MECHANICAL DESIGN OF TWO INSTRUMENT SUPPORT MODULES FOR THE SOAR TELESCOPE

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Abstract. *The **SO**uthern **A**strophysical **R**esearch (SOAR) is a high resolution telescope sited on Cerro Pachón - Chile, a partnership between Brazil and the USA. It is a 4.1m Ritchey-Chrétien alt-azimuth design which supports Instrument Support Modules (ISMs) mounted at the two Nasmyth foci. Both ISMs are identical in shape, each of them with three focal stations for scientific instruments. They also carry a Comparison Lamp System (CLS), guider mechanism and an acquisition camera, which are shared between the three instruments. Beam steering mechanisms direct light from the SOAR science field or the CLS to the instrument in use. In one side, dedicated to infrared instruments, light is sent to the lateral ports by dichroic mirrors which reflect IR and transmit wavelengths from 400-900nm to the guider. In the other side, dedicated to optical instruments, light is directed to the lateral ports by the use of first surface pick-off mirrors. Guiding is done off-axis. During operation, both ISMs can be rotated by ±180° and must carefully control differential flexure between the guider and focal planes. A method of accurate relative flexure measurement based on a long distance microscope has been devised. Mass simulators are used to reproduce nominal payloads for each ISM. In this paper, the ISM mechanical design and its support sub-modules are described in details.*

Keywords*: ISM, beam steering mechanism, guider mechanism, comparison lamp system.*

1. Introduction

1.1. Background

The SOAR Project is a collaboration between Brazil (represented by CNPq and FAPESP) and the USA (represented by the University of North Caroline (UNC), Michigan State University (MSU) and the National Optical Astronomy Observatories (NOAO)) to build a 4.1 meter high resolution f/16 Ritchey-Chrétien altitude-azimuth optical telescope. Sited on Cerro Pachón - Chile at an altitude of 2,700 meters above sea level, the SOAR Telescope has the 8 meter Gemini South Telescope in the neighborhood, only 0.4 km apart (Fig. 1). Brazilian management for both telescopes is located at the Laboratório Nacional de Astrofísica (LNA/MCT) in Itajubá - MG, Brazil. As an alt-azimuth design, the SOAR telescope has two Nasmyth foci, on each of which is mounted a rigid stainless steel box with three focal stations for scientific instruments. Movable internal mirrors are used to permit real time selection between any of these instruments. Selection between both boxes is done with the telescope's tertiary mirror turret, located at the center of the 4.1m primary mirror (Fig. 2). SOAR is a challenging ground-based telescope designed to provide high precision pointing and to have an extremely large instrument payload capacity (Krabbendam, 2000 and Sebring *et al.*, 1998). To avoid excessive interaction with the telescope structure, both ISM boxes are not directly supported as a cantilever beam at the altitude bearing. Instead, it is supported by an Instrument Support Cage (ISC) with one end at the Nasmyth bearing and the other lying on a sided support structure (Fig. 2).

The effort for building two ISMs includes all tasks involved in the development of beam steering mechanisms, guide probe mechanisms, comparison lamp facilities, and testing/alignment tools. The design of both ISMs permits up to three scientific instruments to be simultaneously mounted and permanently available for immediate use at each Nasmyth focus. Internal components are different to accommodate the different needs of the IR and 'Optical' (wavelength < 900nm) instruments. The guide probe system is internal on the IR-ISM and external on the Optical-ISM. One of the three instruments will be mounted on the straight through port and other two on the lateral ports. On each ISMs top surface there is a comparison lamp facility and the final optics and camera for the tip-tilt guider system. On its bottom surface there are an acquisition camera and the ISM electronics box.

Figure 1 - Aerial view of the 4.1m SOAR Telescope (front) and 8m Gemini Telescope.

