SOAR AO system: project description

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We propose to build an inexpensive AO system optimized for the visible range of the spectrum ($\lambda = 0.4 - 1$ μm). With natural guide stars brighter than 12^m, diffraction limited resolution of $0\overset{''}{.}04$ will be achieved in the R band over a small ($\sim$ 10") field, giving SOAR unique capabilities unmatched by any other telescope. The same system will be upgraded with a Rayleigh laser guide star and in this mode will compensate near ground turbulence, improving the seeing limited FWHM by a factor of 2 uniformly over a $3'$ field of view. Both high resolution and seeing improved modes will be used with a dedicated red optimized CCD imager which will be part of the AO system. In addition, the SOAR IFU spectrometer and another, as yet unspecified, instrument will be fed by the AO module. The AO system will support queue scheduled operation and rapid selection of the active instrument.

1 Introduction

Most modern large telescopes are now being equipped with Adaptive Optics (AO) systems. Next door to SOAR, Gemini is planning two systems, a near infrared coronographic imager (NICI) and an ambitious multi conjugate AO (MCAO) system with multiple Na laser guide stars (LGSs). One of the 8m VLT telescopes will have a working AO system (NAOS) in 2001 (with more AO systems to follow) and for a while will have exclusive capabilities on the southern sky. How does SOAR fit into this picture of modern ground based astronomy with 8m class telescopes using sophisticated AO systems?

It would make little sense to compete with Gemini and the VLT in the near infrared. If both 4m and 8m telescopes are equipped with AO systems, diffraction limited resolution at 8m would be 2 times higher, and sensitivity 4 times better than at SOAR. As S. Ridgway noted, with AO "the rich get richer and the poor get poorer" [2]. However, there is no corresponding effort to exploit AO in the visible, where SOAR may have its unique scientific niche. In this document we therefore propose an optical AO system for SOAR.

Over the next few years both SOAR and Gemini S will be commissioned and start science operations. The coherent plan for Tololo and Pachón will optimize the 4m Blanco for wide field imaging and spectroscopy, and SOAR for high resolution imaging & spectroscopy, leaving 8m class science to Gemini.

Gemini will clearly do it's best, high redshift science in the near and mid IR over a small to medium FoV of $1' - 5'$. SOAR was conceived with built in tip-tilt correction, and will do z = zero science at the highest possible spatial resolution over a medium FoV of up to $5'$ or so, while the Blanco will use a FoV of up to $40'$ to do imaging and multiple object spectroscopy at somewhat lower image quality.

SOAR equipped with an AO system working in the visible range will form a powerful complementary part of the SOAR, Blanco, Gemini system

The AO system proposed below combines two distinct operational modes in a single instrument. The first, *high resolution* mode permits diffraction limited imaging with relatively bright ($10^m - 12^m$) natural guide stars (NGSs) in a small ($10''$) compensated field. The second, *improved seeing* mode will compensate ground layer turbulence with a Rayleigh laser guide star (LGS), to improve the natural seeing by a factor of ~ 2 with effectively uniform PSF over a FoV of up to $3'$. In this mode it is possible to tune the altitude of the Rayleigh LGS and parameters of the AO system in order to achieve the optimum tradeoff between angular resolution and field of view for a given science program. For example it would be possible to adjust the system to achieve $0\farcs1$ resolution over a 30" FoV.

In Sect. 2 the scientific case for SOAR AO is outlined. In Sect. 3 the performance of the proposed system is estimated and compared to tip-tilt compensation, using the improved data on Pachón seeing. A system concept is presented in Sect. 4, and its implementation plan is discussed in Sect. 5.

2 Science case for SOAR AO

The detailed performance estimates presented in the next Section define the potential of the proposed AO system in its *two* operational modes.

1. In the **improved seeing mode**, image quality will be uniformly improved over a moderately large field of $3'$ diameter. Relatively faint guide stars can be used for tip-tilt correction (which is still needed with the LGS), hence sky coverage will be practically complete.

The improved seeing mode will enhance the capabilities of regular SOAR imaging: median seeing will be improved to good seeing and good seeing will become excellent. Exposure times needed to achieve a given SN ratio in the background limited case are inversely proportional to the square of the image size, so even a modest factor of 1.4 improvement in seeing doubles the telescope efficiency in this case.

