DRAFT Rev 1 SOAR Scientific Requirements

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Contents

1 Executive Summary

The SOAR telescope will be built on a southern-hemisphere site with excellent seeing. The SAC agrees that the general science drivers for SOAR are:

PRIMARY SCIENCE REQUIREMENT SOAR must achieve comparable fractional encircled energy to the Gemini-S specification over a larger field of view, at a given wavelength in the interval $\lambda\lambda$0.3-2.3 μm, maintainable over the 20-yr operational lifetime of the telescope.

Observing Mode	Capabilities			% Partner 4m Science	
	Blanco	SOAR	Gemini	Blanco	SOAR
Spectroscopy $\lambda\lambda$0.3-1 μm					
45$'$ MOS	S,B.D	-	-	5	-
5-15$'$ MOS	-	S,B	B	-	5
2D over 0.5-5$'$	-	S,B	B	-	5
1-10$''$, low R	(S)	S,B	B	5	8
1-10$''$, high R	(S)	-	B,D	5	2
Low R, $\lambda\lambda$0.31-0.36 μm	-	S,B	-	2	-
Spectroscopy $\lambda\lambda$0.9-2.3+ μm					
45$'$ MOS	<1.7 μm	-	-	5	-
5-15$'$ MOS	-	S,B	?	-	5
2D over 10-20$''$	-	S,B	?	-	5
Single object, $R < 15{,}000$	<1.7 μm	S,B	?	-	10
Single object, $R > 30{,}000$	<1.7 μm	S	B,D	-	5
Optical Imaging					
40$'$ field, lower angular res.	S,B	-	-	10	-
10$'$ field, higher angular res.	-	S,B	B	-	6
Tunable filter (R=50-1000)	-	S,B,D	-	-	5
IR Imaging					
>10$'$, low angular res.	B??	-	-	5	-
2-5$'$, high angular res.	-	B	B?,F	-	5
Tunable filter (R=50-1000)	-	D?	D?,F?	-	2

Table 1: Here S = shot-noise limited, B = background-noise limited, D = detector-noise limited, F = diffraction limited, () signifies reasonable but not ideal performance. *The entries in the last column in particular are meant to generate spirited debate!*

SECONDARY SCIENCE GOALS (not prioritized):

- careful control of scattered light, with the specific aim that coronographic reduction of scattered light at λ2.2 μm not be limited by mirror scatter
- technical capabilities that complement the Blanco 4m telescope, to avoid duplication of instruments.
- continued provision for up-to-date instruments, mounted for long-term use and rapidly selectable on-line in queue-mode. This should allow users to obtain $\lambda\lambda$0.3-2.3 μm imaging and spectrophotometry with high efficiency, and to conduct long-term monitoring and surveys with stable calibrations.

REQUIRED INSTRUMENTAL CAPABILITIES The SAC believes that the scientific capabilities of a SOAR telescope meeting the above general requirements and goals will fit in with what can be done on the Blanco and Gemini-S telescopes in the way indicated in columns 2-4 of Table 1. These columns show which telescopes will be best suited for carrying out each type of observation.

In addition, the SAC has surveyed our constituency to determine the mix of science which the partners currently wish to carry out. The results are shown in columns 5 and 6 of the table. These are expressed as percentages of the total predicted hours of use; the sum of all entries in columns 5 and 6 is 100%. Only the desired science which can reasonably be done on a 4m telescope is shown. Programs are distributed between SOAR and Blanco according to the relative capabilities shown in columns 2-4.

MINIMUM FIRST-LIGHT INSTRUMENT COMPLEMENT Based on the contents of the above table, the SAC concludes that SOAR should have the following minimal instrument complement to carry out a reasonable fraction of the desired scientific programs:

1. VERY HIGH-EFFICIENCY OPTICAL SPECTROGRAPH. A simple bench-mounted, on-axis instrument optimized for throughput, offering resolutions up to $R \simeq 30,000$, and ideally working down to the atmospheric UV cutoff ($\lambda 0.32\ \mu$m). This instrument would address $\simeq$10% of the partner science. Estimated cost: $xxM.
2. INFRARED SPECTROGRAPH. A versatile near-IR spectrograph offering a range of spectral resolutions and plate scales. Highest priority is for efficient spectroscopy of stellar objects, but there should at least be limited long-slit and IFU capabilities. Would address $\simeq$15% of the partner science. Estimated cost: $xxM.
3. INFRARED DIRECT IMAGER. Must work out to at least $\lambda 2.5\ \mu$m and provide 3-pixel sampling of SOAR's 25th percentile best images (i.e. $0\overset{''}{.}08$/pixel). Should have the largest possible format consistent with this sampling. Should provide a wide selection of filters and, ideally, a collimated beam for a tunable Fabry-Perot filter or similar spectral capabilities. Would address $\simeq$5-7% of the partner science. Estimated cost: $xxM.
4. OPTICAL DIRECT IMAGER. CCD array directly at f/16 telescope focus, 4K×4K format, basic filter wheels and shutter. Must provide 3-pixel sampling of SOAR's 25th percentile best images, and then the largest affordable field of view consistent with that sampling. Would address $\simeq$5% of the partner science. Estimated cost: $xxM.

All cost and time-fraction estimates are rough guesses, subject to major revisions. At face value, this complement of standard instruments on Blanco and SOAR would satisfy almost 3/4 of partner science goals.

If inadequate funds exist to build all four instruments in time for first light, the SAC recommends that the priority order be that in the above list. However, we do not believe that SOAR can be successful scientifically until at least the two spectrographs are available.

CAPABILITIES THAT MUST BE ADDED FOR SOAR TO COMPETE SCIENTIFICALLY The SAC believes that even with the above minimum instrument complement, SOAR will be beaten soundly in many important science areas by several other southern-hemisphere 4m-class telescopes until it has the following additional capabilities. *The SOAR partners will not have guaranteed access to either of these instruments at other telescopes.* We therefore strongly recommend that the partners urgently seek funds to add at the earliest possible time:

- HiGH-SPATIAL RESOLUTION OPTICAL SPECTROGRAPH, configurable with an on-axis Integral Field Unit (IFU) and deployable multiple IFUs. This instrument is needed to take exploit SOAR's very high image quality for the widest possible range of scientific programs, through the AO system and over the tip-tilt stabilized field ($\simeq 10'$), respectively. The first-light High-Efficiency Optical Spectrograph would not do this to any significant degree because of its negligible field coverage. Estimated cost: $xxM.
- LOW-ORDER AO SYSTEM working down to $\lambda 0.4\ \mu$m, with laser guide stars if technically practical. The SAC currently believes that the highest-priority science application for this system is optical spectroscopy over a two-dimensional field of view. Estimated cost: $xxM

HIGH-PRIORITY 2ND-GENERATION INSTRUMENTS Second-generation instruments which have been discussed and which should be added to the above complement at the earliest possible time are:

- OPTICAL REIMAGING CAMERA. Designed around the tip-tilt corrected field of SOAR, reimaging to a more suitable f/ratio and providing collimated beam space with tunable Fabry-Perot filter and other deployable elements. This would offer far more scientific flexibility than the simple direct imager envisioned for first light, and would produce significantly better results for problems involving on/off band measurements of emission or absorption features. Estimated cost: $xxM.
- MULTI-OBJECT INFRARED SPECTROGRAPH. If not provided by the first-light IR spectrograph. Like its optical counterpart, this would fully exploit SOAR's high quality images over a two-dimensional field of view. Whether this would replace, upgrade, or complement the first light instrument depends on whether this new instrument could also cover all of the basic requirements for spectroscopy of stellar objects. Estimated cost: $xxM.

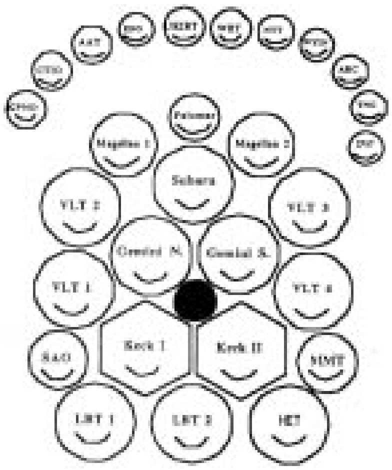

Figure 1: SOAR's aperture (shaded) compared to its global competitors at first light after 2001. (Figure adapted from R. Racine.) US SOAR partners have general access only to the SOAR, Blanco, Mayall, and WIYN 4m-class telescopes, and to the Gemini 8m telescopes. Brazilian SOAR partners will have explicit rights to use only the three southern hemisphere telescopes.

2 Scientific motivation

The future SOAR community includes many US astronomers (through NOAO) and Brazilian, MSU and UNC astronomers, so everyone's requirements will not be satisfied exactly. An important consideration in the scientific prioritization process has been the availability of the Blanco 4m telescope and its instruments that complement SOAR's capabilities (thus, SOAR will not duplicate those capabilities). For example, the $45'$-diameter field at the prime focus of the Blanco telescope means that SOAR does not require such a wide field of view. SOAR will produce up to 4× tighter energy concentration than the Blanco 4m, at the expense of covering only 6% of the Blanco field of view, thus complementing the Blanco's capabilities. SOAR's first-light competition is shown in Fig. 1.

Our overriding emphasis on image quality is appropriate because, for point sources of angular image diameter w, the time to reach a given signal-to-noise ratio is $\propto (w/D)^2$, and the limiting flux density which can be observed with a given signal-to-noise ratio is $\propto w/D$ if the observations are background (not detector-noise) limited. More generally, the simple-minded formulae in Table 2 were used to estimate the dependence of exposure time on other parameters in different observing regimes:

- t = exposure time to reach a given signal to noise ratio (s/n)
- F = object flux
- D = telescope diameter
- w = image diameter. $\sim$ is used here to imply proportionality rather than approx equal.