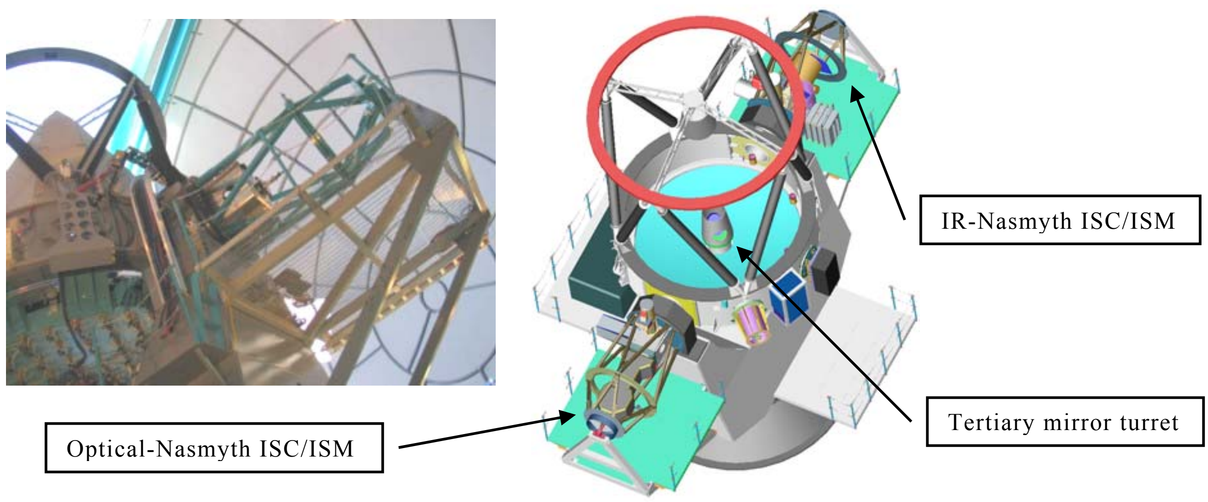

Figure 2 - SOAR Telescope mount with ISC/ISM installed.

As originally established, the first generation of instruments is given by: PHOENIX (a high dispersion Cryogenic Echelle spectrometer), mounted on the straight through port of the IR-ISM; SPARTAN (a near-infrared imager), mounted on the right side port of the IR-ISM; OSIRIS (Ohio State InfraRed Imager/Spectrometer - a multi-purpose infrared imager and spectrometer), mounted on the left side port of the IR-ISM; GOODMAN (a high throughput, multi-object spectrograph), mounted on the straight through port of the Optical-ISM, and SIFS (the Brazilian SOAR Integral-Field Unit Spectrograph), to be mounted on the right side port of the Optical-ISM port. The left side port will be used by a second generation instrument.

1.1. Technical Overview

The SOAR ISM Project is described in detail by Santoro *et al.* (2004). Both ISMs boxes were made from five 304 stainless steel plates and four corner buttresses for rigidity. These plates were welded together and precisely machined with tight tolerances on thickness, flatness and paralellicity. The front face was left open to allow internal machining and the drilling of instrument mounting holes. Each ISM has three ports for scientific instruments, one port for a calibration lamp facility and one small port for an acquisition camera. It is bolted to a mounting plate, which in turn is bolted to V-struts of the ISC (Fig. 3). The whole assembly is bolted to the Nasmyth bearing of the telescope, as shown in Fig. 2. The back focal distance is nominally 200mm for the straight through port and 150mm for lateral ports with full science field of 15 arcmin in diameter. Remotely controlled beam steering mechanisms direct light from the science field of the telescope or CLS to any instrument so that all instruments can be permanently available.

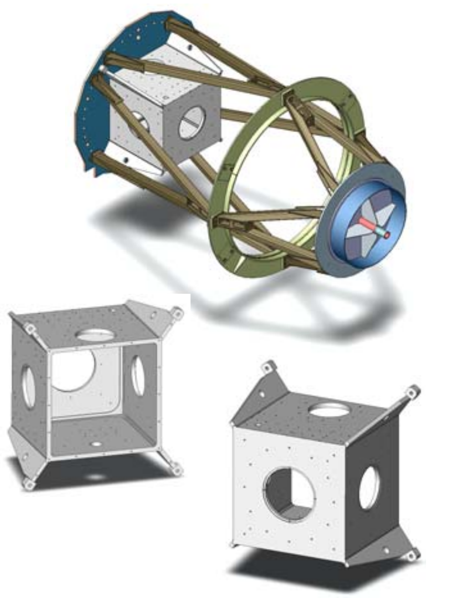

Figure 3 - ISC/ISM isometric views.

Guider mechanism, which is shared by the three scientific instruments, is provided for each ISM. In both ISMs, a guide probe can be positioned anywhere within a patrol field of 10x10 arcmin. The guider optics transfers the light from an object to the guide camera, which is rigidly mounted on the top of the ISM where it is easily accessible. In the IR-ISM, the guide probe is inside the ISM while in the Optical-ISM it is external, on the straight through port. The guider mechanisms must meet tight tolerances for differential image motion due to flexure between the guide probes as the instrument is used over the entire ±180° of Nasmyth rotation. In this sense, ISM boxes and its internal components must be rigid enough to control differential flexure between the guider and all three focal stations. Flexure was measured using a Telescope Simulator device, together with mass simulators to reproduce masses and moments of the instruments.

