IV. Requirements for SOAR Instruments

1 Introduction

Previous chapters of this document have outlined the current science goals of the SOAR partners, the general science requirements that are already being incorporated into the conceptual design of the SOAR telescope, and general performance scalings that define how best to exploit the telescope. This chapter develops the priorities and guidelines for instruments. It is not the intent of the SAC to "design instruments by committee". But, to ensure that partner science goals and Observatory operational requirements are met, instruments *must* follow the specifications and address the priorities outlined herein. The Appendix to this chapter describes general instrument requirements associated with the telescope structure and its interfaces, and serves as a preliminary *SOAR Instrument Builders Handbook* .

The SAC, through its individual partner representatives, reviewed ≈ 120 SOAR-specific observing proposals from the astronomers at the partner's institutions (and in the case of CTIO, also culled from the observing proposals submitted over many years to the CTIO TAC.) Many of these projects involved observations that combined several different techniques in tandem. The types of instruments and their characteristics needed to accomplish these projects were summarized by the SAC. (In cases, where requested instrumental characteristics differed from those deemed feasible, feedback was solicited from the astronomers who authored them.)

A general description of the different types of projects is given in Chapter III of the *Soar Science Requirements Document*. Figure 1 classifies these projects by their instrument requirements. Of these projects ≈20% either were deemed most suitable for execution on the CTIO Blanco Telescope or were of sufficiently specialized nature that they required a specially built, user instrument. Figure 1 shows that the remainder had instrument needs which were distributed equally in observing time amongst the 5 general categories discussed in the next section. In a broad sense they all subscribe to a "science over the isokinetic field" paradigm. Instruments are therefore specified to span $\simeq 5'$-diameter fields where feasible. However, the partners also have a strong interest in stellar spectroscopy, with very high throughput to compete with larger telescopes. When these observations are sky limited or are of crowded fields, they are best executed on SOAR rather than the Blanco Telescope.

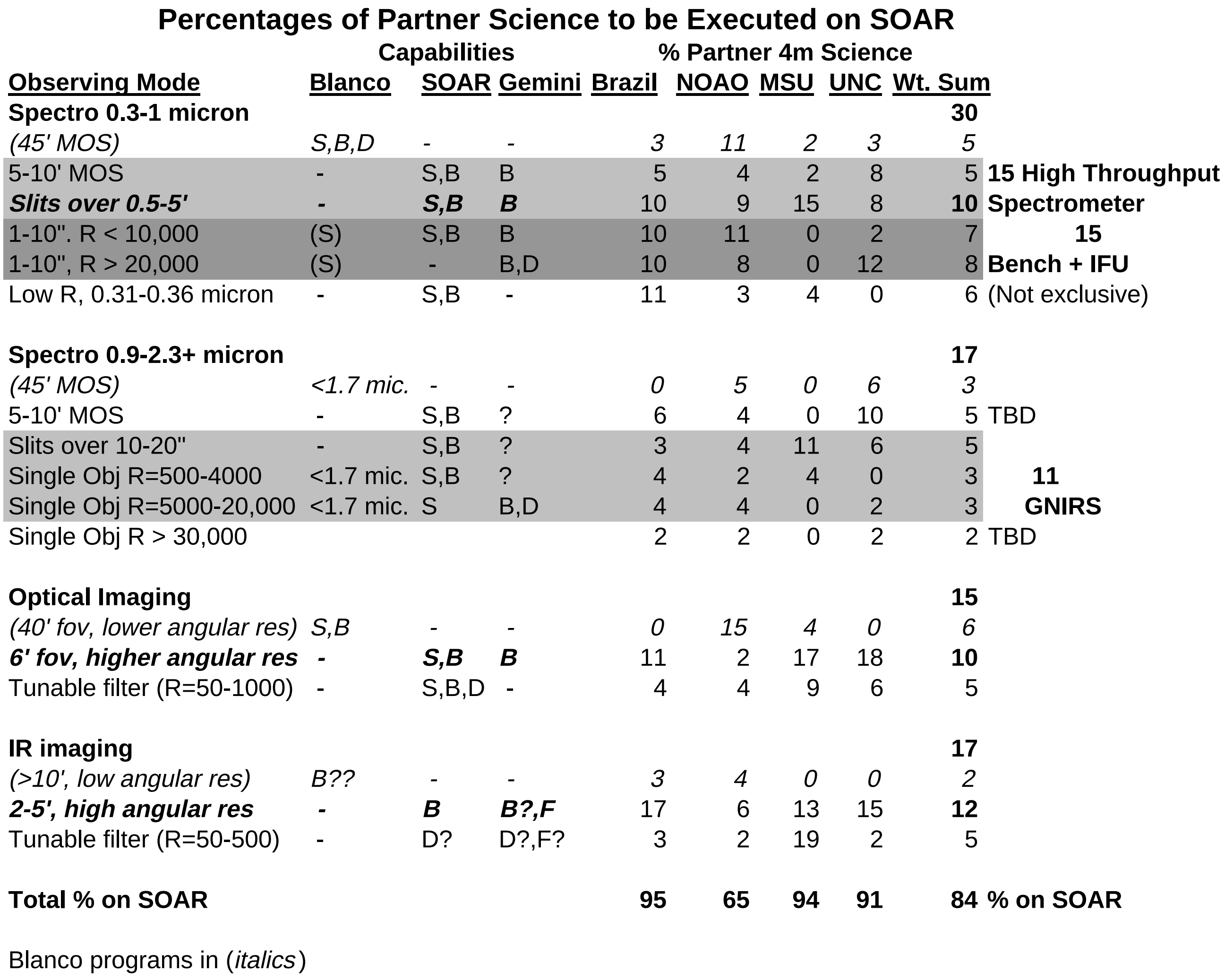
2 Proposed Initial Instrument Complement for SOAR

2.1 Optical Spectrographs

It was decided that the two classes of optical spectrographs would be considered "one instrument" for construction purposes, even though they will probably be physically distinct.