In Table 2 the object flux is carried along explicitly as a reminder that exposure times blow up rapidly if there is another noise source beyond the photon noise from the object itself. Plots of exposure times to reach a given limiting magnitude are shown for the V, I, H, and K-bands in the Appendix in §5. The performance of SOAR in bottom decile and median conditions are compared to the Keck telescopes, SIRTF (a future IR-optimized space telescope), and HST.

In the following, we summarize SOAR's niche in the Blanco/SOAR/Gemini-S environment for various broad scientific programs.

Regime	Dependence	Typical Application
1. Shot noise limited	$t \sim D^{-2}F^{-1}$	Imaging/spectroscopy of bright objects
2. Background limited	$t \sim w^{2}D^{-2}F^{-2}$	Imaging /spectroscopy of faint objects
3. Detector-noise limited	$t \sim D^{-4}F^{-2}$	High-res. spectroscopy at intermediate mag.
4. Diffraction+BG limited	$t \sim D^{-4}F^{-2}$	λ>3 μm for SOAR

Table 2: Scaling relations for SOAR. The detector-noise limited case assumes that multiple readouts are needed, with number proportional to total exposure time. If there were only one readout per observation, the result would change to $t \sim D^{-2}F^{-1}$.

2.1 High Spatial Resolution Imaging & Imaging Spectroscopy over a Moderate Field

As an example of the types of projects possible with SOAR's tightened PSF over a narrow field appropriate for AO, consider the measurement of stellar dynamics near the obscured center of the nearby active elliptical galaxy Centaurus A, with the goal of constraining the mass of any black hole that may be there. This must be done using K-band spectroscopy because of the high extinction. For such a study, the constraint on mass is inversely proportional to the spatial resolution squared, w^{-2}, and would best be done on SOAR with low-order AO because it will offer better angular resolution than either a low-order AO system on the Gemini 8m or HST with NICMOS.

High spatial resolution is also required in imagers and spectrometers to minimize crowding in stellar fields, for example in the cores of globular clusters and in the Magellanic bar. Stellar work in general requires high-resolution (R≃30,000) and, to be competitive, often multi-object multiplex (e.g. radial-velocity monitoring in clusters over a field 5-10$'$ in diameter). High and very high ($R \geq 10^5$) multi-order spectroscopy of single objects is also required (e.g. weak lines or lines in crowded spectral regions, $^6Li/^7Li$ abundance ratios to test Big-Bang nucleosynthesis, C and O isotope ratios to test mixing, tests of depletion onto grains, element abundances in Quasar metal-line systems.) In all but the most crowded regions, these programs can execute on the Blanco.

The Gemini telescopes are being optimized for work in the thermal IR ($\lambda \geq 2$ μm). However, backgrounds are large. So even with their excellent IR properties, all but the faintest objects which they can study in the thermal IR will be bright enough for easy complementary near-IR/optical observations with SOAR. Similar requirements for optical observations of objects which are only moderately faint come from follow-up to space-based (e.g. SIRTF, HST, AXAF) and radio observations. A hint of what SOAR should be able to do here is shown in Fig. 2, where a grid of [O III] emission line profiles are superimposed on the HST WFPC2 image of the nuclear region of the Seyfert galaxy NGC 1068. An imaging spectrometer for HST would not have the flexibility, field of view, or range of spectral resolution possible from the ground.

The study of X-ray, γ-ray, and radio sources has been a major use of 4m telescopes for years, and work complementary to HST UV observations is currently very productive scientifically. A more Gemini-specific example would be observing the $\lambda\lambda$3-5 μm spectra of a supernova even at moderate redshift, to study the decay of important isotopes. Such observations will require the Gemini telescope. But most likely the supernova would be bright enough to obtain the important $\lambda\lambda$0.3-2.5 μm spectra with SOAR, using Gemini time for only the most demanding $\lambda\lambda$3-5 μm work.

2.2 PSF Wings – High Dynamic Range Imaging

All two-point correlation functions in astronomy are power-laws which drop faster than $1/r^2$; the closer we get to an object, the more novelties there are to find. It is therefore useful for SOAR to employ a coronagraph in its near-IR imager to filter the telescope pupil for scattered light control. This, in conjunction with regular optics cleaning, will facilitate new science such as imaging spectroscopy of mass-loss envelopes around W-R and Mira stars and planetary nebulae (Carney 1997), the structure of protostellar disks, the background starlight in quasars, and searches with tunable filters for brown dwarf candidates in multiple star systems.

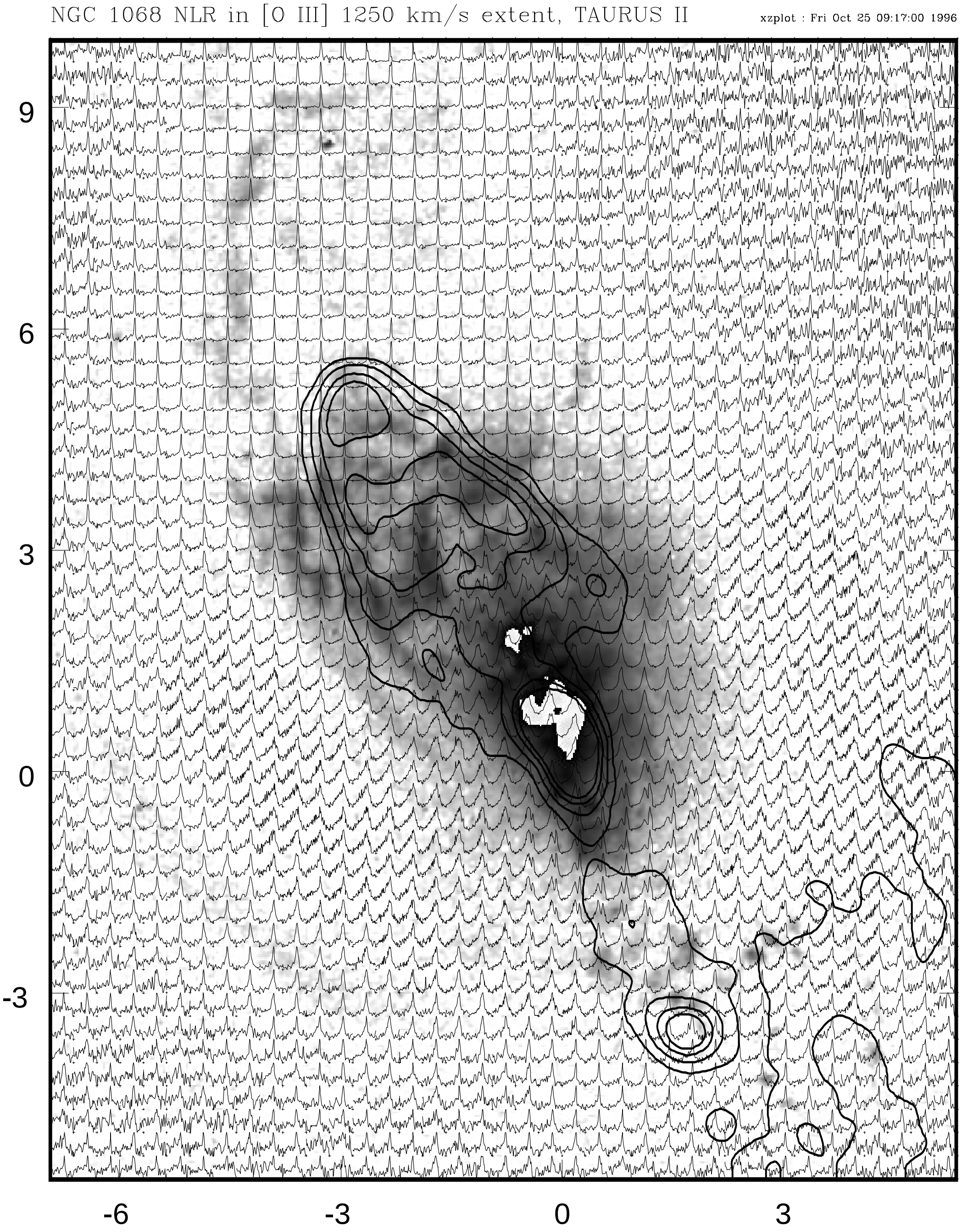

Figure 2: [O III] spectral grid across $10 \times 15''$ around the active nucleus of NGC 1068; 2250 km s^{-1} extent, intensity autoscaled at each point. The spatial and flux variations of the line profiles highlight the interaction of the quasar wind and radio jet with the galaxy ISM. The AAT TAURUS-II Fabry-Perot was used in $0''.9$ seeing. 90-sec monochromatic exposures were stacked into spectra which are plotted on the HST WFPC2 continuum-subtracted [O III] image together with VLA contours of the radio jet. With an FP or IFU spectrograph, SOAR should be able to map at 6× this spatial resolution the kinematics of similar, but more distant emission-line nebulae that will be imaged with the Advanced Camera on HST.

2.3 Supplementary Scientific Programs

These emphasize doing the same things that could be done faster on an 8m (because of its D^2 advantage), but using a cheaper telescope to observe the brighter objects or to observe with lower wavelength resolution. Of course, at the same linear scale a 4m can cover 4× the angular field of the 8m. If the objects have this density on the sky and are resolved in both telescopes, the 4m is now equally efficient. Various examples of such projects possible on the SOAR/Blanco system are:

2.3.1 Low Spectral Resolution Optical/IR Spectroscopic Surveys

Generally in astronomy a single object within a class cannot serve as a "Rosetta Stone" for the entire class. When this has been claimed in the past, it has usually been learned later that the "prototypical" object was not fully representative of the class in general (usually, it had special characteristics which made it easier to observe, which is why it was selected for observation in the first place). In general, one needs to study a statistical sample of objects before valid conclusions can be drawn. Such samples usually span a range of source brightness due either to distance or intrinsic luminosity distribution. While the most demanding observations of the faintest sources will require the largest telescope, brighter sources will not. For example, determining the luminosity function of a group of objects (the embedded stars within a stellar cluster, galaxies at moderate redshift or quasars) will span a large range of magnitudes. Both the SLOAN and 2DF surveys will generate 100,000 low-dispersion stellar spectra.

