The Soar Telescope Project:
A Four-Meter Telescope Focused on Image Quality

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**Introduction:** In the era of 10-meter class optical telescopes, 4-meter apertures still have their strengths. Key among these are: (1) they collect enough light to pursue efficiently many long-term synoptic programs that follow time-variable phenomena. (2) Their image quality can be optimized at tractable cost to maximize the efficiency of background limited imaging and spectroscopy. (3) They can provide a constantly resident suite of well-calibrated, comparatively inexpensive and therefore program-optimized instruments that can be brought quickly to bear on targets of opportunity or those in (1) & (2). Science enabled by the first capability might be spectrophotometry of Cepheid stars in other galaxies or matter transfer in compact binaries. Microlensing by sub-solar masses (including planetary mass) binary companions represents the third class, as do spectral studies of distant supernovae that have been detected with automated photometric surveys. Background limited observations become competitive if the telescope minimally degrades the image quality at an excellent site. A 4-meter with 0.′33 images is just as efficient as a 6.5-meter with 0.′5 images. Hence there is a strong scientific case for development of very high quality 4-meter class telescopes at superb sites. SOAR is one such effort.

**Background:** Initiated by the University of North Carolina (UNC) at Chapel Hill in 1990, the SOAR Telescope Project is now a collaboration between UNC, Brazil, Michigan State University, and the National Optical Astronomy Observatories (NOAO). Funded at a level of $28 million, the objectives are to design, construct, and commission a 4-meter optical/IR telescope within 4 years, at Cerro Pachon in Chile. The telescope is to be operated by the Cerro Tololo Interamerican Observatory (CTIO). US astronomers will receive 30% of the time through NOAO in exchange for this support. Instruments will be provided by partner institutions.

Extensive comparison of competing optical designs for SOAR over the past year have resulted in a decision to optimize encircled energy to address the broad scientific objectives of the partnership. A Ritchey-Chretien design has been chosen with extremely challenging specifications. Low-scatter optics and careful attention to baffling, coatings, and other aspects of system design will minimize stray light. Tip/tilt image stabilization will be integrated fully into the telescope.

A Project Office has been established at NOAO, and concept design work is underway in response to established scientific and technical requirements. Contracts for concept development of the SOAR facility, an active optical system, the telescope mount, and for initial leveling of the site have been let. Official ground-breaking ceremonies will be held in 4/98.

**Scope:** The SOAR Project includes development of the Cerro Pachon site, a rocky promontory approximately 0.4 km northeast of the Gemini site. A compact facility will be constructed, including space for instrument and telescope maintenance. The telescope will feature an active optical system that includes a figure-controlled primary mirror (M1), an actively aligned secondary (M2), fast tip/tilt image stabilization at M2 or the tertiary mirror (M3), an optimization wave-front sensor, and control electronics and software.

The telescope mount, to be developed and tested at the manufacturer’s facility, will include support flanges for Nasmyth and bent-Cassegrain instruments. Initial instrumentation, under consideration as part of the telescope project, includes a 6x4.5K CCD mosaic camera, an IR mosaic camera, bore-sight optical and λλ1–5 μm IR stellar spectrometers, and a moderate-field (up to 19 arc min-diameter) multi-object optical spectrometer (MOS.)

The SOAR Project Team, CTIO, the core Operations Team, and the sub-system manufacturers will support integration, debug, and commissioning. A key goal will be to minimize the duration hence costs of the integration period. First light is planned for the end of 2001.

**Philosophy:** Several key strategies will optimize performance of the SOAR Telescope:
1. Seeing at C. Pachon is excellent. It has been documented via studies for Gemini, and is compared to several other sites in Fig. 1. The principal engineering objective is that the image quality of the SOAR telescope degrade the top-quartile seeing FWHM of the site by less than 40%. This is quantified in Fig. 2, which shows both the intrinsic and the delivered image quality for our specifications, as functions of $\lambda$.

![Fig. 1 (left) The top panel (from Gemini) compares the distributions of $r_0$ at Cerro Pachon, Cerro Tololo, La Silla and Mauna Kea. The bottom two panels show long-term statistics on $r_0$ as measured with a differential image motion monitor at C. Tololo. The bottom panel shows large nightly variations in $r_0$ at C. Tololo, emphasizing the need for a pre-emptive observing queue for maximum observing efficiency. Fig. 2 (right) Anticipated delivered image quality for the SOAR telescope with and without tip/tilt image stabilization for median (dashed) and top-quartile (solid) seeing at C. Pachon. The tip/tilt curve refers to the center of the isokinetic patch. Two degradations are shown, with the specified maximum 0.18 FWHM emphasized. Degradations for AO are shown smaller, to reflect non-optical benefits.