2.1.1 High-Efficiency, Optical (Stellar) Spectrograph

Goals are to maximize efficiency for work on faint compact sources, to access both the large number of spectral diagnostics in the rest UV and also the Ca triplet at 850nm at zero-redshift,



Percentages of Partner Science to be Executed on SOAR

	Capabilities			% Partner 4m Science					
Observing Mode	Blanco	SOAR	Gemini	Brazil	NOAO	MSU	UNC	Wt. Sum	
Spectro 0.3-1 micron								**30**	
(45' MOS)	*S,B,D*	*-*	*-*	*3*	*11*	*2*	*3*	*5*	
5-10' MOS	-	S,B	B	5	4	2	8	5	**15 High Throughput**
Slits over 0.5-5'	***-***	***S,B***	***B***	10	9	15	8	**10**	**Spectrometer**
1-10". R < 10,000	(S)	S,B	B	10	11	0	2	7	**15**
1-10", R > 20,000	(S)	-	B,D	10	8	0	12	8	**Bench + IFU**
Low R, 0.31-0.36 micron	-	S,B	-	11	3	4	0	6	(Not exclusive)
Spectro 0.9-2.3+ micron								**17**	
(45' MOS)	*<1.7 mic.*	*-*	*-*	*0*	*5*	*0*	*6*	*3*	
5-10' MOS	-	S,B	?	6	4	0	10	5	TBD
Slits over 10-20"	-	S,B	?	3	4	11	6	5	
Single Obj R=500-4000	<1.7 mic.	S,B	?	4	2	4	0	3	**11**
Single Obj R=5000-20,000	<1.7 mic.	S	B,D	4	4	0	2	3	**GNIRS**
Single Obj R > 30,000				2	2	0	2	2	TBD
Optical Imaging								**15**	
(40' fov, lower angular res)	*S,B*	*-*	*-*	*0*	*15*	*4*	*0*	*6*	
6' fov, higher angular res	***-***	***S,B***	***B***	11	2	17	18	**10**	
Tunable filter (R=50-1000)	-	S,B,D	-	4	4	9	6	5	
IR imaging								**17**	
(>10', low angular res)	*B??*	*-*	*-*	*3*	*4*	*0*	*0*	*2*	
2-5', high angular res	***-***	***B***	***B?,F***	17	6	13	15	**12**	
Tunable filter (R=50-500)	-	D?	D?,F?	3	2	19	2	5	
Total % on SOAR				**95**	**65**	**94**	**91**	**84**	**% on SOAR**

Blanco programs in (*italics*)

Figure 1: Percentages of partner science to be executed with candidate SOAR instruments. Here S = shot-noise limited, B = background-noise limited, D = detector-noise limited, F = diffraction limited, () signifies reasonable but not ideal performance. A dash in a telescope column means that that telescope+instrument combination is not competitive.

to minimize field variations in the monochromatic PSF, and to have low flexure for accurate background subtraction.

The “B” options aim to enable limited stellar work (while not pushing spectral-R beyond a photon starvation limit set by source counts that equal the read noise of anticipated CCD’s), to reach optical spectral features at higher redshifts, to provide an ADC to maximize S/N for exposures away from the zenith, and to provide multi-object spectrophotometry over a limited FOV.

The “C” options are designed to extend the FOV for multi-object spectroscopy to the size of the isokinetic field, to improve throughput and to preserve full spectral resolution in poor seeing.

2.1.2 High-Spatial Resolution Optical Spectrograph

The goal is a spectrometer that provides proper two-dimensional sampling over $\approx 5 \times 10''$ area, with more grating options than the High-Efficiency Optical Spectrograph, and overlapping in wavelength with the IR spectrometer. This will permit e.g. stellar work on the (crowded) cores of bright star clusters, and the study of stellar populations in the cores of low-redshift galaxies. Because fiber-coupling is required to reformat spectra on the detectors, the instrument can be bench-mounted. Lower throughput than the High-Efficiency Optical Spectrograph is acceptable.

The goal of the "B" options is improved performance for stellar population work and provision of an easy upgrade path to additional fiber feeds from multiple integral-field units (IFU's) and an active optics (AO) system.

The extended options in the "C" list are for actual implementation of a multiple IFU (which would complement the Blanco Hydra-S by providing spatial resolution at each point and sampling closer than 23″), for implementation of an AO feed, and/or to extend wavelength coverage into the near-IR.

2.2 Near-Infrared Stellar Spectrograph

The "A" requirements call for a spectrograph able to attain 2-pixel sampling of the best quartile, center-field, tip/tilt stabilized images ($\approx 0\overset{''}{.}1$/pixel at 1500nm). This enables "work between the OH sky lines" and accurate sky subtraction.

The "B" options are for higher spectral resolution to broaden the range of stellar studies, an echellete mode to span a longer wavelength baseline for extinction measurements and for simultaneous measurement of spectral diagnostics in the ISM, and an IFU to permit 2-dimensional sampling of extended objects and crowded star fields.

The "C" options are for a longer slit to improve sky subtraction and to permit crude mapping of extended objects.

2.3 Near-IR Imager

The requirement is to preserve the near-diffraction-limited performance of the telescope at 1400 nm while enabling imaging in both broad bands (JHK) and narrow bands over as wide a field as possible within the isokinetic patch.

2.4 Optical Imager

The requirement is to provide 3-pixel sampling of best quartile, tip/tilt stabilized images and to cover the isokinetic patch in best quartile seeing, while enabling imaging in both broad bands (UBVRI) and narrow bands (including diagnostic emission lines in the UV) to do high-fidelity on/off-band image subtraction.

3 Detailed Instrument Characteristics

Using the partner projects as a guide (and with feedback from the authors) the SAC assigned the following (rough) priorities to the different instrumental features which are needed to execute the proposed scientific observations (whose basic goals are outlined in the section above).

The highest priority of the SAC was to avoid the trap of designing an instrument by committee. Thus the features listed below are neither meant to be exhaustive nor restrictive. “A” features are those necessary for almost all of the projects, which any acceptable instrument “must have”. “B” features are those which a majority of the projects requested and are “highly desirable” in any initial instrument but may be optional if financial or engineering constraints so dictate. “C” features are also highly desirable and may well be important for innovative work but were not perceived as absolutely necessary for an initial instrument.

Both the “B” and “C” features should be considered as goals for later upgrade if they cannot be accomplished in the initial instrument complement (whether for financial or engineering reasons.) These priorities are listed below for each general instrument class:

3.1 Very High-efficiency Optical (Stellar) Spectrograph

A list

- A simple short-slit instrument optimized for highest through put with R $\approx$5000 at 850nm.
- Spectral response: UV atmospheric cutoff (320 nm required, 305 nm desirable) to 850 nm.
- Spectral PSF consistency appropriate to better than 1% sky subtraction over the useful field of view (measured as D’(80)/D(80) <2% (where D’ is the deviation in D).
- Flexure <0.1 pix / hr.