On SOAR, near simultaneous spectra will be obtained from $\lambda\lambda 0.34 - 2.3\ \mu$m ($-5\,\mu$m [G].) For stellar work, the spatial multiplex for maximum efficiency on Galactic populations is estimated (Beers 1997) to be N = 10-50 simultaneous spectra over a 5-10$'$ field of view. The numbers are similar for galaxy clusters at the maximum redshift at which clusters can be identified with contemporary techniques (nearer clusters are large enough to be good targets for Hydra.) The most distant clusters are apparently being observed in the act of formation. In this case, spatially resolved spectra over each object will measure their internal velocities to study the evolution of dark-matter envelopes (80% of the starlight in a cluster galaxy at I = 24-25 is contained within $1\farcs5$ diameter.)

2.3.2 Synoptic Imaging & Spectrophotometry

Many programs require that observations of fairly bright objects be repeated at predetermined intervals. Programs such as studying the temporal variations of many different emission lines in AGN broad-line regions via reverberation mapping, or calibrating the distances to Local Group galaxies from variable stars fall into this category. Because the objects are relatively bright, observing them with Gemini would be possible but would not make efficient use of that facility. One often requires spectrophotometry, and so at least a 4m aperture. Because these are mostly point objects, exposure times will be minimized with a tight PSF. These projects are far more efficient if SOAR is queue scheduled to adjust to the nightly seeing variations found at CTIO (see §4.10.) Imagers and high-resolution ($R \simeq 30,000$) spectrometers, in both optical and IR, should be available a large fraction of the time (Smith 1997). This will also help to ensure stable calibrations.

Another class are "targets of opportunity", e.g. monitoring microlensing events for photometric signatures of terrestrial-size planets in nearby galaxies, determining q_0 from supernovae, or UV/optical/IR light outbursts associated with high-energy flares from gravitational energy release near compact objects. Being able to follow spectral evolution over a large wavelength range is crucial to understanding the astrophysical nature of these objects. Quick access is required to the telescope, often in only a few hours. Again, a preemptive observing queue (with TBD criteria) will enable this science, and it is feasible for the scientist to "eavesdrop" during the observerations to "fine-tune" the program for maximum payoff. The scheduling of the Gemini telescopes will in general be too inflexible to follow most of these targets.

2.3.3 High-Resolution Spectrophotometry of Bright Objects

High spectral-resolution studies of objects fainter than V∼17 mag have already been taken over by 8m-class telescopes (Keck) because of their D^4F^2 advantage in exposure time (Table 2 & Fig. 13), but 10-15 mag stars in our Galaxy and the Magellanic Clouds continue to be natural targets for 4m telescopes. At the fainter end, this gets down to moderate stars in Local Group galaxies. There is great scope for studies of chemical abundances and line profiles in stellar atmospheres and interstellar clouds. For stellar abundance work, S/N>30 is required.

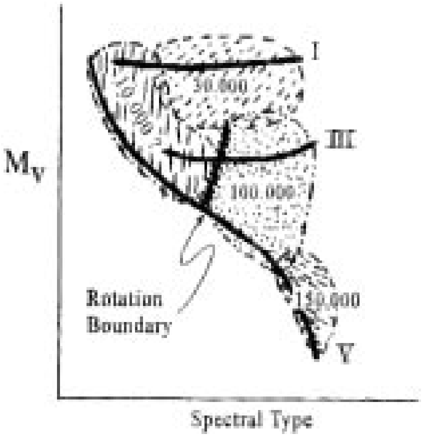

Figure 3: R-values required to resolve line profiles in Galactic stars. Hot stars to the left of the "rotation boundary" spin rapidly at 100-300 km/s. (From Gray, in *Instrumentation for Large Telescopes.*)

As an extreme, SOAR should be able to attain $50 < \mathrm{S/N} < 100$ for a V=14.5 star at R=50,000 in a 4 hour exposure (Beers 1997). (Gemini would need only a 50-min exposure, but these programs need years of work.) With this, one can study patterns of elemental abundances in the Galaxy halo, temporal evolution of [Fe/H] and other abundance ratios, correlations of kinematics and abundances, and heavy element production in explosive nucleosynthesis. The latter studies are most effectively persecuted on low-abundance stars where lines are weak, so required spectral resolution is higher and exposures are long.

In all but the most crowded fields, these programs can execute on the Blanco 4m (albeit somewhat slower than at SOAR because of its worse images), provided it is equiped with high-throughput optical and IR spectrometers with $R \leq 30,000$. Fig. 3 shows the R-values required for detailed study of stars in different parts of the HR diagram. In crowded fields, an AO system on SOAR feeding an IFU spectrometer would be the obvious way to multiplex.

3 Technical Requirements to Enable Partner Science

3.1 Telescope Properties

We translate the primary science requirement of tight image cores to mean $<0''.18$ degradation of top-quartile conditions ($0''.25$ d50 encircled energy at $\lambda 1.4$ μm) for optical and near-IR fields matched to forseeable detector mosaics. To meet this, tip/tilt wavefront stabilization at first light is a specification. Low-order adaptive optics (AO), at the level currently implemented at CFHT, is a goal in the first two years of operations.

The goal that coronagraphic performance not be limited by mirror scatter leads us to consider super-polished M1 and secondary (M2) mirrors. A suitable goal is to achieve mirror surface rms roughness in spatial wavelength bands 20-200 μm, 2-50 mm, and 5-150 cm of 0.8, 1.6, and 2.5 nm, respectively; this is slightly better than the HST M1. The power spectral density on our polished M1 must not have many large peaks at spatial wavelengths <10 cycles/aperture; i.e. the surface brightness of any such "mirror speckle" should be <10% of the azimuthally averaged scattered light brightness at that central angle. Rigorous dust control is essential; our goal is to ensure that scatter from dust accumulated between mirror washings be less than mirror+coating scatter.

SOAR can extend its instrument suite by accomodating Gemini instruments that will not fit on the Blanco. It will support rapid reconfiguration to one of several long-term instruments to support synoptic and, ultimately preemptively queued, observing.

3.2 Instrument Properties

All instruments should be designed to exploit the superior energy concentration of SOAR. In practice this means fields up to $10'$ for tip/tilt correction at a pixel scale of $0''.10$, and $1'$ with pixels $0''.04$ for an AO system operating in the optical red. Imagers to span these fields are current technology except for IR

Nebular line	Where seen?	Permitted line
[Ne III] 3342	PN, Nova, SNR, HII, AGN, SS	Na I 3302
[Ne V] 3346	Nova, PN, SNR, AGN, SS	O III 3312
[Na IV] 3362	PN	O III 3328
[Ne V] 3426	Nova, PN, SS, AGN	O III 3344
[N I] 3467	SS	O III 3415
[Mg VI] 3488	Nova?	He I 3448
[Fe VI] 3492	SS	N IV 3481
[Fe VII] 3587	SNR, Nova	He I 3513
[Fe VI] 3663	Nova	He I 3531
[Cl II] 3679	Strongest optical Cl line	He I 3554
[Ca VII] 3687	PN, Nova	He I 3587
[S III] 3722	PN, Nova, SS, HII, AGN	He I 3614
[O II] 3729	PN, Nova, SNR, HII, AGN, SS	He I 3634
[Fe VII] 3759	SNR, Nova	$H\infty$
		He II 3690
		He II 3696
		He II 3699

Table 3: Diagnostic emission lines for λ<0.37 μm.

mosaics which are being developed. For spectroscopy, the first probably requires a multi-object spectrometer (MOS) based on deployable, fiber-fed IFU's, the second a single monolithic IFU spectrometer. The science programs can be broadly characterized as dependent on properties of the PSF core and wings.

3.2.1 Spectroscopy

Blanco capabilities Hydra will provide multi-object spectroscopy (MOS) of point-sources with fairly wide (>23″) separations over a 45′ field and over $\lambda\lambda$0.36-1.0 μm. There will be a selection of resolving powers in the range R=1,000-5,000 plus single echelle orders with R=16,000 & 24,000, or (using a small image-slicer fiber feed) up to 30,000 with a cross dispersed echelle.

Gemini capabilities Gemini-S GMOS will have multiple-slits over a 5.′5 diameter field, with $R \leq 10^4$. This will presumably be optimal for spectroscopy at the faintest limit (D^2F^2 advantage for background-limited work). But, like Hydra, GMOS will only work efficiently down to λ0.36 μm so will miss many diagnostic lines found in zero-redshift objects (see Table 3), and will be only 15-20% efficient because its IFU capability is essentially appended to a standard MOS. A really efficient spectrograph (>50%, perhaps with an image-slicing IFU), perhaps with high UV transmission, on SOAR would be competitive.