Many scientific projects at SOAR are limited not by the number of photons or detectivity but rather by *confusion* from crowding of unresolved stars. These include studies of stellar populations in nearby galaxies and in globular clusters. Advantages of improved image quality become substantial in this case allowing SOAR to rival the performance of 8m class seeing limited telescopes.

In the near IR, tip-tilt compensation alone brings significant resolution gain, which the Spartan imager is being designed and built to exploit. It is important to match this resolution in the visible in order to provide multi-wavelength information which is essential for some of the proposed SOAR science. *The seeing improvement mode will yield comparable resolution and FoV in the optical to that which will be obtained n the near-IR using Tip-Tilt and Spartan*

Additional advantage will be obtained by the improved quantum efficiency of the new CCD to be used in a dedicated AO imager, as compared to the CCDs currently used in the SOAR optical imager (which is optimized for UV) or at the VLT. Thus, at longer optical wavelengths, the AO imager will surpass the SOAR imager in *both* resolution and sensitivity.

Among the broad range of projects that will benefit from the seeing improvement are (a short and non-exhaustive list):

- Studies of star formation in nearby galaxies.

- Kinematic and dynamics of nearby galaxies from high resolution maps of radial velocities.
- Search and photometry of distant supernovae.
- Studies of globular clusters.
- Studies of Galactic nebulae (PNe, HII regions, reflection nebluae etc.)

By tuning the parameters of AO system (LGS altitude, command matrix), it will be possible to achieve even greater resolution gains on faint targets while sacrificing the compensated field. This operational mode could be used in a wide range of single-object studies: morphology of distant galaxies, environments of young stars, etc.

2. In **high resolution mode,** the PSF will be dominated by a strong diffraction-limited core with a FWHM of about $0\farcs04$. Only a fraction of the total energy will be concentrated in this core; however, a Strehl ratio of 0.35 is expected at 0.66 micron under good seeing. Deconvolution of such images to remove the PSF wings will be straightforward. Compensation quality will degrade rapidly with increasing distance from the guide star, with a total compensated field of about $10''$. In good seeing the guide star can be as faint as $12^m - 13^m$ when working in the R or I bands. Even for V-band work in median seeing, a 10^m guide star will suffice.

This mode will be used for high spatial resolution studies of the environments of relatively bright stars, both by direct imaging and with an IFU. The small number of IFU pixels limits the FoV more than the anisoplanatism.

The following problems can be addressed:

- Star formation: jets and other emission structures around nearby T Tau stars.
- Environments of nearby Miras, symbiotics, WR stars, & Be stars.
- Close multiple stars: photometry and resolved spectroscopy of the components. Detection of new components.
- Compact HII regions and compact clusters of massive stars (like R 136).
- Ejecta of Galactic novae and supernovae.

Apart from direct resolution of fine structures, spatially resolved spectroscopy with the IFU permits detection of small coordinate shifts of an object as a function of wavelength. This technique gives access to sub-milliarcsecond effective resolution, as attempted previously by differential speckle interferometry. The applications include, for example, study of the orientation of stellar rotation axes, measurement of inclinations and masses of close spectroscopic systems, and mapping mass exchange flows in close binaries.

The list of potential projects can be extended. No optical AO systems are currently planned for medium and large telescopes, which means that the capabilities of SOAR AO will remain unique for at least several years.

For objects fainter than 12^m, significant improvement of resolution over atmospheric seeing can still be achieved, although not down to diffraction limit. This mode overlaps with seeing-improvement regime discussed above.

3 Performance estimates

3.1 Method and input data

The expected performance of the proposed AO system was estimated using the modal simulation code [3] and new data on the Pachón seeing [4], as summarized in Table 1. These estimates should be taken as preliminary; they serve to identify promising system configurations and parameters rather than to give ultimate and precise numbers which will be provided at the conceptual design stage.

Compared to standard optical atmospheric propagation theory, we take into account the finite outer scale of turbulence, as actually measured at Cerro Pachón. This leads to a smaller seeing limited PSF (for a given turbulence integral or given r_0) and to a faster improvement of seeing at longer wavelengths, compared to the standard theory. This is in large measure due to a decrease in the amplitude of image motion when the outer scale is taken into account. Thus the standard theory overestimates the relative gain to be obtained from tip-tilt correction alone.