On the top surface of both ISMs, a CLS containing broadband and spectral line lamp projectors are installed. These calibration sources can be remotely controlled and directed to any instrument using the CLS beam steering mirror system mounted inside the ISM. The beam steering mirror has a second small mirror on its rear surface. When the beam steering mirror is in the calibration configuration, light from the center of the science field is directed via this mirror to an auxiliary port at the bottom of the ISM where an acquisition camera will be mounted.

2. General Description

2.1. ISM Technical Scope

From a mechanical point of view, the ISM Project comprises detailed mechanical design, integration, performance testing and support for integration/debugging at the telescope site. The original technical scope includes many tasks and specifications (Ingerson, 2000). A primary one refers to the rigidity of the ISM boxes, which are free to be rotated by ±180° so that during operation, the direction of the gravity vector changes continuously. Still, optical and mechanical components as beam steering mechanisms and guide probe mechanisms must be designed so as to minimize relative displacement between the guide probe position and Nasmyth focal planes. This means that image motion in the instrument focal planes due to flexure in the system must be controlled within tightly specified values. In this sense, the mechanical design of internal components for both ISMs must be such that the "vectorial sum of the displacements from all sources expressed as resulting image motion in the instrument focal planes shall be no more than 26µm for ±180° of Nasmyth rotation" (Santoro *et al.*, 2004). Other tasks as comparison lamp facilities, handling cart, telescope simulator for flexure evaluation and lab tools are described below.

2.2. Beam Steering Mechanisms

Remotely controlled beam steering mechanisms were supplied by the ISM Project. They are mounted inside both ISM boxes to direct light from the science field of the telescope or from the CLS to any of the three scientific instruments. Two dichroic mirrors are used inside the IR-ISM and two first reflection pick-off mirrors are used inside the Optical-ISM. In the IR-ISM, the maximum field-of-view is 8.5 arcmin in diameter, which is the maximum size allowed to the dichroic mirrors. In the Optical-ISM, the pick-off mirror was sized accordingly to requirements of the corresponding scientific instrument. There are several possible configurations for these mirrors, all of them analyzed using CAD tools to detect all possible collision during operation. When the comparison lamp mirror is out of the field, light goes to one of the three scientific instruments. In case both dichroic mirrors are out of the field, light goes to the straight through port. In case one dichroic mirror is in the field, light is directed to the corresponding side port. In this case, an amount of 8 arcmin in diameter of light reaches the guide probe, which is located behind the steering mechanisms. When the comparison lamp mirror is in the field, 8.5 arcmin of light reaches any instrument port. For the Optical-ISM side port, which is to be used by the Brazilian spectrograph, light is directed to the instrument using a small first reflection pickoff mirror. Light not intercepted by this mirror will be used for guiding.

The mechanical design specification for the steering mechanisms within the ISM stipulates that when changing from one configuration to another and returning to the initial configuration, the position of objects at the focal plane should be reproducible and repeatable to about ±0.05 arcsec (15µm). This defines the positional precision and repeatability required for those operations (Heathcote, 2000). Based on specifications as well as the limited space inside the ISM, commercial-off-the-shelf (COTS) linear stages are being used, all from Parker Daedal Inc. These stages have the advantages of being light, compact, low profile, precise and repeatable. A DC QuickSilver embedded controlled motor drives a pre-loaded ball-screw so that the resulting motion system allows a real resolution of 1.25µm, bi-directional repeatability of ±1.3µm and positional precision of 10µm considering 256mm of travel. It also has the required stability for the application and it is fast enough to reconfigure any mirror in about 10 seconds. Dichroic mirrors and CL mirrors are kinematically mounted in a cell using stainless steel hard points. Tip, tilt and piston adjustments are available for collimation procedures during integration. Figure 4a shows the IR-ISM furnished with two dichroic steering mechanisms and one CL mirror mechanism. As can be seen, light from the telescope will be directed to an acquisition camera and simultaneously from the CLS to the instruments in use. Figure 4b shows a dichroic mechanism in detail. As can be seen, a fiducial system with emergency switches is available. Mechanical detents and hard stops are also implemented in all mechanisms. Figure 4c shows both dichroic mechanisms under test and the IR-ISM guide probe behind them.