Gemini-S will also have HROS, offering R≃50,000 echelle spectroscopy from ≃λ1 μm down to the atmospheric UV cutoff. As Fig. 13 in the Appendix shows, HROS will significantly outperform SOAR for high-resolution optical spectroscopy of faint (V>17) objects (D^4F^2 advantage for detector-noise-limited observations declining to D^2F^2 advantage for fainter, background-limited point sources). Compared to a SOAR, Gemini will of course still have a D^2 advantage in this shot-noise limited regime, but exposures will be tractable on SOAR ($t \propto F^{-1}$ rather than F^{-2} as in the background-limited case). The Blanco can provide R=30,000 optical spectroscopy of brighter (non-background-limited) point sources using the image-slicer fiber feed, and could do as well as SOAR because image FWHM will not be a significant parameter. **SOAR will be hopelessly outclassed for the optical spectroscopy of fainter objects and higher spectral resolutions.**

The situation differs somewhat in the near-IR because there is no planned first-light IR spectrometer for Gemini-S, while 2nd generation Gemini IR concepts are tending to favor a MOS approach at low R optimized for cosmological studies. Here $R \leq 6,000$ to work between OH lines, which is too low for stellar atmospheres. (Atmospheric T-structure and detailed abundances require $R \geq 50,000$. Important IR lines include Br α at λ4 μm and CO_2 at λ4.7 μm.) One option is for SOAR to partially fund a copy of the GNIRS, which can reach $R \simeq 18,000$, and higher with a new grating. Another is for Australia with other Gemini partners to build a fiber-fed, multi-object near-IR spectrometer for Gemini. Some variant of this instrument might be suitable for SOAR.

SOAR's spectroscopic niche From the above and considering the strong stellar interests of the SOAR partnership, the areas where SOAR would most complement the Blanco and Gemini-S are:

1. Low-resolution spectroscopy which includes the $\lambda\lambda$0.34-0.36 μm range. At $R \leq 1000$, etalon-based tunable filters provide superior multiplex (by their larger sky coverage) and comparable sky subtraction to slits or IFU's. (However, they have Airy rather than $sinc^2$ intrinsic spectral profiles.)
2. For higher resolution, a high-efficiency, bore-sight optical spectrograph. GMOS throughput will be the usual 15-20%. It is possible to build a spectrograph with a theoretical efficiency of 60%; such an instrument on SOAR would be competitive with Gemini on point-source targets, and even if it didn't really hit 60% would certainly take pressure off Gemini at the brighter end of the background-limited range.
3. To observe more than single stars, a fiber-fed IFU spectrometer could be built to cover a 15-20$''$ diameter field at the seeing limit. This would probably not be the same instrument as #2, and would provide 2D spectroscopy working at the full angular resolution of the telescope, and with holographic gratings would give a variety of spectral resolutions even up to $R \simeq 100,000$. This will be good with tip/tilt, but far better matched to the field of an AO system, at which point we would be competitive with Gemini and HST (better image quality than Gemini, same image quality but bigger aperture than HST) over that fraction of the sky near a bright enough natural guide star (or virtually everywhere with a laser system.)
4. To compete with the large number of multi-object spectrometers (MOS) being built for larger telescopes, the spectrometer in #3 should be upgradeable to provide an MOS mode. Arguably, a novel approach to this would be to use distributed-IFU's to provide full angular resolution at roughly a dozen points within SOAR's 15$'$-diameter field.
5. The IR entries for Blanco in Table 1 are for the case where Hydra capabilities are extended to the transmission and handling limits of fibers, currently λ1.7 μm. Single object, high resolution assumes that at least Phoenix is available on both SOAR and Gemini. The other Gemini entries are question marks because they have no plan for a first generation instrument, and both the timescale and capabilities of any second-generation instrument are unknown. A single object, bore-sight instrument like a clone of the GNIRS exploits SOAR's image quality if equiped with an image slicer to work over $\simeq 2 \times 3''$ (this also maintains throughput in less than optimal seeing) and a higher resolution grating to give $R \simeq 30,000$ on stars.

3.2.2 Imaging

Blanco & Gemini capabilities Wide field optical imaging will be provided by the Mosaic imager at the Blanco prime focus. The 40$'$ diameter corrected field of the Blanco will always have images $>0\farcs5$ FWHM. GMOS will image over a 6$'$ field at Gemini, exploring background limited targets with small image quality degradation but low spectral resolution.

The Blanco entry in Table 1 for wide-field, low angular resolution IR imaging signifies that perhaps some instrument could be put on one of the sideports at Cass. More likely, CTIO hopes to have a 2.5m telescope that would be heavily used for IR imaging to a shallower limiting magnitude. The Gemini entries with question marks signify that their present plans do not include such an instrument during the first several years of operation, although this may change with Australia in Gemini. The only definite IR imager for Gemini-S is for the themal-IR (diffraction-limited regime).

SOAR's imaging niche SOAR may satisfy the demand for high-resolution imaging at intermediate magnitudes by providing the optical waveband with a tip-tilt corrected field nominally 5$'$ in diameter if we adopt a $4K^2$ mosaic and just a filter wheel ($\simeq$3$'$ diameter if we recollimate for a tunable filter), and $2\farcm5$ on a $2K^2$ array for the near-IR. SOAR's image quality would be comparable to Gemini in the optical and at least the inner $1\farcm5$ diameter would be correctable by low-order AO. For $\lambda>3$ μm, SOAR is diffraction-limited compared to Gemini, and the proposed 2.5m telescopes are diffraction-limited compared to SOAR for $\lambda<1.5$ μm. So, SOAR's imager could plausibly be HgCdTe-based but should properly sample best-quartile tip/tilt stabilized images.

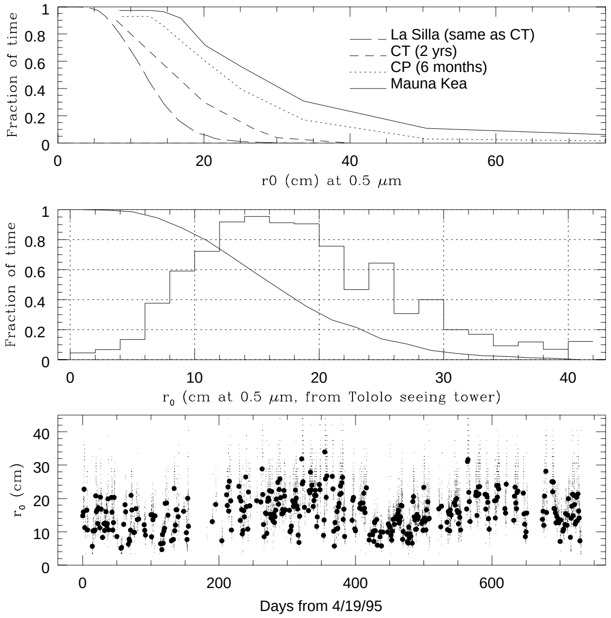

Figure 4: (top) distribution of r_0 at $\lambda 0.5$ μm for various Chilean sites, compared to Mauna Kea. (middle) 2 years of differential seeing motion data scaled to $\lambda 0.5$ μm and the zenith from the 10m-high DIM-monitor tower on Cerro Tololo. (bottom) The large dots plot median r_0 for each night. The wide dispersion in r_0 during many nights underscores the need for queue scheduled observing and rapid instrument selection; block-scheduling may be efficient during the few months of each year when seeing is less variable.

3.2.3 Bare-bones Instrument complement

Instrument funds are limited, so not all of the above can be provided in the first few years of operations. Please refer to §1 where the minimum complement is tabulated.

4 Derived Characteristics of the SOAR Facility

4.1 Site selection

SOAR will go beside Gemini-S on Cerro Pachon. Being a smaller structure, the SOAR facility will be placed at a site with better airflow. It lies at the "prow of the ship", bounded on one side by a smooth slope that faces into the prevailing winds.

The top panel in Fig. 4 shows that Cerro Pachon and Cerro Tololo are very good sites.[1] The middle panel shows the seeing distribution at Tololo in terms of the Fried parameter r_0. Distribution of r_0 is skewed to smaller values at Cerro Tololo than at Mauna Kea (median 16 cm *vs.* 27 cm), because boundary layer turbulence across the MK summit ridge is often very weak. Unfortunately, there are as yet no data of comparable statistical significance for Cerro Pachon (the data shown in the top panel of Fig. 4 span only 96 nights), nor data on atmospheric properties of relevance to AO such as the Greenwood frequency or the height h variation of refractive index $C_n^2(h)$. (The latter establishes the distribution of isoplanatic angles.)[2]

Monitoring of Cerro Pachon indicates that >60% of the nights are photometric, and 77% are suitable for spectroscopy (better numbers than Mauna Kea.) Water vapor is 1-2 mm at the summit (2.7 km) of Pachon (comparable to Mauna Kea, and several times smaller than at Cerro Tololo) during the winter, but this is not

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[1] One cause for concern is the susceptibility of all Chilean sites to damp El Nino conditions. All global warming climate models predict more frequent and more intense El Nino events, and there is evidence that this is occuring.

[2] Starting in Jan '98 Gemini will sponsor a campaign of SCIDAR and balloon measurements to determine these quantities from ground to 25 km altitude with a vertical resolution of 10m, as well as to establish the strength and variability of jet-stream winds over CTIO that produce turbulent shear. The characteristic speckle time and wavefront outer scale will also be determined from a network of 4 small telescopes separated by several meters.