The mean vertical turbulence profile is approximated by 7 layers at altitudes from 0 to 15.8 km, with the ground layer containing 65% of the total turbulent energy; this is the same model used for the Gemini MCAO simulations [1]. However, it must be remembered that the turbulence profile is in fact highly variable, and that the size of the compensated field and achievable seeing improvement are subject to this variability.

Table 1: Seeing at Cerro Pachón (at zenith)

Probability	25% (good)	50% (median)	75%
Fried parameter at 0.5 micron, cm	20.0	15.0	10.7
Standard FWHM at 0.5 micron, arcsec	0.50	0.67	0.94
Finite-outer-scale FWHM at 0.5 micron, arcsec	0.40	0.55	0.79
Finite-outer-scale FWHM at 2.2 micron, arcsec	0.24	0.33	0.49

Note: at zenith distance of 45° seeing degrades by a factor of 1.23.

Table 2: Parameters of tip-tilt and two AO modes for median seeing

Option	Zernike compens.	Sub-apert.	Guide stars	FoV	FWHM (0.5 μm)
Tip-tilt	3	4.2 m	1 NGS, $5^m - 17^m$	$2' - 3'$	$0''.50$
High resolution AO	66	0.5 m	1 NGS, $5^m - 10^m$	$10''$	$0''.03$
Improved seeing AO	66	0.5 m	1 LGS, 10 km, 5^m	$3'$	$0''.35$

The main parameters of the SOAR AO system as input into the simulations are listed in Table 2; we assume that 66 Zernike modes can be compensated. For comparison, we also estimate the performance of tip-tilt compensation using the same atmospheric model. In fact, compensation quality achieved with tip-tilt and one guide star degrades at angular distance of $> 1'$ from the GS, hence the useful field of view (FoV) is loosely estimated to be $2' - 3'$. It is possible to improve the uniformity (at the expense of reduced resolution gain) by using three tip-tilt stars instead of one, but this capability is not yet present in any of the SOAR instruments, and so is not considered here.

The estimates given here assume that the telescope is ideal. Although everything is being done to assure that SOAR will take full advantage of the excellent seeing at Cerro Pachón, the AO system can help correct any residual telescope aberrations. In this more realistic case, the gain from using AO will be increased, as compared to our predictions.

By compensating 66 Zernike modes with a bright NGS, a Strehl ratio of 0.06 can be achieved at 0.5 micron in median seeing, increasing to 0.16 under good seeing. At 0.8 micron, Strehl ratios are 0.35 and 0.52, respectively. The diffraction-limited FWHM is $0''.034$ and $0''.046$ at 0.5 and 0.8 micron.

3.2 Variation of PSF over the field

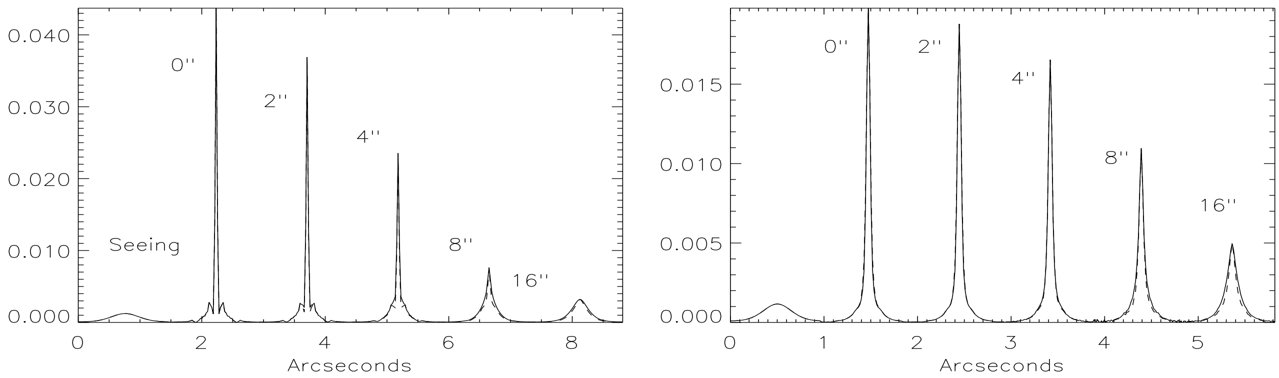

Figure 1: Stacked PSFs on-axis and at increasing distance from the guide star in high resolution mode. Seeing-limited PSF is plotted first for comparison. Left: median seeing, 0.5 micron, bright NGS. Right: good seeing, 0.66 micron, 12^m NGS.

