
Offset	.01	.26	3.2

Table 2. Measured blind and offset pointing accuracy of the SOAR telescope mount, in seconds of arc.

The measured tracking drift rate (open loop) is shown in the following plot on the left, and shows a mean rate of about 0.012 arc seconds per second. The plot on the right shows the residual tracking errors with the mean drift rate removed.

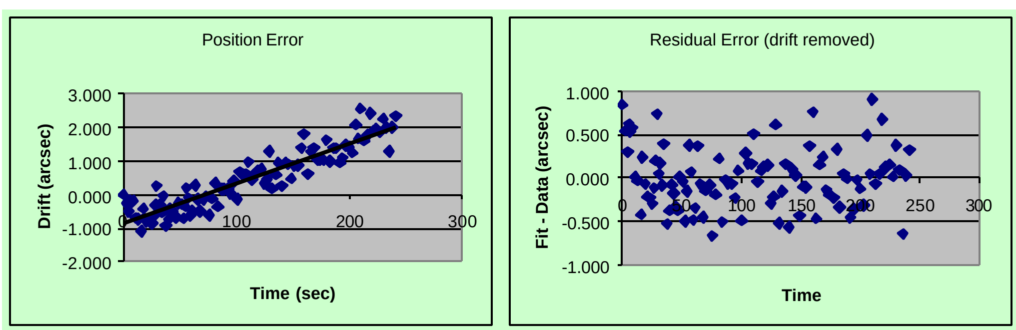

Figure 14. Measured tracking drift rate and residuals for the SOAR telescope mount.

Presently, the focus of activity on the mount is in making final optical support system alignments. Temperature sensors are being installed. In April, the instrument selector cage (ISC) will be installed. In addition the bench for the optical imager will be installed on the designated the bench cassegrain port.

The original budget for the telescope mount was $3,754,846. The account for the telescope mount was closed with total expenditure of $3,900,856. Remaining activities are covered by the integration account.

Figure 15. Instrument selector cage

5. Optical Assemblies

Optical assemblies covers a number of systems. The project has taken delivery on the first guider camera—a Leach fast CCD camera. Performance of this first guider is to specifications. The readout noise is less than 4.2 electrons and the dark current is 12 electrons per pixel per second. Orders have been placed for the second and third units.

Part of this WBS category involves the instrument selector boxes (ISB). There are two ISBs, one that selects between optical instruments on one Nasymth port and one that selects between infrared instruments on the other Nasymth port. The IR side ISB is due to be delivered in July 2003 and the optical ISB in August.

The calibration wavefront sensor (CWS)/ acquisition camera system is completed and remains in La Serena. It will be sent to the site in March 2003 and it will be mounted on the telescope in April.

The budget for optical assemblies is fixed at $415,845.

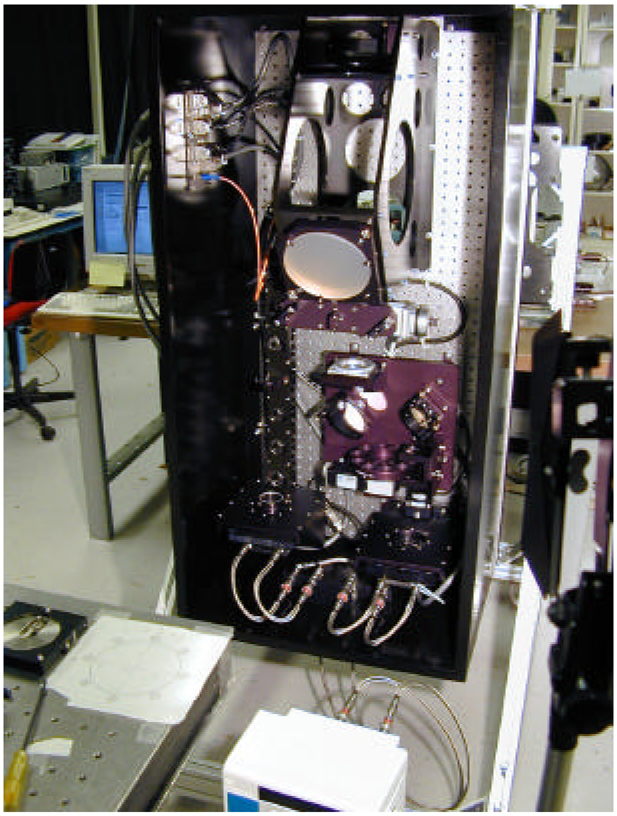

Figure 16. Calibration wavefront sensor

6. Electronics and Controls

A second-generation weather station has been built on the SOAR site. This category covers the entire panoply of HVAC, power, water, air control, and other environmental controls. It also includes the emergency stop system. All of the above systems have been installed. New systems being added include the instrument chiller and the calibration lamp system.