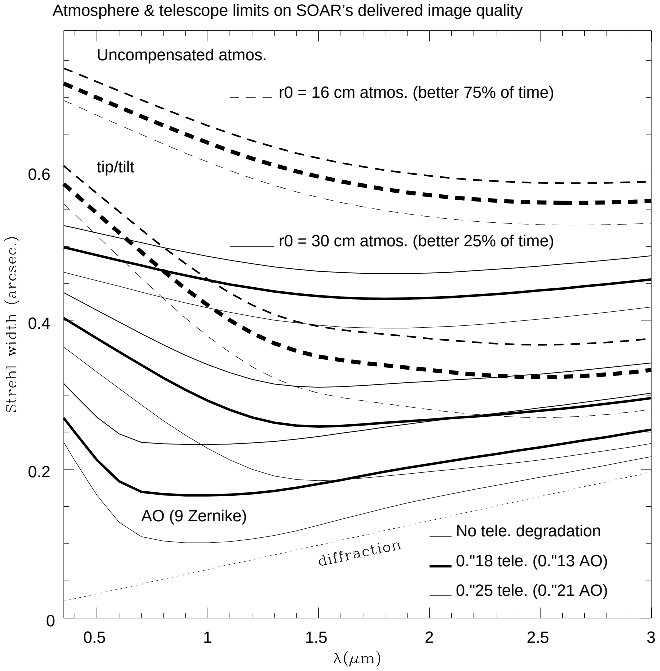

Figure 5: Estimated delivered image quality with and without tip/tilt image stabilization for median (dashed) and top quartile (solid) seeing at Cerro Pachon; two degradations due to telescope+enclosure are shown, for median winds. If mirror seeing and wind shake are within spec., degradation should be at most 0.″18, otherwise it can reach 0.″25. The improvement with low-order (9-Zernike) AO is shown for top quartile seeing; AO degradation is shown smaller (but conservatively smaller) to reflect non-optical benefits.

a characteristic that SOAR will directly exploit. On nights when the inversion layer rises above the summit of Cerro Tololo, it is often still below the summit of Pachon.

Gemini is placing their M1 20m above the ground, but this is driven by the requirement to get the Mauna Kea telescope outside the thermal boundary layer at that site. The favorable Tololo seeing distribution plotted in Fig. 4 was determined from a DIM-monitor placed only 10m above the ground, but these measurements are entirely site-specific. Once the SOAR site is cleared on Cerro Pachon, CTIO will erect a tower for wind measurements at several heights. These measurements may justify placing our M1 below 20m.

4.2 4m aperture

At Cerro Pachon, where median seeing at $\lambda 0.55\ \mu$m is 0.″5 FWHM, the ratio of M1 diameter to Fried coherence length D/r_0 can be small at near-IR and red wavelengths even for 4m telescopes. The image quality that can be delivered by AO on a telescope of diameter D is $\propto r_0/D$, where r_0 is roughly proportional to the wavelength of observation. Thus the SOAR 4m telescope will provide its sharpest images at wavelengths half those of an 8m, see Fig. 5. With tip/tilt at $\lambda \leq 2\ \mu$m, SOAR will also compete well with HST (or, after 2007, its archive[3]) because of HST's warm optics, smaller field of view, and smaller aperture so larger diffraction limit. SOAR's expected performance relative to the Blanco 4m is shown in Fig. 6.

4.3 Tightening the PSF

We will tighten the core of the PSF (out to a couple of arc-second radius) by minimizing telescope vibrations with stiff structures, using "active guiding" with a tip/tilt/fast-focus unit operating at 30+ Hz, upgrading to a low-order AO unit sometime after first light, and diagnosing the wavefront and updating the active optics

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[3] The Next Generation ST is currently envisioned to work at longer wavelengths, so it may not be competitive with SOAR at shorter wavelengths.

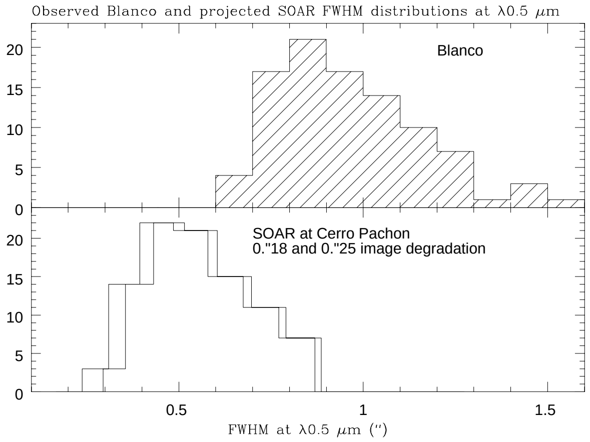

Figure 6: How the distribution of tip/tilt stabilized images at SOAR on Cerro Pachon will compare in their d50 values to those currently attained at the Blanco 4m on Cerro Tololo, both at $\lambda 0.5$ μm.

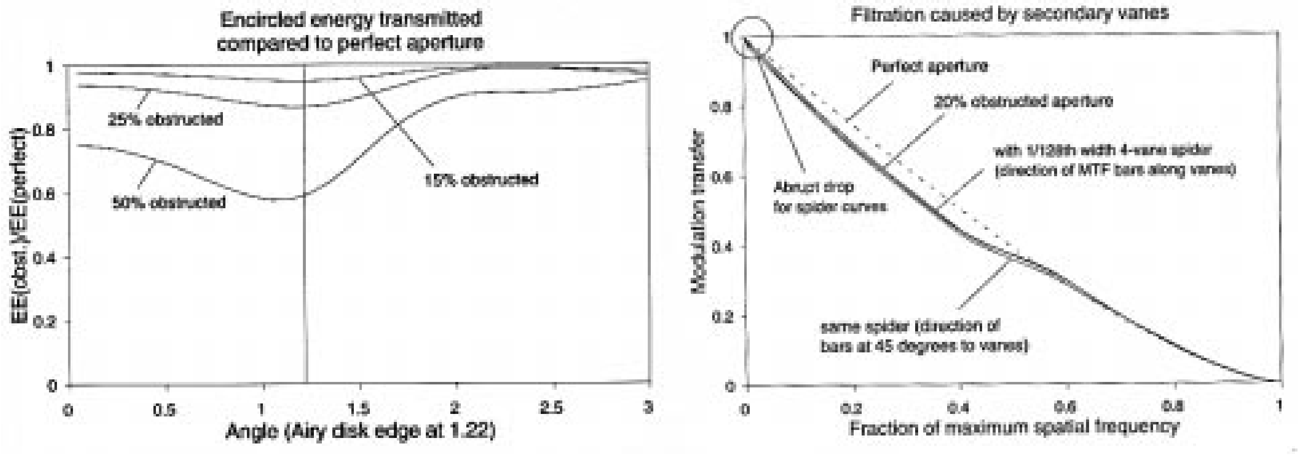

Figure 7: (left) How M2+its baffle Fourier-filters the pupil to alter the diffractive encircled energy. Ratios of encircled energies are shown for different linear obstruction fractions from M2 and a standard Cassegrain baffle. (Nasmyth baffles differ slightly.) M2+baffle obscures 19% of the pupil diameter. (right) Filtering of the telescope modulation transfer function (MTF) by the spider+the f/16 M2+baffle. (From *Star Testing Astronomical Telescopes*, by H.R. Suiter.)

as necessary (whenever a reference star is available). We will tighten the wings of the PSF (out to $\simeq 50''$) by polishing M1 to minimize diffractive surface scatter, optimizing baffle design and placement using scattered light codes, and implementing a regular mirror washing program to remove dust and other contaminants.

4.4 Wavelength coverage

As Fig. 5 emphasizes, there is a critical interval near $\lambda 2$ μm where the highest quality images will be provided by SOAR if only tip/tilt correction is applied, or a similar range at shorter wavelengths with low-order AO (such as to be installed on the Mauna Kea Gemini-N telescope at its first light).

AO is a first-light goal for SOAR; tip/tilt is a requirement. Tip/tilt will stabilize the PSF to translations across a field of up to $10'$-diameter. With these capabilities SOAR will offer higher $\lambda\lambda 1$-5 μm Strehl ratio[4] and

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[4] Image quality is quantified by two PSF-independent parameters, the Strehl width and Strehl ratio (the latter often refered to as just "the Strehl".) The Strehl width is the diameter of a cylinder, of the same height as the peak intensity of the delivered image, with volume that contains all of the light in the delivered PSF; it has units of arcseconds in the focal plane. Strehl ratio is the ratio of the central intensity of the delivered PSF to that of the central intensity of a perfect, diffraction-limited PSF. Large increases in Strehl can lead to small decreases in Strehl width. However, provided the PSF is properly sampled, higher Strehl greatly improves

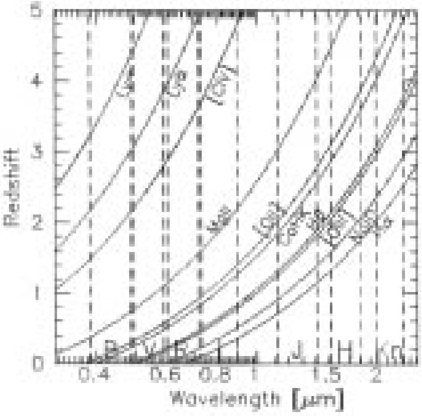

Figure 8: The observed wavelengths of common spectral features as a function of redshift, compared to the standard passbands. Over the range z=1-2 all the main restframe visible features lie in the I, J, and H passbands, while the visible regime is devoid of strong features. Hα can be seen in the H-band until z=1.8, while [O II] is accessible out to z=3.8. Both lines are good signposts for star formation. Very high redshift objects can be identified from the Lyα and Ly∞ features, which are seen at $\lambda < 0.45$ μm for z > 2.7 and z > 3.9, respectively.

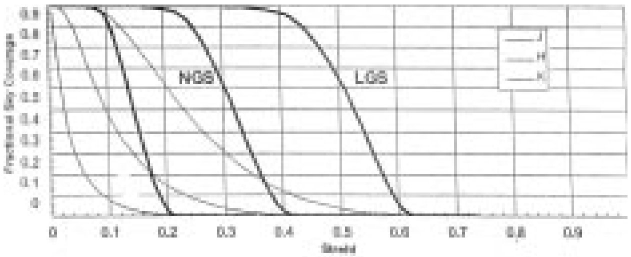

Figure 9: Fractional sky coverage at given Strehl ratios for NGS and LGS systems working at the J, H, and K bands.

better thermal IR performance than the Blanco telescope. Because of its smaller aperture diffraction Gemini-S will deliver better image quality at λ>3 μm, with IR imaging instruments likely to emphasize the highest spatial resolution over a correspondingly small field of view. But SOAR can still match or beat Gemini-S image quality at λ<3 μm by adding AO of an order comparable to Gemini. High spatial resolution at λ<3 μm opens up many spectral lines of great astrophysical importance in low-redshift objects, as well as UV lines in high redshift objects (Fig. 8.)