B list

- R up to 20,000 at lower throughput.
- Extended spectral range to 1000 nm.
- ADC Correction down to 360 nm, (must be removable to preserve U).
- Multi-slit mask with ˜$3'$ FOV (with ADC for accurate spectrophotometry).
- Motorized slit mask exchange.

C list

- Multi-slit mask with >$3'$ FOV.
- Image slicer/dissector for spatial resolution (over a few arcsec FOV).

3.2 High-Spatial Resolution (IFU) Optical Spectrograph

A list

- 2D-coverage with 2-pixel sampling matched to best quartile, center field, tip/tilt stabilized images ($0\farcs15$/pixel at ≈1000nm) using an integrated IFU or image slicer with minimum of 1500 contiguous spatial samples, arranged over $\approx 5 \times 10''$ field.
- <5% cross-talk introduced by seeing.
- R up to 30,000.
- Wavelength coverage: 360-1000nm with one octave (factor of 2) interval on the detector at once.
- Throughput: 15% at 350 nm (including CCD + telescope).
- Flexure: < 0.04 pix/hr.
- Sky subtraction: 1% residuals over 180 ° field rotation
- Multiple fibers in fixed sky pattern (or applicable sky suppression strategy)

B list

- >15% throughput at <350 nm (including CCD + telescope).
- Sky subtraction: <1% residuals over 180 ° field rotation
- Provision for slit translation or other means of accomodating interchangeable fiber feeds.

C list

- Multiple IFU – 1000 spatial samples divided between several deployable heads distributed across the isokinetic field.
- Operation to 1400nm with necessary thermal suppression.
- AO feed with spatial scale $0\farcs08$/pixel to ensure 2-pixel sampling of top-quartile, center field, AO corrected images.

3.3 Near-Infrared Stellar Spectrograph

A list

- Spectroscopy of point sources over 1000-2500nm
- Sufficient sky coverage for simultaneous sky determination
- Configured so that $2K \times 2K$ array will fill a single atmospheric window (J,H,K) with R=4000.

- 2-pixel sampling of best quartile, center-field, tip/tilt stabilized images ($0\farcs1$/pixel near λ1500nm)
- R $\approx$18000 (2 pixels)
- Detector $1K \times 1K$ pixels
- < 0.1e-/s dark, <30e- ron
- Slit 20$''$ long
- Throughput 30% w/detector
- Flexure < 0.1 pixel/hr worst case.

B list

- $0\farcs3$/pixel for median seeing
- R > 20,000
- Cross-dispersion 900 - 2500 nm coverage at low R.
- IFU
- Detector $2K \times 4K$ pixels
- < 0.01e-/s dark

C list

- 900 - 5500 nm range.
- Slit 60$''$
- 900 - 2500 nm echellete mode at higher R ($\approx$2000) than is contemplated in B priority list.

3.4 Near-IR Imager

A list

- $0\farcs08$/pixel
- 80$''$ FOV
- 6 filter positions
- Cryo pupil stop, D(80)<1% of pupil size
- Throughput 30% with detectors and filters

- Spectral range 1000 - 2500 nm
- 2500nm dark current < 1e-/s
- 1$\farcs$6"$\times$1$\farcs$6 subarray (20×20 pixels) readout at 100Hz

B list

- 20 filter positions
- FOV 200 $''$ diameter
- $16 \times 16''$ subarray (200×200 pixels) readout at 20Hz

C list

- “Tunable” filter (R=100 to 800).
- R<2000 grisms + aperture masks
- Coronograph
- Extended spectral range to 4000nm.
- Field of view >200$''$ diameter.

3.5 Optical Imager

A list

- 0$\farcs$08/ pixel (with provision to "bin up" in poor seeing).
- FOV matched to isokinetic patch (5$'$)
- ADC operation down to 320 nm
- Provision for a minimum of 6 parfocal filters

B list

- More filters.
- Filter that gives spectral R tunable over 100-800.
- Dual CCD’s (one "red" sensitive, one optimized in the UV)

4 Adaptive Optics for the SOAR Telescope

Even with this instrument complement, a SOAR telescope without adaptive optics (AO) will be beaten soundly in many important science areas by several other southern-hemisphere 4m-class telescopes. We therefore strongly urge at the earliest possible date a **low-order AO system** with priorities:

1. Working over $\lambda\lambda$0.4–2 μm and a field of view of 1-2$'$
2. Laser guide stars if technically practical.

The SAC believes that the highest-priority science application for this system is optical spectroscopy over a two-dimensional field of view. This is elaborated in §2.3 of Chapter III *SOAR's Place In Southern Hemisphere Astronomy.* The most likely configuration is to bench-mount the AO system on one of the Nasmyth-focus optical benches, to feed the IFU spectrometer.

Appendix – SOAR Instrument Builders Handbook

Provisions to Accommodate Gemini-class Instruments

A goal for the SOAR telescope is to accomodate a generic Gemini instrument. The specification is the unballasted mass of the Gemini Near-Infrared Spectrometer (GNIRS, which weighs as much as, but is smaller in two of its dimensions than, the Gemini limit) because a clone of this is the only Gemini instrument that has been identified as a candidate for SOAR. The long-slit of this instrument can be reformatted with an image slicer to span up to a 6×8 arcsec^2 field. Because this instrument is sensitive to the thermal-IR, it is advisable to minimize the number of warm fore-optics. The approach with the least optics is to adopt its f/16 as the f/ratio of the SOAR telescope, and this is the prefered route because SOAR will attain best images in the thermally sensitive H and K-bands.[1]

Modifications to a Gemini IR instrument for operation at the SOAR telescope are minor:

1. The radius of field curvature at the f/16 focus will differ between SOAR and Gemini. Both telescopes are close to their respective Ritchey-Chretien (RC) designs, which differ because of different back focal distances and physical plate scales. In practice the difference is negligible (see SOAR Optics Definition [SOD] document for details) over the field of the GNIRS. It becomes significant over the full $7\rlap{.}'5$-diameter Gemini field at SOAR (see the SOD.)[2]

2. A clone of the GNIRS will need a slightly different pupil cold-stop when it resides on SOAR because SOAR's pupil is at M1 not M2, a 2m difference. This requires that the cold-pupil in a SOAR IR instrument be undersized to avoid seeing the warm telescope. The ability to change pupil stops is not a specification of current Gemini IR instruments, but is easily designed into new ones. In the GNIRS the entrance window acts as a field lens, and it appears that SOAR would need a different window than Gemini. This is an easy change when the instrument moves between the two telescopes.