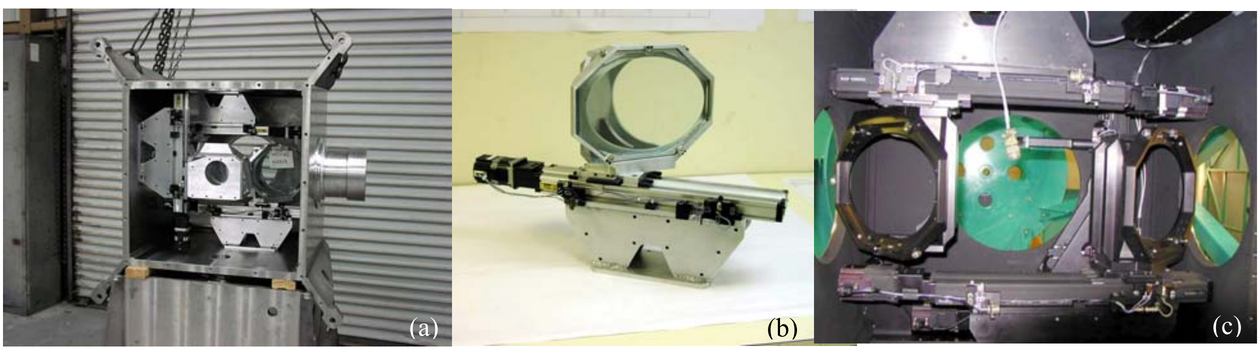

Figure 4 - SOAR IR-ISM steering mechanisms.

Each support weighs about 6kg and is made by 6061-T6 aluminum alloy and cold rolled steel. FEA for these mounts show that when positioned as a cantilever beam, resulting flexure produces an image motion of about 30µm for 180° of Nasmyth rotation. When positioned upside down, flexure analysis predicts a shift of 40µm in the guide image relative to the instrument.

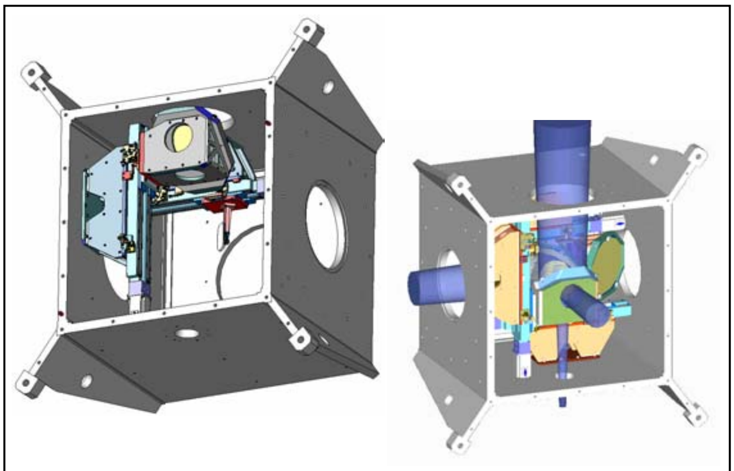

Figure 5 - SOAR Optical-ISM steering mechanisms.

Figure 5 shows isometric views of the Optical-ISM furnished with the IFU pick-off mirror mechanism and a CL mirror mechanism. The IFU pick-off mirror support weighs about 1kg and is made by 6061-T6 aluminum alloy. The first surface mirror needed to feed the target and sky IFUs is 86x58mm. In this case, light directed to the guider will be blocked and vignetted in a region about 100 arcsec wide around its border. The obstructed zone will be a semicircle 225 arcsec in diameter with a strip 225 arcsec wide going to the bottom of the support. For this mechanism, kinematic mount is provided for fine adjustments during the collimation procedure.

2.3. Guide Probe Mechanisms

As a primary requirement, guider sub-assemblies must be rigid enough to maintain the relative flexure between the guide camera and the detector of the scientific instrument in use to within acceptable limits. Apart from flexure, care was taken during fabrication and alignment of components and sub-assemblies to maintain high levels of performance for all possible configurations.

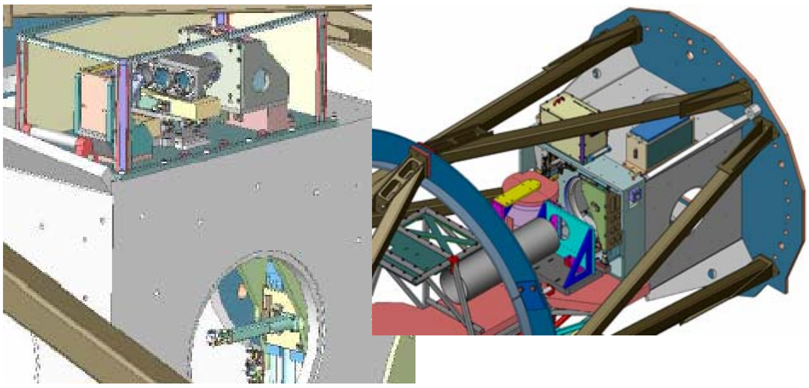

Figure 6 - IR and Optical-ISM Guider mechanisms.