SOAR imaging therefore fills two niches: high angular resolution, especially at λ<2.4 μm, and somewhat more general capability at λ>3 μm where the Blanco is thermally deficient and Gemini-S will lack field of view. While we do not regard optimum thermal performance at λ>3 μm as a science driver, it does allow daytime operation, and echo-sonde data at Cerro Tololo show minimal atmospheric turbulence for several hours after sunrise.

SOAR will therefore be optimized to operate over $\lambda\lambda 0.34 - 2.3$ μm, with a goal to operate out to $\lambda 5$ μm for thermal-IR and occasional morning observations. Morning operation will not be allowed to interfere with mirror thermal preconditioning for optimal nighttime observing or calibration of these observations.[5] Pointing and tracking capability must allow effective daytime use at $\lambda\lambda$3-5 μm.

4.5 Low-order AO

A first-light goal for SOAR is to incorporate a low-order (the equivalent of a 19 or 37 element bimorph) AO system similar to Gemini. The considerable expense of this system may be justified by the science that results from

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the effectiveness of post-detection schemes.

[5] For this reason, daytime operation may be precluded if SOAR uses a 20cm-thick primary mirror. The 10cm-thick mirror can be preconditioned as late as the early afternoon without impacting nighttime operation.

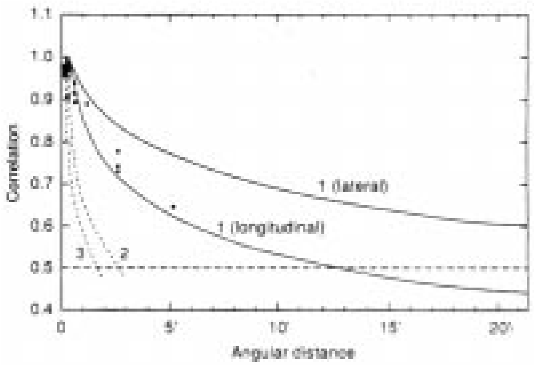

Figure 10: Correlation between the Zernike components of a wavefront as a function of the angular distance between the tip/tilt reference and target sources, for $\lambda 0.5$ μm on a 4m telescope. The curves assume variations with height h in $C_n^2(h)$ that are often appropriate at Mauna Kea. (1) Longitudinal (tilt) and lateral (tip) correlations for wavefront gradients; (3) correlation for 3rd-degree Zernike terms (up to Z_{10}) assuming correction of the wavefront as it appears at the telescope entrance pupil.

System f/ratio	8192^2 15 μm pixels	21 μm pixels
16	$6.5 \times 6.5(4.6, 0.05)$	$9.2 \times 9.2(6.5, 0.07)$

Table 4: Fields and (radius, pixel scale) in arcminutes that are covered by a contemporary CCD mosaic (left col is SITE $2\text{K} \times 4K$ 3-edge buttable), with two different pixel pitches selected to encompass future possible detectors with large charge wells. It is worth noting that 12-inch diameter Si wafers will be the semiconductor standard long before SOAR's first light, and that 18-inch diameter wafers are already being planned. CCD manufacturers will eventually retool, although the current limit is set by the purity of silicon wafers.

sharper images and IFU-based spectroscopy, probably mostly of star-forming regions within our own Galaxy. The system will be limited to targets brighter than J=16 mag, and by the time SOAR enters operation, may need a laser to cover a competitively large area of the sky (see Fig. 9.)

By its smaller ratio D/r_0, SOAR theoretically is capable of producing smaller best images than Gemini for the same degree of AO correction, at a wavelength about half that at which Gemini delivers its best images. Gemini-N will have low-order AO in the near-IR across an unvignetted $2'$ field, and a $12'$, unvignetted tip/tilt-stabilized field (only $7'$ of which will be accessible at the two stations fed by M3.) Gemini's maximum vignetted field at f/16 is $18'$-diameter.

SOAR images in median seeing will have $0''.3$ Strehl width at $\lambda 2$ μm (including diffraction). To compete with Gemini, we have specified that SOAR span a $7'$-diameter field at f/16, with the full guide field of $15'$ diameter accessible with some restrictions. The inner $2'$-diameter will be correctable with AO.

4.6 Field of view with tip/tilt

SOAR remains competitive with Gemini by spanning what is probably the largest optical field of view that can be tip/tilt stabilized under top quartile seeing at Cerro Pachon.[6] Fig. 10 (data from the CFHT) and Table 4 show that this $\simeq 10'$ field can already be spanned by a mosaic of contemporary optical CCD's, with 3 pixels sampling the stabilized core of the one-dimensional PSF. This field is required for competitive observations of e.g. field galaxies (see Fig. 11.)

At f/16, SOAR will span a $7'$-diameter field. Below $\lambda 1.6$ μm where SOAR's larger aperture-diffraction is not the limit, SOAR's image quality will at least match that of Gemini over a $2'$-diameter field. Both f/16 foci are tip/tilt stabilized.

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[6] The isokinetic field appropriate for conditions at CTIO will be derived from measurements contracted by Gemini over the next year or so. These will be used to update SOAR's specifications, as required.

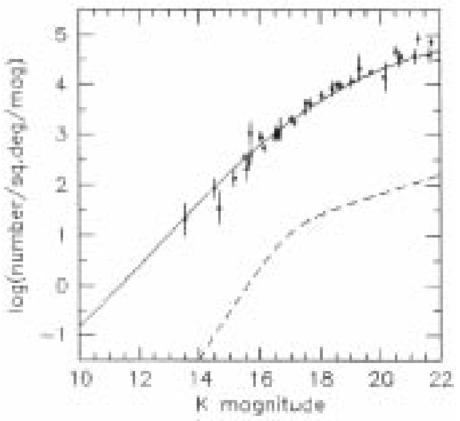

Figure 11: The number of galaxies (solid line) and QSO's (dashed line) as a function of K magnitude, based on fits to the observed K-band galaxy counts and B-band QSO counts. There are >50 galaxies in a 15′ field for K > 16, and at K = 20 there are over 10^3 (plus ≃ 5 QSO's.)

4.7 Multiple instruments quickly accessible

A minimum of three facility-class instruments will be on "hot standby", each positioned at the Nasmyth/bent Cass. foci. An IR-imager, and optical imager and spectrograph will reside permanently on one side, while an IR-spectrograph with limited imaging capability would reside at the Gemini-compatible f/16 port. Any one instrument must be fully configured for science within 2 minutes of its selection. Up to 3 "user" instruments may also be present at the bent Cass. ports. In addition, it is a project goal to provide space which could be upgraded at a later time for a small Cass. instrument. This is an appropriate place for a polarimeter because M3 induces 5% polarization when feeding the Nasmyth ports.

4.8 Ability to accept Gemini/CTIO instruments

The considerable mass of a Gemini instrument could be counterbalanced by a cluster of several instruments at the other f/16 port. A goal is to accomodate a generic Gemini instrument, the specification is the unballasted mass of the Gemini Infrared Spectrometer (GIRS, which weighs as much as but is smaller than the Gemini limit.) The GIRS is the only Gemini instrument that has been identified as a candidate for SOAR.

Modifications to a Gemini IR instrument are minor. It will need a slightly different pupil cold-stop when it resides on SOAR because the spider morphology differs. Moreover, the pupil is closer to the focus in SOAR than Gemini (where it is 16 m away). The ability to change pupil stops is not a specification of current Gemini IR instruments, but is easily designed into new ones. Gemini IR instruments also do not have rotating pupil masks, but the M2 spiders in Gemini contribute only ≃10% of the telescope emissivity of 2.5% (most comes from the mirror coating.) The radius of field curvature at the f/16 focus is identical on SOAR and Gemini.[7]

Gemini IR instruments have a telecentric focus, also not a specification of the SOAR optics (although the current optics are telecentric, which adds a third lens to the field corrector.) This should only be an issue for wide-field applications, which we will defer to the Blanco in any case.

4.9 SOAR as a complement to the Blanco 4m

The SAC believes that SOAR should complement the Blanco 4m, each optimized for different sorts of observations. We should resist the temptation to divert effort to making SOAR do things that can be done just as well by the Blanco; that would just leave less resources for equipping SOAR to do the things which it can do best.

In the age of SOAR, the Blanco 4m will be available for wide-field (45′-diameter) MOS with minimum fiber separations of 23″, prime focus imaging, high-resolution point-source spectroscopy, and has the potential for wide-field spectropolarimetry. SOAR will not have these capabilities; it is best suited for

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[7] Flattening the f/16 field of SOAR produces 0″.06 of defocus at 3′ radius, so the optical implications of adopting a flat field are not large and may be prefered for future instruments.