In high resolution mode, the PSF changes over a $10''$ field are already dramatic (Fig. 1). It is evident, however, that even at low Strehl ratios, the diffraction-limited core is very prominent, favoring deconvolution.

In improved seeing mode, the resolution gain is modest, because high atmospheric layers are not properly sensed with a Rayleigh LGS. On the other hand, and for the same reason the compensated field is much larger, with a very uniform PSF over the whole field. The PSFs in Fig. 2 were computed for an LGS altitude of 8 km. Under good seeing, the FWHM at 0.66 micron improves from $0''.37$ to $0''.21$ (1^m gain in the central pixel intensity). Better resolution gain can be achieved at the expense of compensated field if the LGS is placed at 20 km. Under good seeing, moving LGS from 10 to 20 km improves FWHM at 0.66 micron from $0''.21$ to $0''.075$. At 0.8 micron, a FWHM of $0''.07$ becomes possible (Strehl ratio 12%, gain in the intensity of central pixel 2.6^m).

The objectives of the seeing improvement mode are very similar to those which motivated the implementation of tip-tilt for SOAR first light. However, both the resolution gain and PSF uniformity offered by the seeing-improved mode are better than for tip-tilt compensation (Fig. 2). The resolution gain from tip-tilt compensation is less than originally anticipated when the turbulence outer scale is taken into account. Furthermore, variation of the tip-tilt corrected PSF over the $5'$ FoV is significant and becomes even more dramatic in conditions when the resolution gain is greatest (K-band, good seeing). Such a variable PSF poses significant problems in data reduction and may affect the photometric precision.

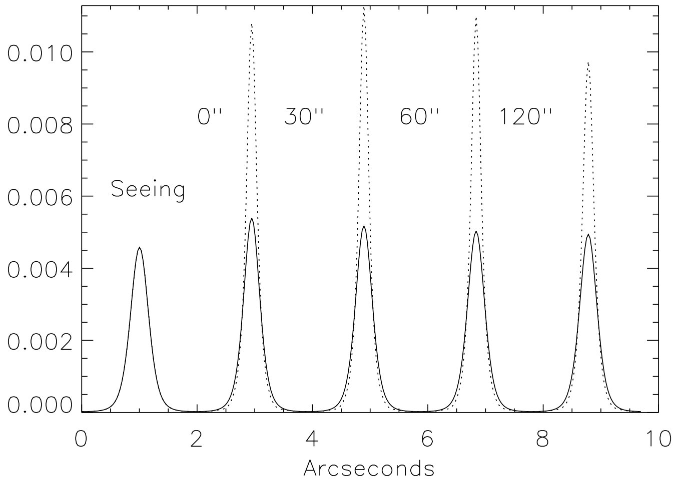

Figure 2: Stacked PSFs on-axis and at increasing distance from the guide star for tip-tilt compensation (full line) and for seeing-improved AO (dotted line). Uncorrected seeing-limited PSF is plotted first. Good seeing, 0.66 micron.