The guide probe in the IR-ISM is inside the ISM with the pickup mirror 290mm from the focal plane (Fig. 6). This avoids interference with the straight through instrument but makes the guide probe shadow relatively large. This is a disadvantage with the straight through instrument but causes no problem on the side ports, which guide on the light passing through the dichroics. In the Optical-ISM the guide probe is outside the ISM, 100mm from the focal plane (Fig. 6). This minimizes the size of the probe shadow and allows guiding as close to the target object(s) as possible.

The optical designs are shown in Ingerson (2000) and Santoro *et al.* (2004). In both cases, a small negative lens mounted on the guide probe is used to collimate the light from a guide star. The resulting parallel beam is then transferred via prisms mounted on the arms of an x-y positioning system to another lens system which re-images the light onto a fast guide camera mounted outside the ISM (Fig. 7). To optimize the image size at the CCD focal plane, the system incorporates a focal reducing lens. Astigmatism was corrected by placing a compensating plate in the converging beam in front of the guide camera, tilted in the opposite direction to the dichroics (Ingerson, 2000). A mechanism is installed between the re-imaging lens and the focal reducer, which moves compensating plates into the beam as required (Fig. 8). This mechanism contains two compensator plates oriented at ±45 degrees which are inserted to correct for the left and right dichroics and a neutral position for use when the straight through port is selected.

In the IR-guider, the transfer optic system can be refocused by moving the re-imaging lenses along the optical axis to compensate for ±13mm of focal plane offset. This is carried out by using a motorized linear stage (Fig. 8). In the optical guider, the range of focus compensation available is significantly less because the collimator is closer to the focal plane and there is no dichroic mirror.

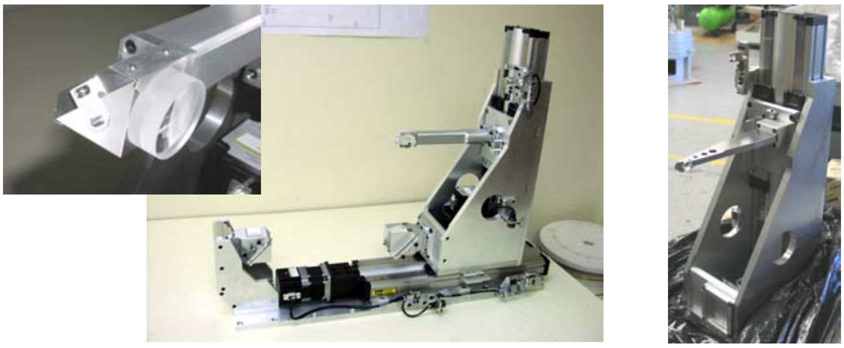

Figure 7 - Guider mechanisms: x-y stages.

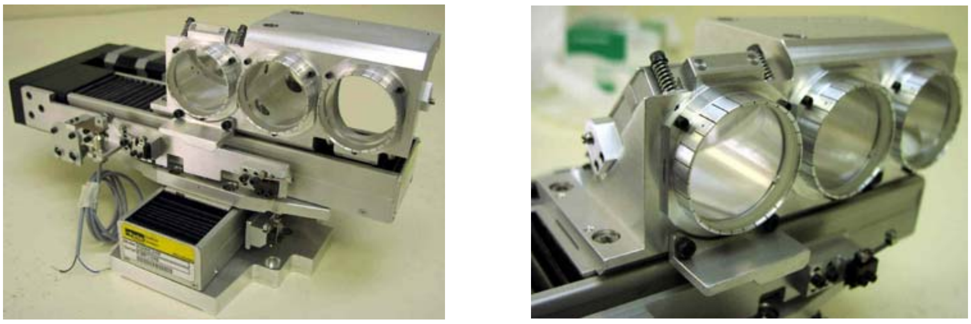

Figure 8 - IR-guider: compensator-focus stage.