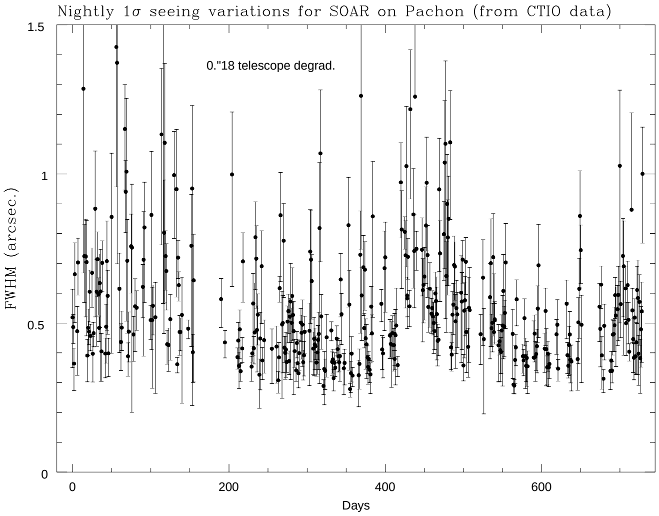

Figure 12: $\pm 1\sigma$ ranges in seeing, derived from the Cerro Tololo seeing monitor. Values have been scaled to expected performance at Cerro Pachon (using the curves in the top panel of Fig. 4), and include $0\farcs18$ of telescope+enclosure degradation. Only nights with at least 6 measurements are included. Seeing variations are smallest in the southern spring; other seasons would benefit from an observing queue.

1. MOS over a moderate field of view (5-15$'$) but sampled at the seeing limit
2. synoptic spectral and imaging observations that span a wavelength range from $\lambda\lambda 0.33 - 2.3\,\mu$m. Note that the Blanco will *not* operate in queue-mode.
3. Bearing instruments consistent with the above that are too massive to go on the Blanco.

The partners agree to the principle that, for the purposes of time trades, 1 night on SOAR is considered equal to 1 night on the Blanco 4m telescope, with no weighting factors for either telescope. All the SOAR partners enthusiastically endorse the concept of such time trades to widen the range of observational capabilities available to each user in the consortium.

4.10 Queued and remote observing

An observing queue makes most efficient use of SOAR during variable conditions, improving our competitive position to Gemini (whose queue will be diluted by periods of block scheduling.) Variations may be unpredictible (e.g. changes in r_0 which the bottom panel in Fig. 4 clearly shows occur as the norm during most of the year), or may be as inevitable as moonrise. Fig. 12 shows some intervals (e.g. days 250-350) where seeing is constant enough for block scheduling, but $\simeq$1/2 of the years shown require an observing queue for reasonable efficiency. A queue allows long-term synoptic programs to progress that require only a fraction of each night. It also allows university partners with only 12 hrs of weekly access to schedule rapid follow-up observations for complementary data after thorough off-line analysis. A preemptive queue without the astronomer at the telescope minimizes the disruption of academic teaching schedules. The added cost may to some extent be mitigated by reduced observer travel if the SOAR consortium is willing to staff the queue with scientists and students. The telescope and control system must be versatile enough to handle these requirements without undue demands on the skill level and learning curve of the operators.

Note that the synoptic queue provides an opportunity for the astronomer to "eavesdrop" on the observation *via* the global computer network. For public outreach, student training, and for time-critical and spacecraft-coordinated programs, both university partners also require the ability to eavesdrop on observations by allowing "remote observing" at whatever level of involvement can be tolerated with restricted bandwidth.[8] A T1 link will

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[8] Declining telecommunication costs will enhance the fidelity of this experience as time goes by. Experiments with wavelet-based, lossless compression of astronomical images indicate that reliable estimates of sky noise and object morphology across the field of view are possible from 1% of the data.

R-mag	Photons/4-m/ 0.3 μm/msec	# stars in $(40')^2$		quad-cell S/N 120 Hz, RN=5e
		Lat. 30°	Pole	
≤ 14	990	2.3	1.3	110
≤ 15	400	5.0	2.3	44
≤ 16	160	5.3	4.0	18
≤ 17	60	-	7.0	7

Table 5: Photon rates and R-band guide-star visibility. The “quad-cell” in the last column will actually be a 20 × 20 imager (in windy conditions binned during readout) to measure centroids.

be perfectly satisfactory.

4.11 Provision for Acquisition and Guiding

SOAR like Gemini should adopt the HIPPARCHOS/TYCHO catalogs for astrometric reference. Gemini will produce Johnson B and R star catalogs down to 21-mag with $0''.3$ rms accuracy, star/galaxy id and ellipticity information, and will make first-order refraction corrections based on the guide-star color.

The acquisition camera should use these catalogs to identify objects on faint images, and then quickly and reliably position the object(s) on the instrument aperture(s). The guider should correct for field rotation and provide rapid tip/tilt/focus signals at all foci to drive the articulated M2 with sufficient precision to meet the SOAR imaging requirements. Slow focus adjustment should also be provided. The density of stars suitable for tip/tilt/focus determination – 800 stars/deg^2 with mag-R <17.5 at the South Galactic Pole (see Table 5) – means that SOAR needs a guider field covering at least 40 square arcmin outside the science field to include 7 guide candidates (to ensure that 2 are usable).

The f/16 focus might also allow acquisition viewing in a near-IR band close to the one used for observation. (This is not essential because the tip/tilt correction is achromatic, but is convenient and should be easily affordable when we need it.) Here the limiting magnitude should be sufficient to generate guide signals from a star within $100''$ of the line of sight for 90% of the objects at high galactic latitude and for 99% of the sky (excluding the “darkest” dark clouds) within the guide field at high Galactic latitudes. The guide field at f/16 will therefore span an annulus of at least $3'.5$-$7'.5$ radii.

5 Appendix – Exposures to reach given S/N(λ)

Starting in Fig. 13 we summarize the competition between SOAR, Keck, and various space telescopes at different wavebands, assuming tip/tilt correction for SOAR. For K, a telescope emissivity $\epsilon = 0.1$ is assumed. For direct imaging, the ground-based telescopes are shown for bottom decile and median seeing which are then convolved with $0''.2$ telescope+enclosure degradation. The situation for detection of Hα line emission in the near-IR (reflecting a desire to study star formation efficiency at cosmological distances) is shown in Fig. 17. In Fig. 18, read and sky noise variance is summarized as a function of spectral resolution R and object R-mag. for SOAR.

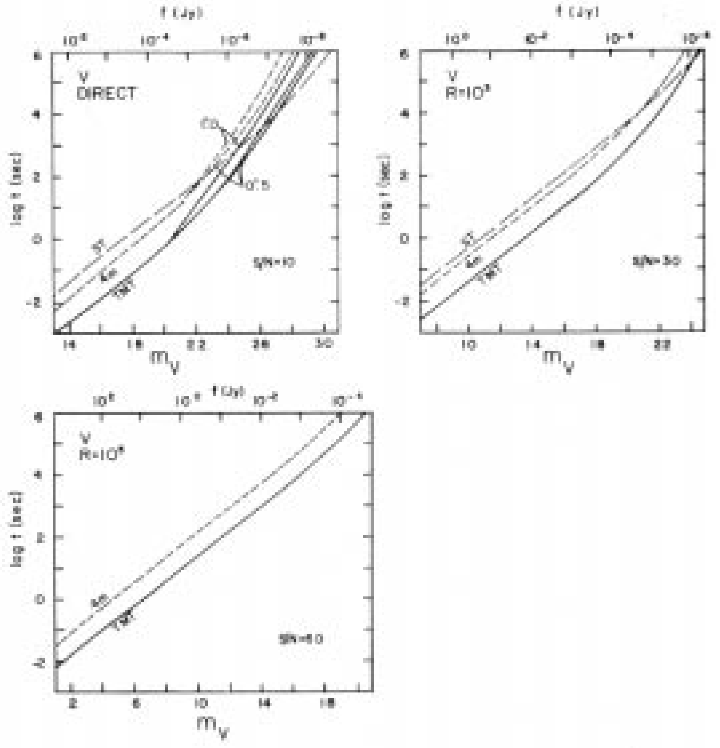

Figure 13: Times required to reach the indicated S/N for direct imaging, moderate resolution ($R = 10^3$), and high-resolution ($R = 10^5$) spectrophotometry for various telescopes in the V-band ($\lambda 0.55$ μm.) (TMT ≡ Keck.) The assumed sky brightness is 21.3 V per square arcsecond, the value roughly one week into a lunation. For HST, the corresponding value is 22.1 V away from the Galactic and ecliptic poles. An effective "slit" width of 1″ is assumed for all spectrophotometry.

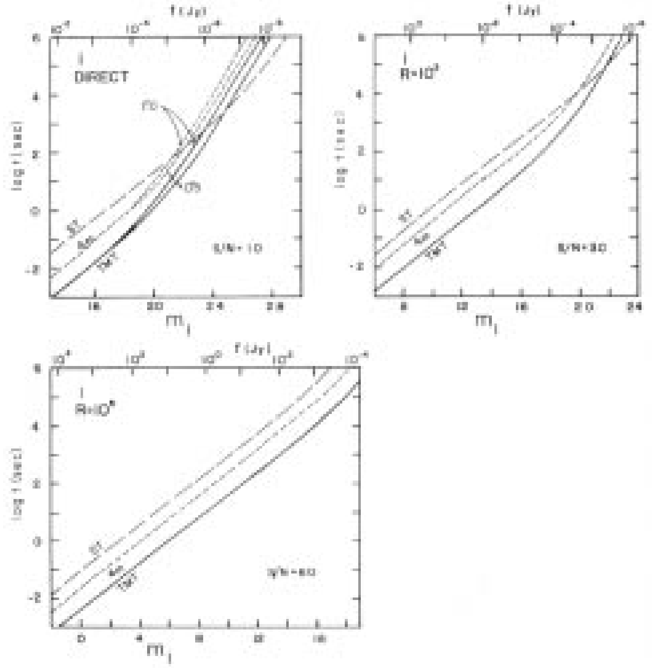

Figure 14: Same as Fig. 13, now for the I-band ($\lambda 0.8$ μm.) Sky has not been filtered to avoid OH lines. Doing so would increase the S/N attained in the direct imaging case. If $R > 5000$ one can work "between the OH lines" to reach fainter sky.