2. The SOAR partners have decided that the existing 4-meter Blanco telescope at CTIO and the SOAR telescope shall be a complementary pair and that SOAR will not duplicate the capabilities of the Blanco. Hence SOAR does not need a wide field of view or prime focus access because the Blanco offers a 45 arc min field.

3. The SOAR telescope will have a generous instrument payload. The trend in at least the near-term is for instrument mass and moments to grow. New materials and technologies may eventually halt this inflation, but it is all telescopes hit limits, often early in their operations. SOAR’s allocations are generous. In addition, there is the possibility of debugging/commissioning Gemini-class instruments on SOAR or even using them for science if that makes sense. Gemini instrument compatibility implies an f/16 focus and 2300 kg instrument capacity at the Nasmyth foci.

4. The SOAR telescope will be designed to execute an observing queue with high efficiency. This will minimize the intrusion of the synoptic programs. If seeing at C. Pachon does vary significantly during the night (something that the current C. Tololo measurements summarized in the bottom panel of Fig. 1 suggest), we would hope that most of the observing will be done in this fashion. It will still be possible for the observer to “lurk remotely” on the Internet if s/he feels the need to participate.

5. Considerable effort will be made to analyze scattered light within instruments and the telescope, by using Monte Carlo multi-scatter codes. Our aim is to limit telescope performance only by dust and diffractive scatter of light from in- and out-of field objects off the optics. Dust will be controlled by washing M1 and M3 at regular intervals, and by using CO$_2$
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**Technical Specifications:** The technical requirements for SOAR are derived from the top-level scientific requirements and the philosophical approaches to design. In abbreviated fashion, they are as follows:

**Optical Configuration:** Ritchey-Chretien at f/16

**Telescope Mount:** Altitude/Azimuth

**Principal Foci:** Two Nasmyth, two Bent Cassegrain, preserve space for Cassegrain Instrument

**Instrument Support:** Instrument Rotators at both Nasmyth Foci

**Instrument Payload:** Nasmyth: 1500 kg. Bent Cassegrain: 300 kg

**Adaptive Optics:** Compatible with upgrade to full AO

**Environmental:** Operation & survival consistent with C. Pachon conditions

**Image Quality:** 0."18 FWHM telescope and facility degradation (no seeing)

**Field:** At least 15'-diameter unobstructed & unvignetted

**Field Correction:** Refractive corrector provided to f/9 instrument focus over flat field

**Pointing Accuracy:** Blind: <2" rms; offsets <1°: <0."2

**Tracking Accuracy:** Open-loop drift: <0."1/min; guided: <0."1

The basic design of the SOAR telescope is Ritchey-Chretien at f/16 on an alt-azimuth mount. M1 will have a clear diameter of at least 4.0m. The principal foci will be at the two Nasmyth locations, requiring three reflections. Both foci will have an instrument rotator and acquisition/guide (A/G) unit. Two different instrument modules will be provided: one has a goal to accept the space/mass envelope of a single Gemini instrument, the other will have provisions for mounting up to three less massive instruments in a co-rotating cluster. The telescope is required to support at least 1500 kg of instruments at each rotator flange, with a goal of 2300 kg. The telescope will be bilaterally symmetric up to the two instrument rotator flanges, so at some future time the two modules could be mixed or matched to mount, e.g. either two Gemini instruments or two co-rotating clusters with up to six lighter instruments.

M3 can rotate to index positions to feed the beam to the desired Nasmyth or bent-Cassegrain focus. M4 in the 3-instrument cluster will allow rapid switching between instruments while sharing guide and acquisition functions. Each of the two A/G's will be compatible with an upgrade to an adaptive optics (AO) feed.

**Concept Design:** The following are current concepts of major subsystems of the SOAR telescope:

**Facility & Enclosure:** The SOAR site was recently leveled to a height of 2701 m above sea-level. Excavations and separate footings for the telescope pier and enclosure ("dome") will be provided. The facility will be a metal building of approximately 180 m², erected nearby on a grade-level slab. Heat capacity of the building and enclosure exterior coatings will be selected to minimize total solar absorbance and to provide optimum thermal “speed”.