Derived Instrument Requirements

To maximize the range of partner science that will execute optimally on the SOAR side of the SOAR/ Blanco system we need five facility-class instruments on "cold standby" at the Nasmyth and bent-Cassegrain foci. The considerable mass of the Gemini-class instrument on one side will be somewhat counter-balanced by two instruments on the other Nasmyth port, see Fig. 2. Up to two additional "user" instruments may be present at the other bent Cass. ports.

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[1] Adopting f/16 complicates the design of some visible-band instruments because the optimal match to CCD pixels ($\simeq$15 μm) leads to a telescope of f/9. The optical imager requires a refractive focal reducer/corrector. This corrector is cheaper than "paving the focal plane with silicon".

[2] Flattening the f/16 field of SOAR produces $0\rlap{.}''06$ of defocus at $3'$ radius, so the optical implications of adopting even a flat field are not large.

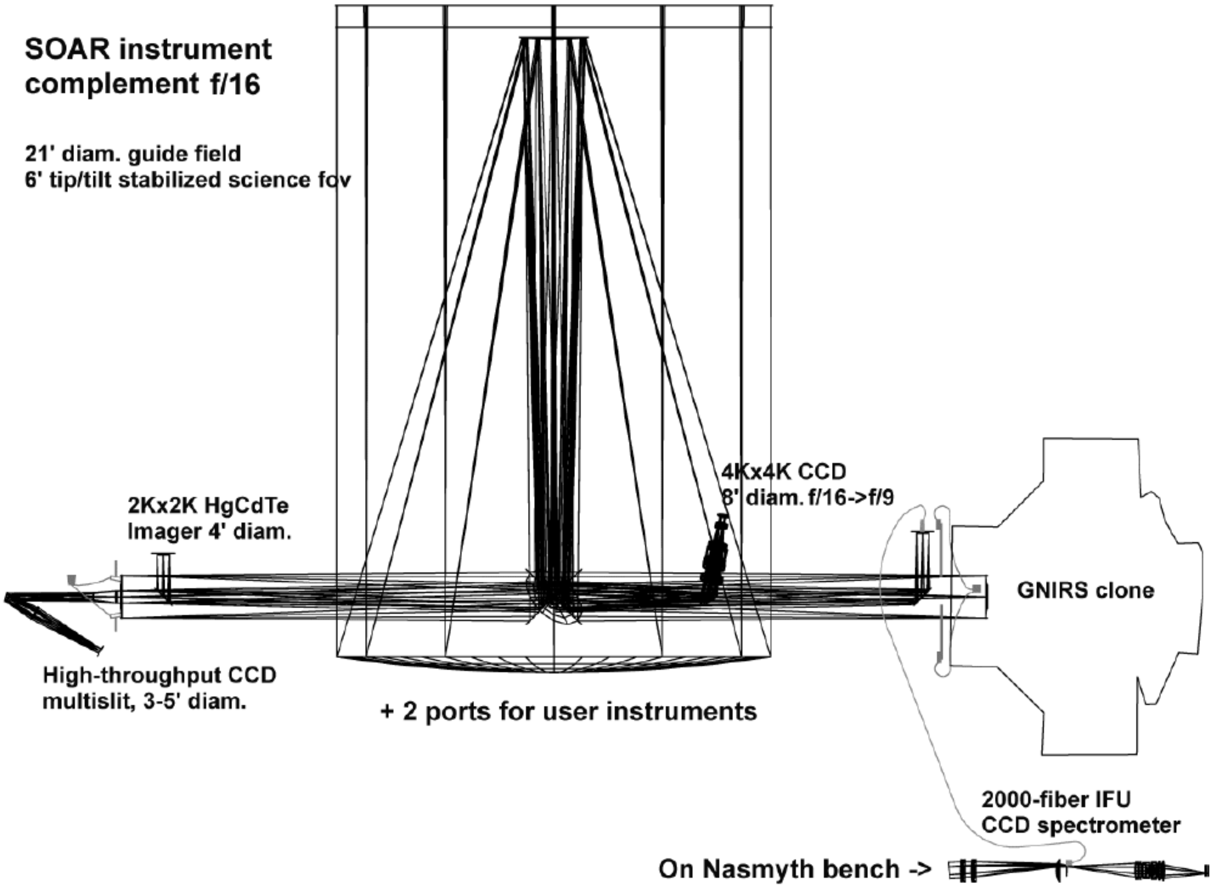

Figure 2: SOAR telescope foci with proposed instruments. Facility Calibration Units are located inline of the IR imager and IFU spectrometer. They feed these instruments directly, or use a double-sided M4 to direct light to the high-throughput optical spectrometer and to the GNIRS. Instruments at the bent-Cass. ports and on the Nasmyth benches rely on their own calibrators. Tip/tilt sensors near the image focus of all instruments must be used to attain the delivered image quality spec.

4.1 General Instrument Requirements

These requirements help to ensure that the high image-quality delivered by the telescope is preserved at the detector, and that high operational efficiency is achieved. Most are elaborated upon in later sections.

4.1.1 Required Compatibility with Guiding Strategy

1. **Project image-degradation specifications can only be met by using a tip/tilt guider.** All instruments must accept the quad-cell guiding sensor provided by the SOAR project (or, like Gemini instruments, provide their own.) This sensor ranges across the tip/tilt isokinetic field (5′-diameter), and sits close to the telescope focal plane to measure critically the instrument flexure. These sensors are discussed in §5.1.

2. The IR imager and spectrometer designs must provide a guiding strategy for work on dark clouds where visible-band guidestars will be very faint.

4.1.2 Instrument Efficiency Requirements

1. An instrument must fully configure itself for science within 2 minutes of its selection. During this interval, M3 and M4 will turn to the relevant port, and the tip/tilt sensor of the newly selected instrument will acquire a tip/tilt-reference star.
2. Instruments should not increase the light scatter of the telescope optics by more than TBD % where it makes sense scientifically.