As previously noted, the IR-ISM guider is mounted inside the ISM chassis while the Optical-ISM guider is mounted outside by using a stainless steel box interface (Fig. 6). This interface box is directly bolted to the straight through port. Such a solution minimizes the field obstruction for the Goodman Spectrograph. The pick-off probe was adapted to support smaller optics and locate the system closer to the focal plane of the telescope. For both guide probe mechanisms, the collimator lens and the pick-off prism are mounted in the same support. By using COTS components (Parker stages and QuickSilver motors), the guide probe has a positional accuracy of 7.6µm, bi-directional repeatability of ±1.3µm and resolution of 1.25µm, considering a square patrol field of 10 arcmin (□200mm). Configuration time is less than 10 seconds. The IR-ISM also contains a system for adjusting the positioning of the compensator plates. Prisms for both mechanisms are kinematically mounted in a cell using stainless steel hard points. This allows tip, tilt and piston adjustments, as well as x-y linear shifts to be done as required (Fig 9). Mechanical detents, hard stops, fiducial switch and limit switches are provided for performance and security.

Figure 9 - Guider mechanisms: prism support.

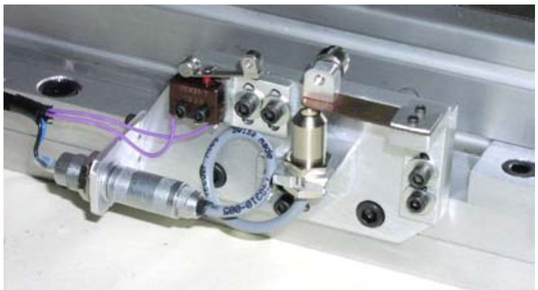

Figure 10 - Fiducial system.

2.4. Comparison Lamp System (CLS)

As described before, the top surface of each ISM is equipped with a CLS. These calibration units generate reference light accurately simulating the f/16 SOAR beam (Ingerson, 2000). Using the steering mirrors inside the ISM, reference light projected by the CLS can be directed to any instrument. Figure 11 shows the CLS optical design and a section view of the mechanical design. Light produced by projectors inside the illumination system is reflected off a semi-specular diffuser and then off a specular elliptical "concentrator" which reflects light not exiting back to the diffuser to be reflected again. This system is considerably more efficient than a classical integrating sphere. The exit of the concentrator is the field stop where light passes through a lens, which locates the pupil in front of the concentrator. Light from this pupil stop then goes to an offset elliptical mirror and where it is then sent to the focus of the CLS. This simulates the beam profile and locates the pupil correctly. The mirror surface is essentially part of an ellipsoid of revolution with one focus of the ellipse at the output of the concentrator and the other on the SOAR focal plane. All light coming from one focus of an ellipse and reflecting off the elliptical surface will be sent to the other focus. In principle, this system generates a perfect image of the field stop on the focal plane. The mechanical design can be divided into four sub-assemblies: structural support tube, mounting tube, off-set elliptical mirror cell and illumination system, almost all made by 6061-T6 Al alloy. Kinematic mount and focus adjustments are provided. The offset elliptical mirror and the concentrator were also fabricated in the CTIO mechanical shop using a CNC drilling machine. Figure 12 shows the integrated system under test.

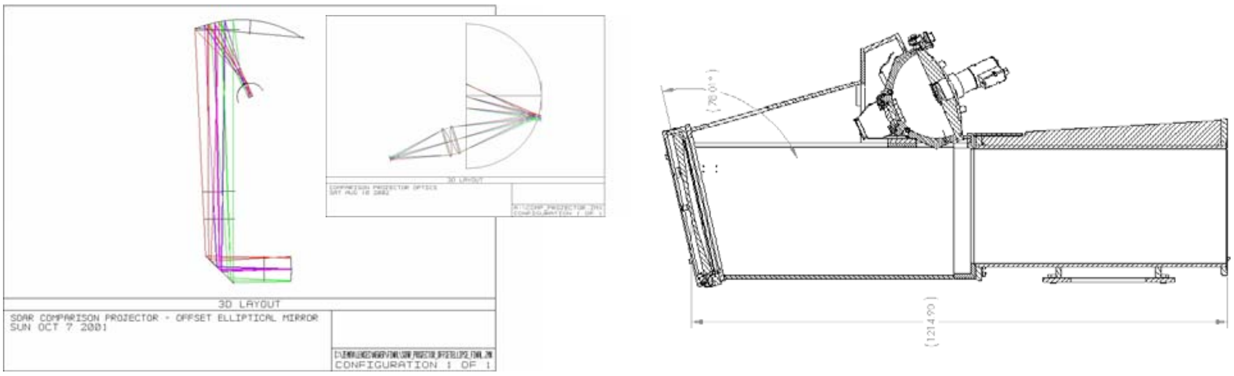

Figure 11 - CLS optical and mechanical design.