We expect to use a rotating hemispherical dome. One current concept employs a pre-fabricated aluminum geodesic. The high conductivity of aluminum and low mass of the dome enables rapid equilibration. Its prefabricated nature would enable rapid and cost-effective integration on site. An alternative is a more conventional gored-steel dome.

**Telescope Mount:** An altitude/azimuth type mount is specified. Current concepts include both monocoque and space-frame designs. The monocoque design uses welded sheet-steel, and accommodates the substantial instrument payload requirements as torque loads at the Nasmyth mounting flanges. The space-frame uses common structural-steel members and supports instruments in trunnions at the Nasmyth locations. Flange mounted Gemini instruments are enclosed in cages to convert the torque loads implied by flange mounting into point loads via a compact strain path.

**Active Optical System:** This consists of a figure-controlled M1, an actively aligned M2 assembly, an M3 capable of rapidly selecting between the two Nasmyth instrument clusters and two bent Cassegrain instrument locations. The system will also provide rapid tip/tilt image stabilization, a wave-front sensor for calibration and optimization of the system, and all the electronics and software necessary for operation.

M1 will be a thin low-expansion glass or glass/ceramic facesheet between 7 and 10 cm thick for rapid thermal equilibration. The facesheet will be supported on figure actuators either hydraulic or electro-mechanical in operation. A carbon-fiber
mirror cell is specified, which will provide an extremely stiff yet lightweight and low heat-capacity structure. The open structure of this cell will provide excellent airflow and good radiation cooling of M1’s rear surface.

Supplemental flushing and selective cooling of M1’s front surface will be provided via a computer-controlled tempered air system. This system provides a variable laminar flow of conditioned air from the outer edge of M1 to a low-pressure region between its inner hole and the M3 rotator. All systems will operate under computer control and the contractors will develop algorithms for optimum performance.

Both M2 and M3 will be low-expansion, lightweight cored-glass or glass-ceramic substrates. These optics will be thermally equilibrated via conditioned air, input through the core structure by small-diameter tubing.

M2 will be actively aligned in five degrees of freedom via a hexapod or Stewart platform system. Correction for optical aberrations will be optimally apportioned between M1-figure and M2-positioning by the contractor-supplied active optics control system.

M3 will be elliptical in perimeter shape, and rotate about the telecentric axis to direct the image to the various instrument ports. It will also feature a high bandwidth (>40 Hz) tip/tilt capability to null atmospheric seeing-induced jitter.

The contractor of the active optical system will provide a calibration wavefront-sensor. Wavefront sensor approaches considered include crossed phase grating, knife-edge, and Shack-Hartmann techniques. Dedicated observation of a bright star will permit stepwise optimization of system parameters and revision of look-up table control parameters.

**Instrumentation:** The SOAR Telescope will provide two Nasmyth instrument positions as well as two bent Cassegrain auxiliary ports. Space will be reserved behind M1 for a small Cassegrain instrument, though in its initial configuration the telescope will not be set up to service that location.

The SOAR Telescope has been configured to provide an image compatible with Gemini instrumentation, and the two Nasmyth instrument locations will be identical and compatible with the interface and loads required to mount these instruments. While it is envisioned that a Gemini instrument will usually occupy one Nasmyth port, the other will sport an instrument adapter which will co-mount some combination of IR and visible wavelength imaging cameras, a stellar spectrometer, and an optical MOS. A facility calibration unit that simulates the telescope beam will also be provided. The instrument adapter will also provide acquisition and guide functions, and imaging elements for the active optical system wavefront sensor. Each instrument is likely to have an integrated tip/tilt/focus quad-sensor that picks off the light of an adequately bright star close to the center of the isokinetic patch. The centroid signal will be sent to the M3 control unit. Stars in the annular guide field will be monitored for instrument derotation as well as on-line photometry.