4.1.3 Required Compatibility with Telescope Utilities

1. Closed-cycle coolers will be used for the normal operation of all IR detectors and instruments. These will be connected to He compressors provided by the Project. LN_2 and heaters can be used to increase ΔT. LN_2 in at least 30-hour holdtime dewars will be used for optical CCD's.
2. Instruments must be able to operate on both 50 & 60 Hz power. Only 50 Hz will be provided at C. Pachon , with 120, 220, or 380 V available. All instruments must be compatible with the TBD grounding strategy to be adopted by the Observatory. Linear rather than switching amplifiers are prefered to minimize pickup. Instrument electronics must be in the form of PXI/compactPCI cards which fit into a single 8-slot PXI chassis. This is described in http://www.natinst.com/pxi/pxispec10.html. This chassis will be insulated and cooled so that it emits < 50 Watts into the environment.
3. All instruments must be compatible with the focal-plane utilities. The Project will adopt those enumerated in the Gemini ICD (Interface Control Document) 1.9/3.6 *Science & Facility Instruments to System Services*. This document also describes the required connectors. The full suite of utilities at SOAR will include dry N_2, 80-100 psi air flowing at 120 l/min, ethylene-glycol/H_2O at 0° C and 15 psi flowing at 6 l/min, a He supply at 300 psi flowing at 3200 l/min, and a vacuum system to control instrument actuators.
4. All instruments must be compatible with the Project-provided array controllers. These are TBD, see §4.8.1.

4.1.4 Calibration Requirements

The required level of *final* calibration is itemized in §4.6.

1. All instruments must be stable enough to be calibrated to TBD levels using database entries. This permits a quicklook data-quality capability to enhance operational efficiency.
2. Nasmyth instruments must be fed by the Facility Calibration units (unless the instrument is fully self-calibrating to the final level itemized in §4.6.)
3. Instruments at the bent-Cass. ports must provide their own calibrators.

4.1.5 Instrument Mechanical Design Requirements

1. Spectrometers built without integral-field units (IFU's) or image slicers must attain full spectral-resolution with at least a $0\farcs5$-wide slit.

2. Uncompensated instrument flexure must change image centroids by <1/4 of the TBD shift introduced by field derotation during a typical science exposure (up to 1 hr for the visible imager, and both visible and near-IR spectrometers; 15 mins for the near-IR imager.) This requirement applies for zenith angles $\leq$60°.

3. Instrument optical designs must include end-to-end error assessments that include atmosphere, diffraction, opto-mechanical tolerances, the alignment strategy, baffling, and optical-inhomogeneity effects. Atmospheric structure relevant to seeing will be parameterized from data being collected by Gemini at Cerro Pachon. The Project will provide seeing models in the form used by the Skylight package, BRDF's of the telescope at certain instrument entrance apertures, and the complete XEMAX prescription of the telescope (including its polarization characteristics at its various foci.)

4.1.6 Thermal IR Requirements

The SOAR telescope is not being optimized for thermal-IR performance.

1. The thermal emissivity of IR instruments must be <3.5% (i.e. <1/2 that of the telescope) in the low-emissivity atmospheric windows $> \lambda$2.5 μm if the IR-array used is sensitive to this wavelength regime. Telescope emissivity is discussed in §4.7.1.

2. For $< \lambda$2.2 μm, all near-IR instruments must have an internal instrument background of <0.5 e/pixel/s. This ensures sky-background limited performance.

3. The near-IR instruments will need foci that are telecentric to the telescope pupil for optimal thermal control.

4.2 Spatial Sampling Requirements

4.2.1 Imagers

Our simulations (Diaz, SOAR Internal Report) show that to minimize sampling error in stellar fluxess obtained from PSF fitting, we must sample the FWHM with at least 3-pixels. For top-quartile, tip/tilt stabilized images, we therefore need $0\farcs10$ pixels in the optical and $0\farcs08$ pixels in the near-IR (both set at their smallest image points in the curves plotted in Fig. 2 of Chapter III *SOAR's Place in Southern Hemisphere Astronomy*.) Binning 2×2 gives $0\farcs20$ ($0\farcs16$) pixels in the optical (near-IR), i.e. 2.1 pixel sampling in bottom-quartile conditions. The combination properly over-samples 75% of the time, and allows us to back off a bit if we choose to bin in the worse 25% seeing. In the optical, which an f/9 focal reducer a $4K^2$ $\simeq$CCD array or mosaic of 15 μm pixels covers the isokinetic field.

4.2.2 Spectrometers

IFU/image slicers restrict sky coverage if the focal plane is over-sampled with 3 pixels. This is because the spectral resolution uses up most of the available detector pixels. Being more limited by sky coverage than by sky flux for most spectral resolutions, we can back off to 2 pixels in best conditions and accept spatial binning in median or worse. We therefore require $0''.15$ pixels for optical and $0''.12$ pixels for the near-IR.

4.3 Spectral Requirements

Fig. 3 shows, for SOAR's first-light detectors and good operating conditions, where in the spectral-resolution *vs.* source-flux plane SOAR beats the Blanco 4m. Gemini wins when these telescopes are photon-starved.

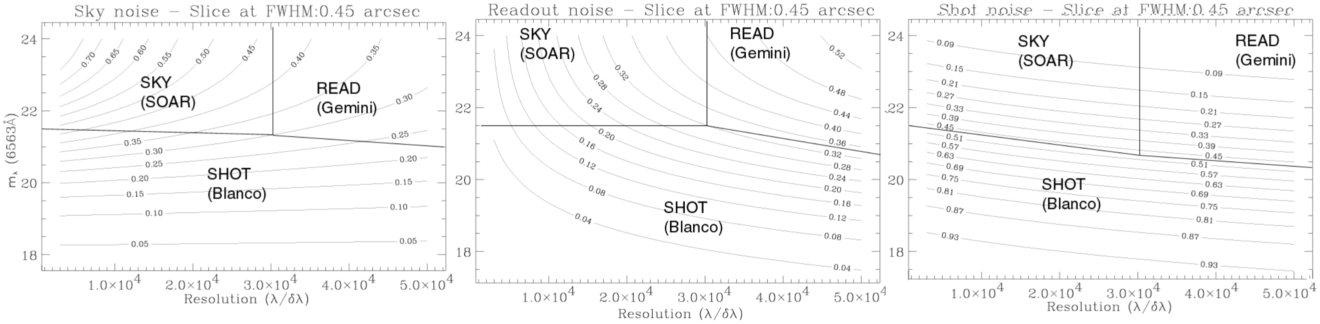

Figure 3: Fractions of the total variance for SOAR that arise from (left) sky, (middle) readout, and (right) shot noise at λ0.65 μm, various spectral resolutions, and in $0''.45$ seeing. Sky brightness is for CTIO dark time, mean extinctions at an airmass of 1.2, total telescope+instrument efficiency of 23%, slit matched to seeing FWHM, detector scale $0''.1$/pixel, readout noise of 1.5 e^-rms, dark noise $1.2\times10^{-4}$$e^-$/pixel/s, no binning, 1-hour exposure, and 100k e^- full well.