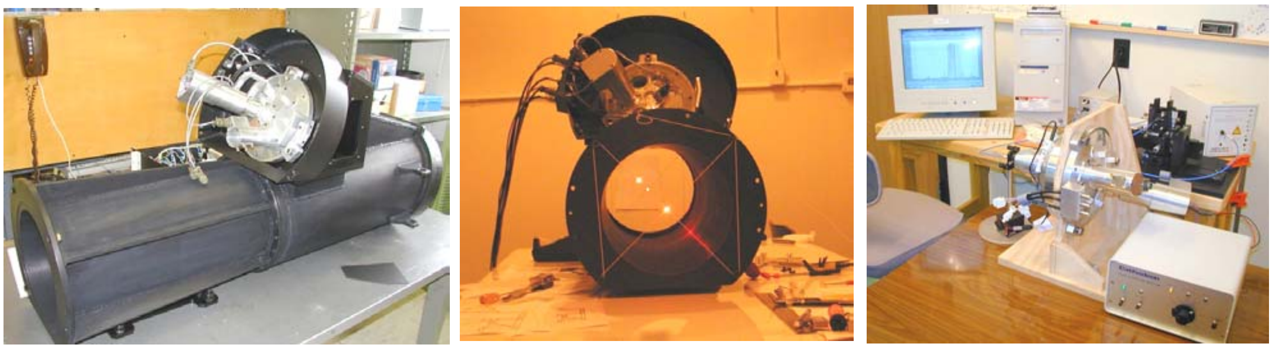

Figure 12 - CLS optical and mechanical design.

The illumination system of each CLS has six positions for lamp projectors, which take the light from a source and image it as well as possible onto the diffuser. Currently there are two such projectors installed. One contains a 10W quartz-tungsten-halogen (QTH) lamp and the other a CuAr hollow cathode lamp. Other hollow cathode lamps would be useful, though their intensity is relatively low. Osram single element lamps could easily be installed in similar projectors for greater brightness. An etalon projector(s) may be used to provide precisely spaced lines at high resolution. Three Oriel pen-ray type spectral line lamps have also been installed in the system. These lamps have been put in slots in the concentrator where they directly illuminate the diffuser and work very well. They provide spectral lines, which are much brighter than the hollow cathode lamps. Currently, Hg, Ne and Ar lamps are installed.

2.5. Acquisition Camera

A small mirror is attached to the rear surface of the CLS steering mirror. Whenever the CLS mirror is sending its light to an instrument, this mirror will direct light from the science field towards the bottom of the ISM, where it will pass through a hole to focus 368mm below the bottom surface of the ISM. An acquisition camera with a 25x25mm CCD, filter slide mechanism and focusing mechanism are mounted at this focus. This camera provides a view of a 3x3 arcmin area at the center of the science field and should be very useful for finding and centering on difficult targets.

2.6. Handling Cart

The handling cart used to carry the ISC/ISM was originally designed and fabricated by Vertex RSI, in Texas. Unfortunately, this handling cart did not permit access to the inside of the ISM through its open front face. To correct this problem, the rotating mounting plate and the frontal A-structure of this cart have been redesigned at CTIO to permit access to the internal components of the ISM. Additionally, this allowed us to install the telescope simulator on the front of the ISM so that laboratory flexure measurements and acceptance tests could be conducted as if the ISM were on the telescope. This modified cart allows the ISC/ISM to be rotated through a full 360°, locked at defined positions and balanced using counter-weights as desired (Fig. 13). Some other modifications have been proposed to facilitate scientific instrument installation and operation on Cerro Pachon.


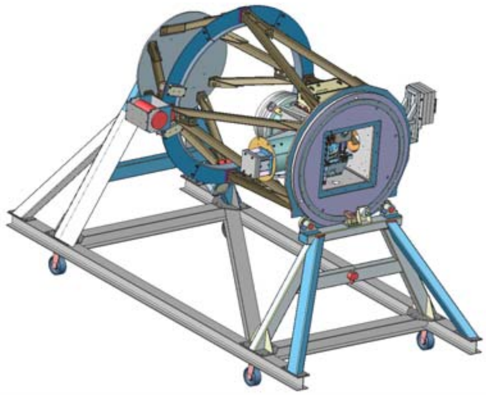

Figure 13 - ISC/ISM handling cart.