3.3 Limiting magnitude in high resolution mode

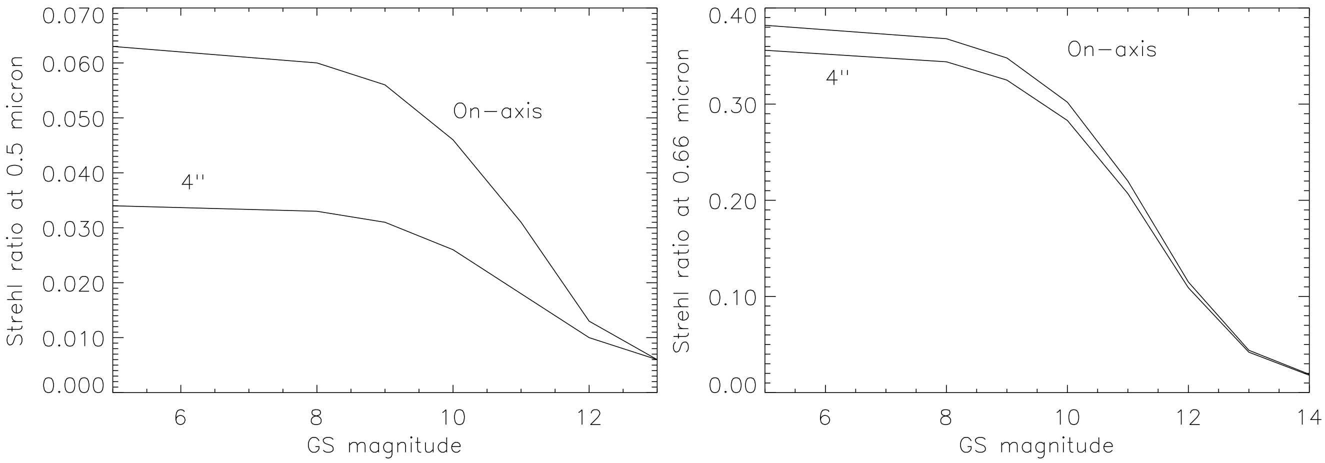

Figure 3: Strehl ratio on-axis and at $4''$ offset as a function of NGS R magnitude in high-resolution mode. Left: 0.5 micron, median seeing. Right: 0.66 micron, good seeing ($r_0 = 20$ cm).

How faint a star can be used as an NGS for the high resolution mode? In Fig. 3 (left) the Strehl ratio at 0.5 micron is plotted against NGS magnitude. Note that with a bright NGS, better Strehls could be achieved for compensation orders higher than 66. Alternatively, when the NGS is too faint (e.g. 15^m), the compensation order can be reduced; the Strehl ratio will then be very low, but some seeing improvement will still be obtained.

Much better performance will be possible under good seeing and at longer wavelengths. In Fig. 3 (right), the astrophysically important case of observations in the R band is presented. Even with guide star as faint as 12^m, diffraction-limited imaging in a $10''$ field is possible. Uniformity of compensation over the field is also better in this case.

3.4 Gain in FWHM

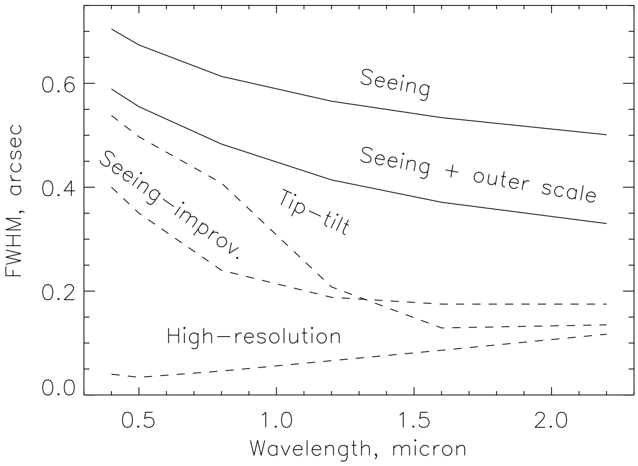

Figure 4: The FWHM as a function of wavelength for median seeing ($r_0 = 15$ cm, left) and for good seeing ($r_0 = 20$ cm, right). The two solid curves correspond to uncompensated images with infinite outer scale (standard theory) and with an outer scale of 25m. The dashed lines trace the FWHM for the tip-tilt (on-axis), improved seeing mode with Rayleigh LGS and high resolution mode with a NGS.

The FWHMs of uncompensated and compensated images as a function of wavelength are given in Fig. 4. The influence of a finite outer scale is very noticeable. The outer scale of 25m is typical for Cerro Pachón and other top class sites [4]. However, it varies considerably with time and may be either larger (e.g. 50-200m) or smaller (15m), so the actual atmospheric image size will be somewhere between the two curves. For a large outer scale, the amplitude of tip and tilt increases, hence the gain brought by tip-tilt and AO is larger.

In high resolution mode, the FWHM is diffraction limited at all wavelengths (on-axis), although the Strehl ratio in the visible is low. The FWHM gain in improved seeing mode at 0.5 micron is 35% for median seeing and 46% for good seeing.