This figure implies that the optical spectrometers on the SOAR telescope should have resolving power $R \leq 30,000$. Larger R at SOAR is less important because SOAR will then be no better than the Blanco, and for the case of high-resolution spectroscopy of faint objects will be $16\times$ slower than Gemini.

4.4 Instrument Flexure Requirements

For accurate sky subtraction, spectrometers need <0.1 pixel flexure in 1-hr ($\leq 15^\circ$ change in zenith angle.) A TBD fraction of the image degradation with zenith angle *z* of $(\sec z)^{0.6}$ will be allowed for flexure in the system error budget.

4.5 Instrument Compensation for Atmospheric Dispersion

It is desirable to correct this effect (see Fig. 4) with an Atmospheric Dispersion Corrector (ADC) in the optical imager when using broad-band filters. Because the ADC is the only

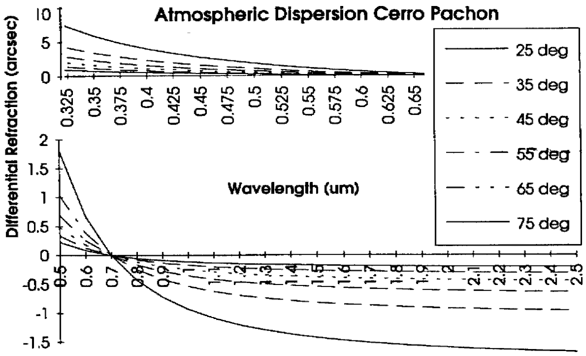

Figure 4: Corrections in arcseconds that are required for STP-conditions at Cerro Pachon, at different wavelengths and zenith angles.

element in the current imager design that attenuates light below 360 nm, it should be removable. Dispersion compensation can be delayed in the near-IR until SOAR implements AO. If the visible spectrometer incorporates an IFU with full spatial-sampling rather than a long-slit or slitlets, then an ADC is not required for exposures near the zenith. (The varying airmass away from the zenith smears the spectrum over more pixels spatially, reducing signal-to-noise especially in the blue.)

4.6 Instrument Calibration Requirements

Our philosophy is that, for efficiency, it will be highly desirable to use as many standard calibrations as possible that are taken within several days of the science data. However, it *must* be possible to calibrate instruments on a night-to-night basis to optimize results under the most critical circumstances.

4.6.1 Requirements Common to a Number of Instruments

Nasmyth instruments will be served by Facility Calibration Unit(s) (FCU). These units are designed to ensure that the distribution and direction of rays in the flat-field illuminator match those of the telescope pupil, and to provide a high surface-brightness comparison or flat-field illumination source. Our specifications are adapted from the Gemini document *Facility Calibration Unit Functional Requirements* by D. Simons (v1.1 3/95), which is attached in Appendix X for reference. Briefly, the unit will provide both continuum and arc spectral-sources for optical and IR instruments. It will produce a surface-brightness gradient of $\sim 10\%$ across the field of view. This will need calibration occasionally against the night sky, to determine the low-order corrections needed to reach our required accuracy of <1% variation.

A separate calibration strategy must be developed for each instrument at the bent and folded Cass. ports. This will include the use of a dome flat-field screen, to be supplied as a facility capability.

4.6.2 Calibration requirements of specific instruments

Here we outline additions to the Gemini document that we will require for SOAR.

IR imagers achieve <5% photometric accuracy from dithered sky flats. Gemini feels that a projection flat-field system will be required to do $\sim 1\%$ photometry. SOAR will provide this from the FCUs, over the 3-4$'$ fov of the IR imager. Flats will be acquired as the difference between two frames, one with the calibration lamp on and one off (see PASP **104**, 441.)

Spectrometers must scatter <10^{-4} of night-sky line flux. Dense calibration lines will be provided by many orders from a small, fixed-gap etalon in the FCU.

CCD's Optimal UV transmission is provided by a thinned backside illuminated chip, but existing UV-optimized CCDs show fringing of 0.5–15% (depending on manufacturer) Peak-to-Valley with fine structure. In principal fringing is directly calibrated in spectrometers if the telescope pupil is correctly mimicked by the calibration system (i.e. all rays reach the CCD from the right directions), and if the spectrometer does not flex. The last is the big problem, and can be dealt with by minimizing flexure in the design and by calibrating the residuals at all telescope and instrument positions.

In the case of intermediate- and broad-band direct imaging, fringing is extremely difficult to calibrate because the flat-field source does not have the same spectrum as the night sky. Deep-depletion, high resistivity chips provide higher QE in the R/I bands with minimal fringing while preserving the high DQE in the visible of blue-optimized chips. It therefore makes sense if there are two CCD's in SOAR's optical mosaic imager for one to be optimized for the UV and the other to be a deep depletion chip with performance tuned for the red/I.

4.7 Instrument Throughput Requirements

4.7.1 IR Thermal Emissivity Requirements

These are summarized in Fig. 5. SOAR aims to obtain 7% emissivity, <1/2 that of the Blanco 4m. This will require regular CO_2 cleaning and perhaps also monthly mirror washes, so the telescope is being designed to facilitate these activities.

4.7.2 Reducing Reflective and Transmissive Losses on Optics

Table 1 summarizes requirements and goals, assuming a Sol-Gel-on-MgF_2 coat on each lens surface.

4.8 Instrument Control Requirements

Instruments must interface with the TBD Data Handling System. This will be based on Gemini concepts, but not EPICS messaging.