2.7. SOAR Telescope Simulator (STS)

A SOAR Telescope Simulator (STS) was designed using a long distance microscope, type QM-1, from Questar. This telescope came equipped with a CCD TV camera type GW-525EX, from GenWac, with pixels 6.35x7.4µm. The QM-1 was specifically optimized for a working distance of 1300mm which gives it an f-ratio essentially the same as that of SOAR (f/16). The main application for this instrument is to measure flexure of the ISM components. A mount was made for the QM-1, which holds it 1300mm from the SOAR focal plane. The mount permits the QM-1 to be moved anywhere within a 10 arcmin diameter field while always maintaining the pupil at its proper position 7.2m from the SOAR focal plane. Figure 14 shows the STS installed on the ISM. Reference precision targets containing illuminated pinholes (50µm in diameter) were also designed and mounts made permitting pinholes to be located at all focal stations. Relative movements of these images as the ISM is rotated are easily measured with the TV camera, permitting flexure of the internals to be accurately quantified.

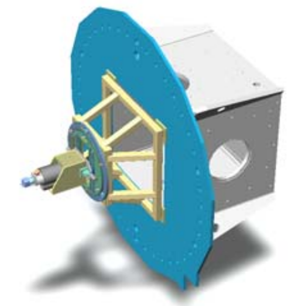

Figure 14 - Telescope Simulator.

2.8. Balance counterweights and Instrument Mass Simulators

During operation on the telescope, the ISM/ISC can be rotated by ±180°. To avoid unwanted torque and flexure, it is essential to keep this assembly under balance. A counterweight arrangement was designed to balance the system allowing manual rotation of the resulting assembly when mounted on its handling cart. The counterweights were installed on the bellyband of the ISC, as shown in Figure 15. This location makes them relatively easy to mount and less likely to interfere with or damage the instruments. These counterweights are made of steel and lead.

Additionally, mass and moment simulators for all instruments are required. The simulators were mounted on their respective ports on the IR-ISM and the whole assembly balanced, allowing accurate flexure measurements to be made (Fig. 15). The simulators are also made of steel and lead. All three simulators together weigh about 1,265kg. The estimated weight for the whole ISM/ISC assembly, including all internal components is 3,280kg. During normal operation of SOAR the simulators will be available to maintain balance whenever an instrument must be removed from the ISM.


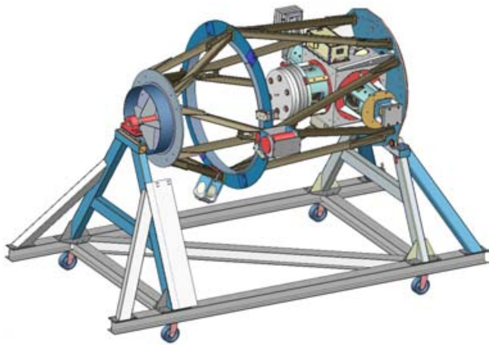

Figure 15 - Mass simulator and counterweight.

3. CONCLUSIONS

Acceptance tests were divided into five parts: flexure tests, performance of the STS, performance of the steering mechanisms, performance of the guider mechanisms, and CLS tests, as described in Santoro *et al.* (2004). Flexure was the most important issue. After analysis, it was concluded that flexure is a little greater than previous specification, although very consistent and predictable. The STS devised for the project was suitable for relative flexure measurements. Performance of steering and guider mechanisms was excellent. The CLS performed as expected. The beam is uniform, has good intensity and simulates the beam profile of SOAR. After acceptance tests, the ISM Project was successfully commissioned on the SOAR Telescope.

4. Acknowledgements

Thanks to all productive discussion and active participation of members of the Cerro Tololo Inter-american Observatory Instrument Shop who have been directly responsible for our success. Also, thanks to the Brazilian Institutes FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and LNA/MCT (Laboratório Nacional de Astrofísica) for their financial support during a long stay of four years in Chile.

5. References

Heathcote, S., 2000, "*Requirements and Specifications for ISB Internals*", SOAR Internal Publ..

Ingerson, T.E., 2000, "*A proposal to Build ISB/Guider/Calibration Systems for SOAR*", CTIO Internal Publ..

Krabbendam, V.L., 2000, "*Active Optical System Design for 4.2m SOAR Telescope*", Proceedings of SPIE - Astronomical Telescopes and Instrumentation, Vol.4003, Germany.

Santoro, F.G., Ingerson, T.E., Schwarz, H.E., Tighe, R., Martinez, M., Gallardo, J., Ochoa, H., 2004, "*Instrument Support Module for the SOAR Telescope*", Proceedings of SPIE - Ground-Based Telescopes Vol.5489, Scotland.

Sebring, T.A., Cecil, G. & Moretto, G., 1998, "*The SOAR Telescope Project: A Four-Meter Telescope Focused on Image Quality*", Proceedings of SPIE - Astronomical Telescopes and Instrumentation Vol.3352, USA.