The original budget for electronics and controls was $577,268. The actual expenditures to date are $660,828. This account is closed and residual work is being handled by the integration budget.

7. Software and Computers

Software development is ongoing but is an extensive, labor-intensive task and is now nearly on the critical path. The telescope control system (TCS) will be distributed among individual PCs that use a PCI or compact PCI computer bus. The TCS and the instrument control systems are based upon National Instruments LabView. Software contracts were awarded to Imaginatics and Rutherford Appleton Labs, for modification of Patrick Wallace's TCS software (kernel) that was developed for several previous telescopes. LabView provides the interface between graphical user interfaces and instrument control. In addition to these external contracts to begin the development of the TCS, the SOAR project is doing internal software development and obtains compatible software from some of the subsystem vendors to control, for example, the active optical system, the mount, and the calibration wavefront sensor. The project is building control software for the dome, the environmental control system, the ArcVIEW CCD controllers, the guiders, and the instrument selector boxes.

Software development is under version control. The release date for the largely complete version 1.0 is March 2003. After that the project plans several subsequent releases on a monthly basis through August 2003.

The original budget for software and computers was $826,827. The current budget is $1,082,605. The account is still active.

8. Systems Engineering

The original budget for systems engineering was $1,084,288. The account was closed out in September 2002 with expenditures of $405,686. This WBS area was closed out early for accounting convenience. Work is spread over other categories.

9. Integration and Test

Major expenses in this category have included contracting for the integration crane for several months, hiring of the dome integration crew, the Pachon buy-in, and AOSS charges. A remaining purchase includes the ambient chiller system. The original budget for integration and test was $937,780. The present budget is $1,041,310 and the account remains open for a variety of tasks.

III. Status of the High Throughput Spectrograph

The University of North Carolina was selected by the SOAR project to provide one of the first-light instruments for the SOAR telescope. Co-PI Christopher Clemens is leading the design and construction of a high throughput (optical) spectrograph in the UNC Goodman Laboratory. Funding for the high throughput spectrograph derives in part from this grant. The spectrograph is an all-refracting imaging spectrograph using state-of-the-art volume phase holographic gratings. It will provide low to medium resolution spectroscopy over the wavelength range 320 to 850 nm and imaging over a 5' square field.

The schedule for constructing the spectrograph has expanded in congruence with the telescope integration schedule. As of March 2003, the mechanical and optical components of the spectrograph are 95% complete. Assembly and integration of mechanical and optical components are underway. The figures below show details of some of the spectrograph assemblies.

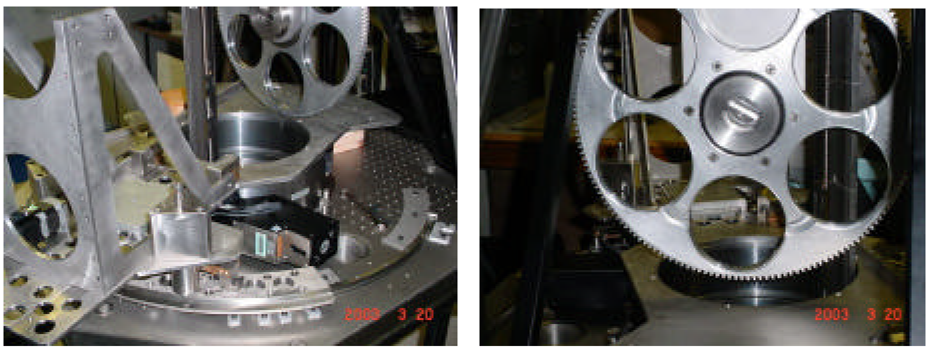

Figure 17. Assemblies in the Goodman Spectrograph

The photo on the left shows the flexure mounted camera platform, which is assembled and ready to receive optics tubes and detector (which will be integrated after delivery to the site in Chile). The photo on the right shows one of two removable filter wheels in the spectrograph. We expect all mechanical assemblies to be complete and tested on or before May 2003. The optics for the camera and collimator are also complete (see below) and ready for assembly into the optics tubes.