4.8.1 CCD Array Controller Capabilities

Instruments must be compatible with the SOAR project array controllers. The SOAR project has identified science that requires high time-resolution over the entire detector array. This requires a multi-channel controller that reads out at a rate of order 20 Mpixels/s and can control either TEC or LN_2 coolers.

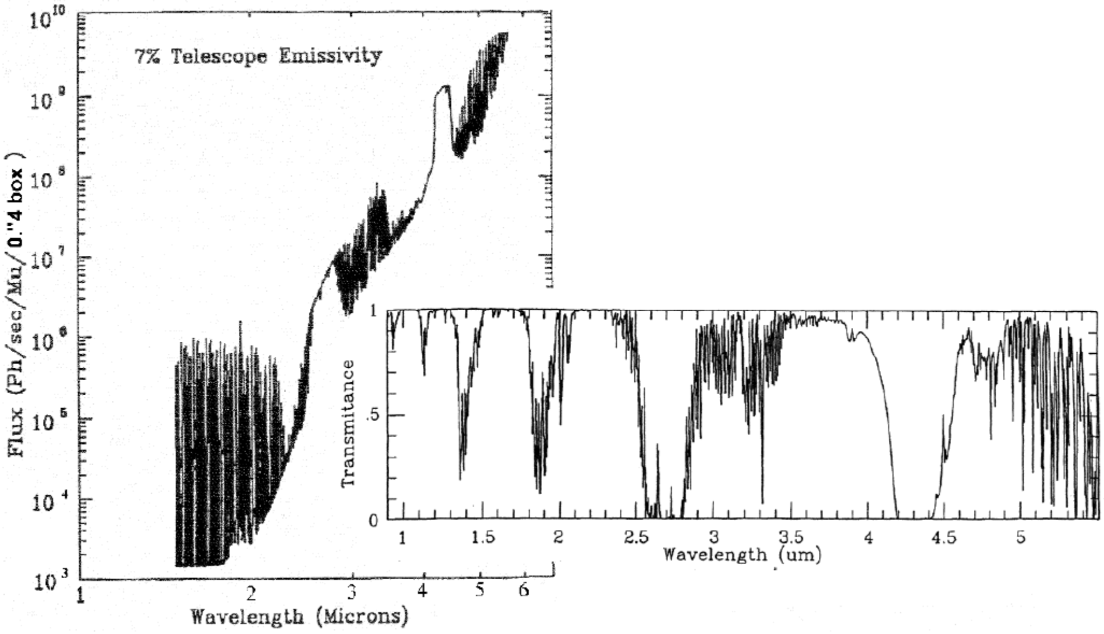

Figure 5: The total background radiation spectrum entering an IR instrument on SOAR. This assumes an atmospheric temperature of 253K, airmass 1, 1.2mm of water vapor, a warm optical train of M1-3 at 275K for a total emissivity of 7%. (Insert): sky transmission at Cerro Pachon, with 1mm of precipitable water vapor at an airmass of 1.

There are two possibilities which also satisfy a commonality requirement to ease maintenance and support. Gemini has adopted the Leach Gen2 controller from San-Diego State University and are awaiting delivery at the end of 1998. Further modifications of this system would be required to operate at SOAR> Another possibility is an ARCON from CTIO. Both would run the optical and near-IR arrays. The SOAR project will decide between these CCD controllers toward the end of 1998.

Broad-band	$\lambda\lambda$0.33-0.4	$\lambda\lambda$0.4-0.7	$\lambda\lambda$0.7-1.1
Reqd.	<1%	<1%	<2%
Goal	<0.5%	<0.5%	<1%
Narrow-band			
Reqd.	<0.5%	<0.5%	<1%
Goal	<0.2%	<0.2%	<0.2%
Reflectivity (fresh coatings)			
Reqd.	>0.88	>0.88	>0.84
Goal	>0.92	>0.98	>0.98

Table 1: Limits on coating and reflectance losses at each optical surface.

4.8.2 Non-standard CCD readout modes

HIGH TIME-RESOLUTION WITH SUB-ARRAY READOUTS Many SOAR science programs require time resolution at rates that exceed the (0.5,0.1) Hz time for a full-frame (IR,optical) readout. Several of these programs would benefit from complete readout control, whereby charge in each CCD row is stepped across the chip at a rate precisely synchronized with that of the astrophysical process under study. Drift scanning is one example, but transfer rates up to 100 Hz/row are also required. This is actually a special case of

CHARGE SHUFFLING This mode is relevant to optical CCD arrays. It operates by clocking charge back and forth across an array, periodically (every 1-10 minutes) moving part of the charge under an opaque mask that obscures part of the chip. If other characteristics of the instrument are “beam-switched” in synchronization, it becomes possible to cancel out ALL time-dependent systematics without incurring the time or noise overhead of multiple image readouts. An application of this is tunable-filter imaging. Here a Fabry-Perot etalon is varied in its wavelength transmission (by altering the plate separation hence optical gap) between on- and off-bands that are selected entirely for their astrophysical content rather than what filters one happens to have. Altering the gap alters in no way the optics or illumination path. Consequently, **all** time-dependent effects that normally limit the reliability of image subtraction are avoided, and very deep narrow-band images result that can go far below sky.

This technique works equally well for long- or multi-slit spectroscopy, where the telescope is now “nodded” onto blank sky every few minutes, as charge is shuffled under the mask, to completely remove time-variable night-sky emission.

These operating modes may drive specifications for the telescope-instrument interaction just as much as does mid-IR beam-switching. Instruments which might not otherwise need interchangable focal-plane maks will require them to support various charge-shuffling modes. These masks can be introduced at the telescope focus (which is curved), best at intermediate foci in reimaging cameras (which can in principal be designed flat), or at the detector itself.

4.8.3 Control Modes for IR Arrays

IR arrays are read out using a direct capacitative connection to each pixel, so there is no analog to charge shuffling while integrating. There is no capability for on-chip binning and so no reduction in read-noise. However, because the signal charge is not destroyed on readout, read noise can be reduced by multiple reads of the same datum, e.g. *n* reads at both the start and the end of an integration achieve a $\sqrt{n}$ reduction. Another method is to read at intervals as the charge accumulates during an integration, and fit a slope to the result.