The following instruments are under consideration by the SOAR Science Advisory Committee (SAC):

**Imagers:** The goal for both visible and near-IR imagers is to span the full isokinetic field that can be stabilized by tip/tilt. This diameter is uncertain because of our current poor knowledge of AO-related characteristics of the atmosphere above C. Pachon. However, it is certainly larger than the span of a single detector chip if proper 3-pixel over-sampling is maintained for precise photometry. Therefore, the baseline optical detector is currently a 3x1 mosaic of thinned EEV 2x4.5K CCD’s with 13.5 µm pixels. This detector will see the sky through a refractive focal-reducer/corrector/field flattener, which converts the f/16 telescope beam to f/9 (0.’08/pixel) thereby providing more efficient sky sampling. An integrated atmospheric dispersion corrector (ADC) will be used. A preliminary design uses a half-dozen spherical lenses to provide good aberration control, high UV transmission, and ADC correction over a 10x10-arcmin field of view. The 3x1 mosaic mentioned above spans 7.9x5.9-arcmin of this field. This camera does not provide a collimated beam, so opportunities for spectral dispersion using conventional techniques are limited. However, work by others with e.g. curved etalon plates for a tunable filter may be useful to us. A goal is to make the camera confocal with f/16, so that the non-ADC elements can be removed from the beam to illuminate the central chip. This configuration would minimize scattered light, at the expense of the field of view. In addition, the pixel scale of 0.’04 would then be well matched to the performance expected for a low-order AO system in the red, if it is implemented later with an adaptive M2.

As Fig. 2 shows, with just tip/tilt image stabilization SOAR should see images with FWHM <0.’35 out to λ5 µm fairly often. Hence, either HgCdTe or InSb detectors are justified, and will be selected on the basis of cost, performance, and the ease of
fabricating a mosaic. In either case, the near-IR camera must reimage for thermal control, so the output pixel-scale is a free parameter to be settled on later, and a collimated space can be provided for dispersive elements.

**Spectrometers:** The requirement remains to obtain spectral information from targets that are distributed across the tip/tilt stabilized field. Object multiplex is still under discussion, but roughly 50 simultaneous targets seem appropriate. An ADC will be used before the entrance apertures to maintain image quality. SOAR's MOS will complement the Blanco's optical spectrometers: Hydra-S, with a minimum fiber separation of 23'' over a 45-arcmin field; and a bore-sight stellar echelle fed by a fiber and small integral field unit (IFU).

Fig. 3 The current concept for the f/16 telescope foci is shown. M4 within the instrument-adapter cube accesses various lighter instruments, while a single Gemini-class instrument is available on the other Nasmyth port. Each port is specified to carry 1500 kg, with a goal of 2300 kg. Either side has an annular guide field of area 40 arc min².

An obvious niche for a SOAR MOS at visible wavelengths would be a single, monolithic IFU to span roughly 10×10'' with 0.15 apertures (for 2-pixel Nyquist sampling.) With fiber coupling this would require an f/5 output beam onto a dual 2×4.5K CCD. If this reimaging is done in fore-optics, the fibers can then be used with minimal focal ratio degradation and a compact, highly efficient double-pass Littrow spectrometer is practical. Throughput would be higher using an image slicer, but with fibers one can envision an eventual upgrade to of order a dozen distributed IFU's each providing spatial information.
across the tip/tilt-stabilized field. Fibers are not currently favored for use in the near-IR, but progress is rapid and the small size of IR arrays makes it all the more desirable to exploit the efficient detector packing of spectra that fibers provide.

**Control Systems:** The Mount, Active Optics, and Facility vendors will also provide control systems. They will be given broad latitude to find the most effective (including downstream) cost solution. The instrument adapter and controller will be contracts to “astronomy shops.” There will also be contracts to develop the Telescope Control System (TCS), and the Instrument and Observatory Control Systems (OCS) that the astronomers interact with. The OCS will have at least the same look and feel as the Gemini counterpart to ensure operator familiarity, and in fact it may be possible to port the Gemini OCS in its entirety. Many parts of their TCS also seem to be quite portable; the Portable TCS under development at the AAO is an alternative. Gemini has designed their highly centralized TCS around the VxWorks real-time OS, EPICS messaging, and VME hardware. Our approach of necessity will be less unified. However, tying together the contractor systems does allow us to upgrade various components that would otherwise be obsolete when SOAR comes on-line in 4 years. For example by using compactPCI and an alternative real-time OS, we can reduce costs and improve performance.

**Fig. 4 SOAR control systems.** Vendor-supplied subsystems are oval boxes. Links are fast Ethernet unless shown otherwise. The Observatory CS handles data, instrument interface tasks, and observer support like star catalogs.