Figure 18. Optics for the Goodman Spectrograph

We have also completed substantial parts of the development of the software control system using the LabView graphical programming language. The picture below shows the front panel interface to the spectrograph. Individual assemblies will be controlled using "smart motors" which download programs from the control computer and execute them autonomously. The majority of the programs for these motors have been written and are currently being tested and debugged.

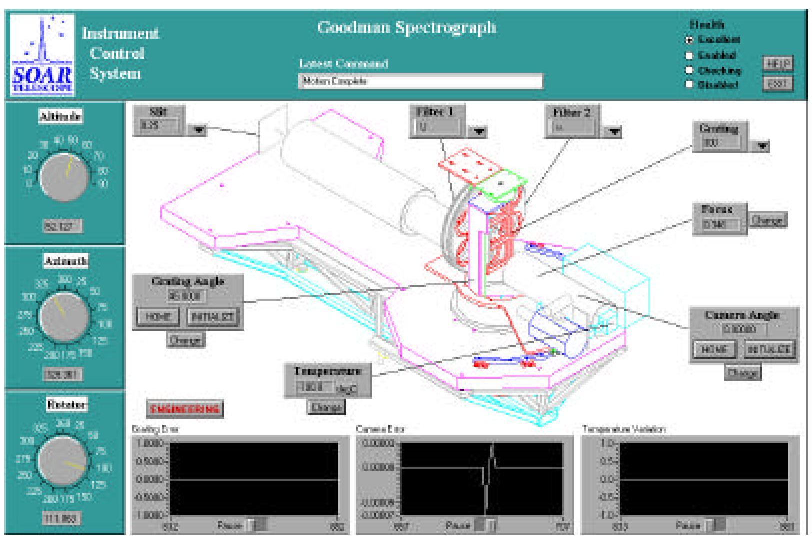

Figure 19. LabView control software for the Spectrograph

We expect to finish laboratory assembly and ship the spectrograph to Chile by August 2003. A few remaining components will be integrated at the telescope site after arrival and the instrument will be ready to commence science operations before October, 2003.

Figure 20. The Goodman Spectrograph frame in the UNC machine shop last year

IV. Conclusions

This report has described the progress, as of March 2003, in constructing the SOAR telescope (section II) and the Goodman spectrograph (section III), the first-light optical spectrograph being built and contributed by the University of North Carolina. At the conclusion of the grant, both the telescope and the spectrograph are nearing completion. Remaining work on the spectrograph is being supported with other University resources. Other partners in the SOAR project are supporting the remaining construction efforts on the telescope.

While the telescope and spectrograph are not yet completed, several lessons can be drawn from the approaches taken by the project team, the board of directors, and the instrument builders. The project early on treated the telescope development and instrument development as separate activities, with the project management team responsible for the telescope only. A result was insufficient funding being dedicated to the instruments at the outset, with the partner institutions responsible for identifying additional resources while the telescope was being built. SOAR will now have a full complement of optical and near IR instruments despite a difficult multi-year struggle to fund these devices. Secondly, the project decided to buy into an experimental CCD chip development effort rather than buy commercial CCDs from, for example, E2V Technologies. The Lincoln Labs/University of Hawaii CCD project promised potentially higher quantum efficiency CCDs spanning a wider spectral range. At this writing, the SOAR project is still negotiating with the University of Hawaii to obtain science-grade CCDs and has, as a backup, purchased several commercial CCDs as well. It is still not possible to tell what benefit we will see from the experimental CCD project. In contrast, another experimental effort involved the development of in-house manufacturing capability of volume phase holographic gratings. This investment has paid off well, with the ability to manufacture science-grade gratings of large enough format. Finally, and most significantly, our active optical system contractor is substantially late in delivering the system. This delay has in turn impacted on staff costs. In retrospect, a higher level of contingency should have been set aside, as the project has had to tap into operations funds to complete the telescope.

Future work includes (1) final figuring of the primary mirror and its optical test, (2) shipment of the entire active optical system to Chile, (3) aluminizing of the primary mirror using the Gemini coating facility, and (4) installation of the optical system. Aluminizing is slated to occur in late January 2004. The project team anticipates first light in March 2004 (SOAR will be dedicated in April 2004). The Goodman spectrograph is scheduled to be shipped to Chile around June-July 2004. All indication are that SOAR should perform well and we should have engineering test time available by mid-2004.

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