Shortest exposure will be the readout time unless a shutter is used. The total readout time for an array depends on the per pixel clocking speed (adjustable in the controller, but faster is noisier) and the number of pixels per output (fixed by the multiplexer [MUX] design). HgCdTe systems need not provide high read-rates, and may choose not to, to reduce the complexity and cost of the associated electronics. MUX flexibility may also be sacrificed on the grounds of simplicity and cost.

The bottom line: one must understand the performance specifics of a given device to assess what is permitted operationally. Examples: the 1024^2 HgCdTe arrays produced by

Rockwell for U. Hawaii read out a frame in four independent quadrants no faster than 500 millisec. The ALADDIN InSb 1024^2 devices also have four quadrants but use 8 output lines per quadrant to read out up to $10\times$ faster (50 millisec.) Electronics for InSb are correspondingly more complex and costly compared to HgCdTe.

5 The Operational Environment for SOAR Instruments

This section describes the environment provided by the SOAR telescope in which the instruments will operate. Specifications are found in Chapter II *SOAR Telescope Requirements*.

5.1 On-Instrument Tip/tilt Sensors

The specified Project image-quality can be attained only if an on-instrument tip/tilt sensor is used. This will be fed from a prism or 45° mirror to sample a star bright enough to close the tip/tilt control loop. The field of view of the probe will be very small (TBD arcsec^2), to minimize obscuration of the science field. The density of stars suitable for tip/tilt control — 800 stars/deg^2 with mag-R <17.5 at the South Galactic Pole (see Table 2) — means that the sensor must span $\sim$14 arcmin^2 to ensure 3 candidates on average. This is within the expected isokinetic field. Cases where there is no tip/tilt reference star will be relatively few. The probablities of getting such a star are similar for SOAR and Gemini, i.e. >90% anywhere in the sky. (The true numbers are somewhat uncertain. Optimistically the probabilities could be as high as 99% even at high latitude.)

Sampling at 400 Hz will allow the tip/tilt unit to fully correct telescope motions up to 40 Hz, and would get the tip/tilt correction well above at least the first harmonic of the lowest telescope resonances.

R-mag	Photons/4m	# stars in $(60')^2$		quad-cell S/N
	0.3 μm/msec.	Lat. 30°	Pole	400 Hz, RN=5e$^-$
≤ 14	990	5	2	60
≤ 15	400	9	4	24
≤ 16	160	17	5	10
≤ 17	60	large	9	4

Table 2: Photon rates and R-band guide-star visibility. RN=5 assumes a fast-read CCD rather than a 4-element APD.

5.2 Object Acquisition

A guide/wavefront-sensing camera will be provided at each Nasmyth side to 1) position accurately an “invisible” object onto narrow ($0\rlap{.}''2$) spectrometer slits, 2) verify field derotation, and 3) monitor telescope active optics during observation. For instruments with integral field units (IFU’s) or image slicers, acquisition requirement 1) is relaxed.

Our acquisition tactic is that we know where all stars bright enough to guide on are, so we only need to view an ≈ 1 arcmin^{2}field to verify pointing. (This is a conservative error box to show the telescope operator in early operations.) The Gemini OCS to be adopted by SOAR will incorporate the HIPPARCHOS/TYCHO catalogs for astrometric reference. Together with the POSII catalog set, these will provide Johnson B- and R-mag down to 21-mag with $0\farcs3$ rms accuracy, star/galaxy id and ellipticity information, and allow the OCS to make first-order refraction corrections based on guide-star color. The Gemini Observing Tool will provide easy offline or interactive selection of guide stars from these catalogs.

It should also be straightforward to monitor variations in the telescope-delivered image quality and atmospheric transmission during an exposure (although not the true seeing measured on the detector within the stabilized isokinetic patch) by grabbing occasional readouts from the guider. It is a project goal to provide occasional filtration of these images, to derive first-order color terms for extinction measurements. These would be tied in with multi-star measurements from a site-wide automated photometric telescope to show conditions along the telescope line of sight during the observation.

5.3 Data Reduction & Archiving

5.3.1 Quick-Look Requirements

The Project intends to adapt the Gemini Observatory and Data Handling Control Systems to the SOAR telescope. These systems provide quick-look capability built around 4 tools: data display tool, movie tool, data reduction tool (which runs scripts to permit quantitative scientific assessment of data), and the observing assistance tool (guide star selection and other observer support tasks.) The specific functions of each tool and their scientific requirements are based on the Gemini document *Scientific Perspectives on Gemini Data Reduction* by P. Puxley (v1.0 3/24/96). A copy of this report is included as Appendix Y. Other capabilities can be added as necessary.

In general the TCS and instrument controller provide World Coordinates together with geometric distortions so that coordinates are available in both pixels and e.g. sky angles. Data error or quality (e.g. a power spectrum) can also be displayed.

5.3.2 Data Reduction Pipeline

It is an eventual project goal to fully reduce data shortly after the exposure ends. This allows the observer to refine subsequent exposures in the observing queue. It will usually be necessary to consult a database of calibration exposures. There are implications for instrument stability, and also for the philosophy of calibrating queue observations (i.e. whether to calibrate in advance of all potential observing setups, or to await observations then calibrate only setups which were used.)

Basic reductions often depend strongly on instrument peculiarities, while final data quality may depend on the success of the first reduction steps. The most time-consuming phase of pipeline reduction is to find the best procedure for the various operational modes of each instrument. These procedures should be established by the end of the commissioning phase. This task will be better done by the instrument builders and frequent users of the telescope. Once the pipeline is well tested, it may be preferable to reduce all data in a standard optimized way rather than distribute custom IRAF software and cookbooks. Reduction of queue observations would be more difficult for the observer, and the Observatory will have all the required (shared) calibrations. Given that there will be many new concepts in SOAR instruments, we feel that keeping control and responsibility for data reduction within the SOAR operations team or in a central group for each partner may be the best way to assure the maximum possible quality for the data obtained. It is is likely that typical observers would have limited or no experience at all in using and reducing data taken with some of the planned instruments.

5.3.3 Data Archive Requirements

SOAR should archive all raw data and calibration frames, as well as the reduced-data products delivered by the operations team. We should at a minimum provide a means of recalling such data on an occasional basis (e.g. when the first distribution is accidently lost or destroyed.) However, the intent is not to provide a full retrieval archive at the level provided by e.g. HST or Gemini.