**Concept Design Approach:** Technical requirements for the SOAR Telescope have been derived from the range of science programs put forward by the SOAR partner SAC. From this set of requirements, the SOAR project team and the earlier SOAR Science Working Group developed a range of concepts. Analytical work, and review of the project in 7/97 by an External Review Board, resulted in a top-level configuration. More detailed concepts for structure, optical system, facility, and instrumentation were then developed.

Two study contracts have each been let for alternate approaches to the active optical system, and the telescope mount. A study contract has also been let for facility architectural design. The results from these studies will be utilized to make decisions between the competing designs. The content of final reports from these studies become the property of the SOAR project and can be used as the basis for competitive procurement. The results of the design studies, the final concept design, and an extremely detailed cost estimate will be provided at a concept design review in 6/98. Upon approval of the partners, the project will proceed into the construction phase.

**Program Plan:**
Detailed design of the SOAR facility will be performed by an architect familiar with the requirements of telescope facilities and construction in Chile. These specifications will form the basis for standard construction procurement, administered by
CTIO in Chile. The facility construction will include installation of all necessary utilities, handling equipment, buildings, civil works, and foundations including the telescope base.

The telescope mount will include all detailed design, steel fabrication and assembly, encoders, motors, instrument rotators, servo-controls, control electronics, and control software. Manufacturers will be required to assemble the complete mount at their facility with mass and space simulators to represent optical assemblies. Final acceptance testing at the manufacturer’s facility, ideally under control of the TCS running on a laptop PC, must demonstrate specified pointing and tracking precision and rates. The contractor will then disassemble, pack, and ship the mount to the SOAR site.

The active optical system contract will include detailed design, optical fabrication, and testing of all components. The contractor will be responsible for all actuators, sensors, control electronics and software necessary to operate the system. Final acceptance testing will be performed with the components assembled in a test stand at the appropriate optical conjugates, demonstrating control of M1 figure, active M2 alignment, M3 rotation, and fast tip/tilt image stabilization with loops closed about the wavefront sensor and simulated guider and tip/tilt sensors. Upon acceptance, the contractor will pack and ship the system.

Integration will be performed in two phases

1. The facility will be constructed up to the rotating plane of the enclosure. During the final stages of construction, the enclosure will be assembled on the ground beside the facility. A temporary roof over the telescope portion of the facility will enable completion of interior finishes. This phase completes when the enclosure is prepared for lifting.

2. This phase commences with the coordinated shipping of the major telescope subsystems to the site. Shipping will not be initiated until Phase 1 completion is assured, and the major telescope components are both ready. Integration of the telescope and enclosure is scheduled to take less than 90 days.

The manufacturers of the major subsystems will provide engineers to ensure rapid installation and debug of their systems. It is also intended that key members of the Operations Team be hired and in place during the telescope installation, to ensure familiarity with the procedures and operation of the system. Additional labor will be provided by CTIO and perhaps partner
institutions. First light will be defined as the ability to routinely acquire and track images with performance that is in substantial compliance with the requirements. The science commissioning team will work with the Project and the Operations Teams to achieve full capability.

Installation of instruments will occur in stepwise fashion upon their completion, with proof masses in place prior to instrument arrival. The Project will end with final acceptance testing in which the performance of the overall system will be validated via test, demonstration, inspection or analysis, and substantial compliance with the specifications is achieved.

**Summary:** The SOAR Project breaks ground in several important areas (Fig. 6.) First, it will provide the best image quality of any 4-meter class telescope, with acquisition and tracking precision to exploit that quality. It will provide a second, nearly co-located telescope to use existing Gemini instruments as available. Fast tip/tilt will be included initially and the telescope will be designed to be compatible with a later upgrade to full artificial laser guide-star adaptive optics. Multiple instruments can be selected quickly and routinely to support operation in a queue-scheduled mode. All this will be done at a project cost reproducible by a consortium of e.g. US state universities rather than nations.

Key elements of the SOAR Program plan call for development of complete functional-subsystems by contractors, test to specifications at their facilities prior to shipping, and a minimal integration period. Early inclusion of the Operations Team will minimize the lag between construction and operation that is usually experienced by telescope projects. SOAR promises to be a powerful scientific asset to its partners and their collaborators.

![Fig. 6 Site preparation activity at C. Pachon, early Feb. 1998, scheduled for completion in mid-March.](image-url)