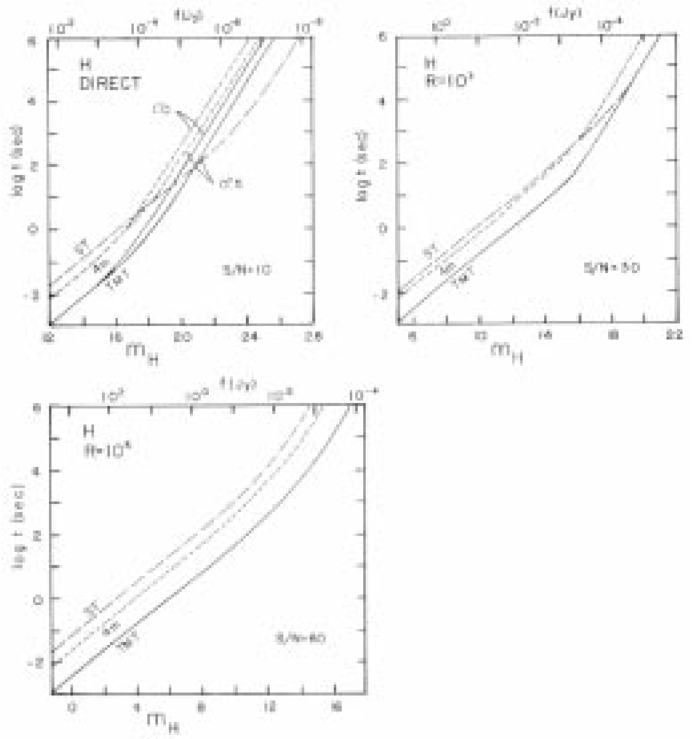

Figure 15: Same as Fig. 13, now for the H-band ($\lambda 1.6$ μm.) By the middle of the H-band, the thermal background from the telescope structure is becoming an important noise source.

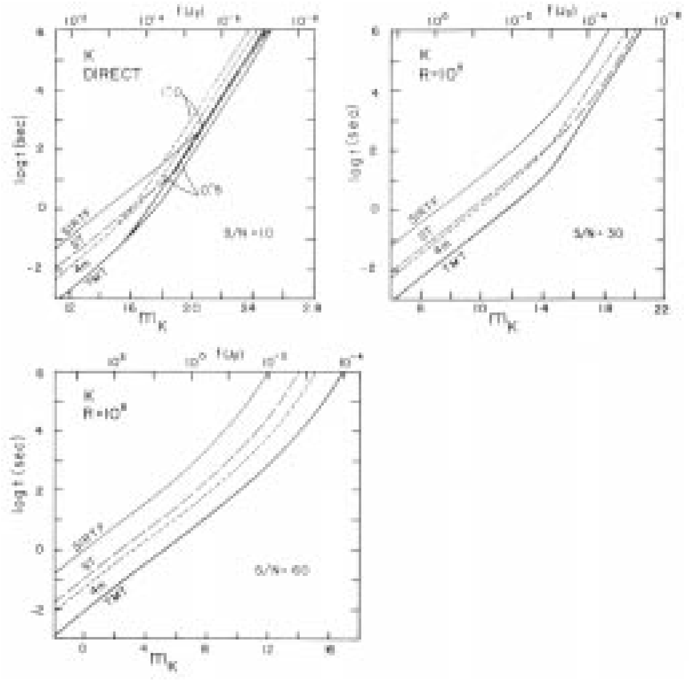

Figure 16: Same as Fig. 13, now for the K-band ($\lambda 2.2$ μm.)

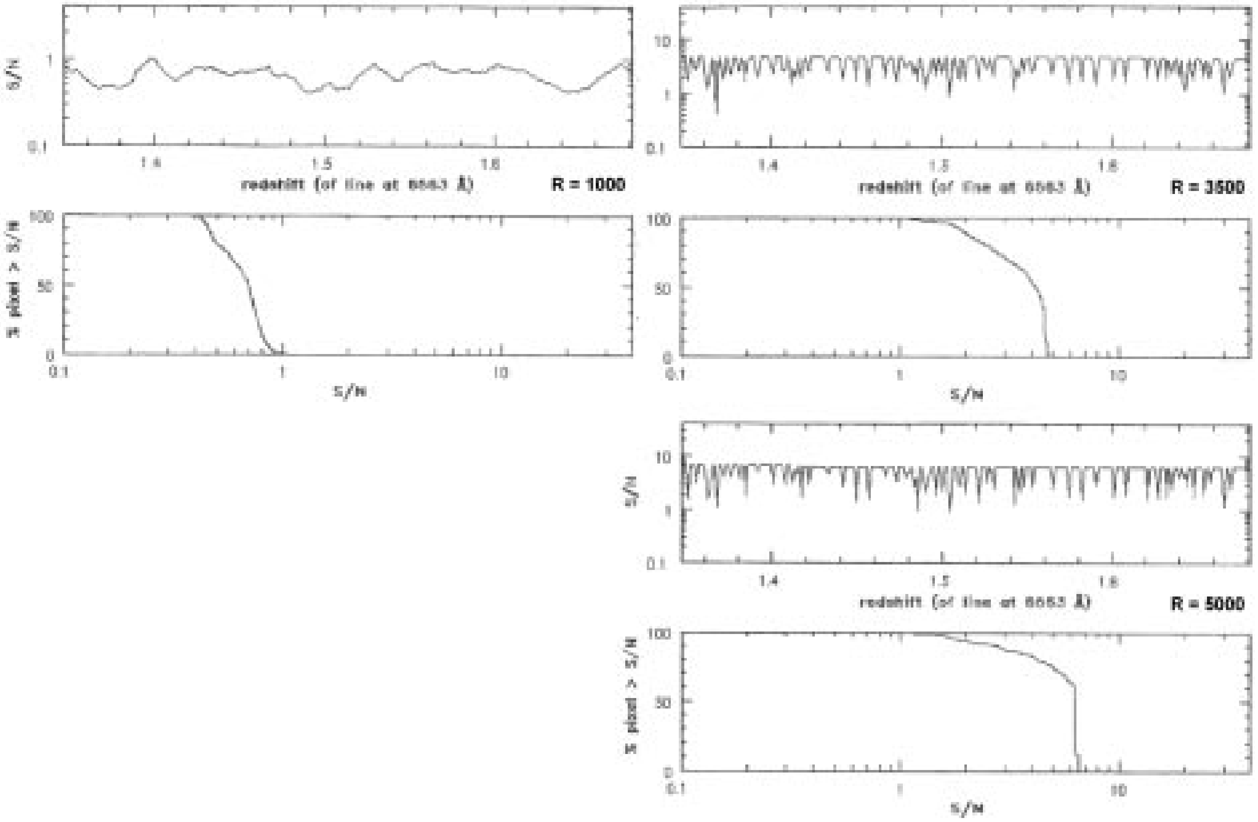

Figure 17: S/N in Hα in the H-band at 2-pixel spectral resolutions R=1000, 3500, and 5000, together with the fraction of redshifts with given S/N or better. A system efficiency of 30% and exposures of 7500s are assumed. The Hα line flux is taken to be 10^{-17} erg/s/cm^{2}arcsec^2, corresponding to a typical galaxy with an Hα luminosity of 0.1 L*(Hα), a star-formation rate of 3 $M_\odot$/yr, and a FWHM linewidth of 100 km/s.

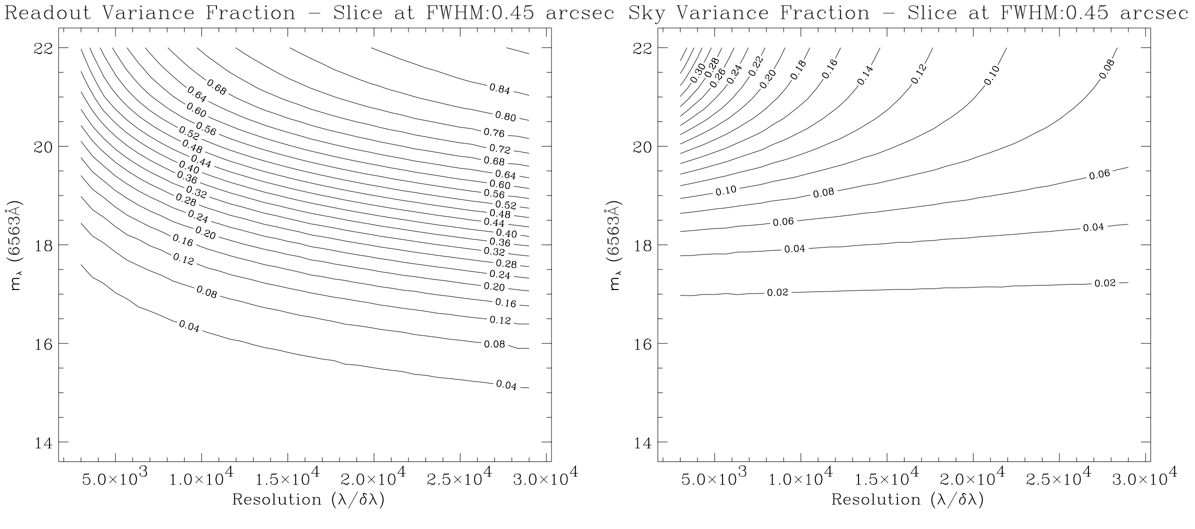

Figure 18: The fraction of the total variance for SOAR that arises from readout & sky noise at $\lambda 0.65$ μm, various spectral resolutions, and in $0\farcs45$ seeing.