Please, note that the FWHM of uncompensated images in the K band is already $0\farcs25$ under good seeing and $0\farcs33$ under median seeing; it improves at long wavelengths faster than $\lambda^{-0.2}$ due to outer scale effects. A telescope with perfect optics, without turbulence in the dome and without wind shake, should be able to achieve this performance (as seems to be the case at Gemini S).

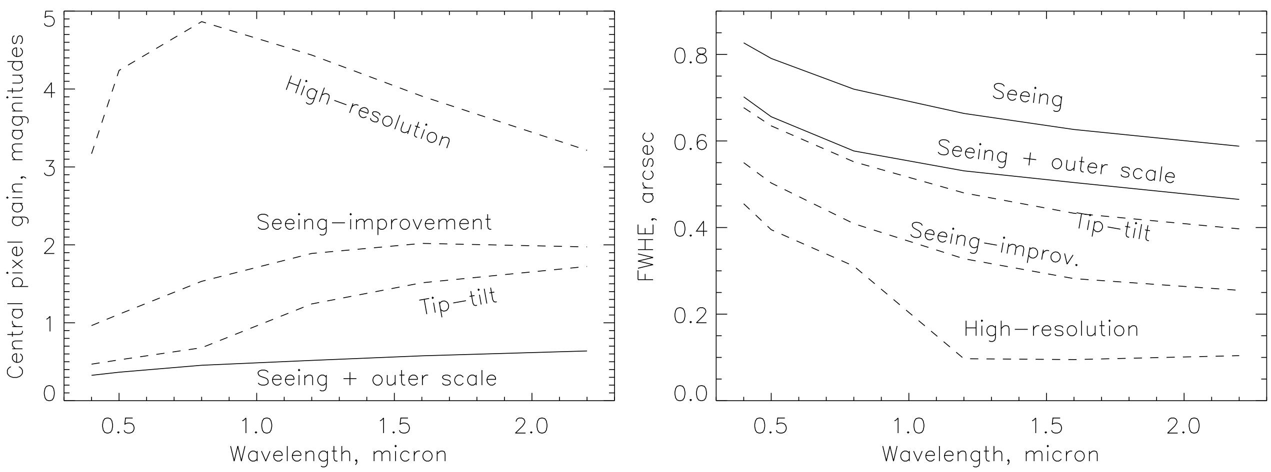

Figure 5: The gain in light intensity at the PSF center (in magnitudes) is plotted on the left as a function of λ for median seeing. For uncompensated images (solid curve), the gain is due to the outer scale effect. On the right, the diameter containing half the encircled energy is plotted for median seeing.

3.5 Gain in Strehl ratio and encircled energy

The Strehl ratio is the most common metric of AO performance. In Fig. 5 (left) the gain in the equivalent characteristic (Fried resolution) is plotted. It corresponds to the gain of the light intensity in the center of the PSF compared to the "standard" uncompensated atmospheric PSF (infinite telescope, infinite outer scale). The gain is expressed in magnitudes. In the right panel, the FWHE (Full Width at Half Energy) diameter is plotted. Gains in FWHE are less than those in FWHM: while AO decreases the size of the PSF, its structure is also changed compared to the atmospheric PSF, developing a narrow core while leaving considerable energy in the wings.

4 System concept

The proposed AO system will be built around a small, commercially available DM in a short time (1-2 years) and with a moderate budget. The objective is to construct a compact instrument which could be mounted on the currently unoccupied side port of the optical ISB The optical concept (Fig. 6) is based on an inexpensive electrostatic deformable mirror (DM) from OKO Tech (Delft, Netherlands). Their 50mm model can have up to 119 actuators, the useful beam diameter is 35mm. The approximate cost of this DM including high voltage amplifiers and interface cards is 37k USD.

An $f/16$ beam delivered from the telescope (optical ISB) is focused in the plane marked (2). The quartz field lens (1) forms a pupil image on the DM (3) at a distance of 56cm; thus, the whole module is rather compact. Part of the slightly diverging beam corrected by the DM is reflected by a dichroic mirror (4) towards the WFS (9). The WFS will have a CCD as light detector (e.g. a CCD39 from EEV) and will be of either a Shack-Hartmann or curvature type. In the latter case, both the intra- and extra-focal images will be projected onto the CCD simultaneously (no fast modulation) and read

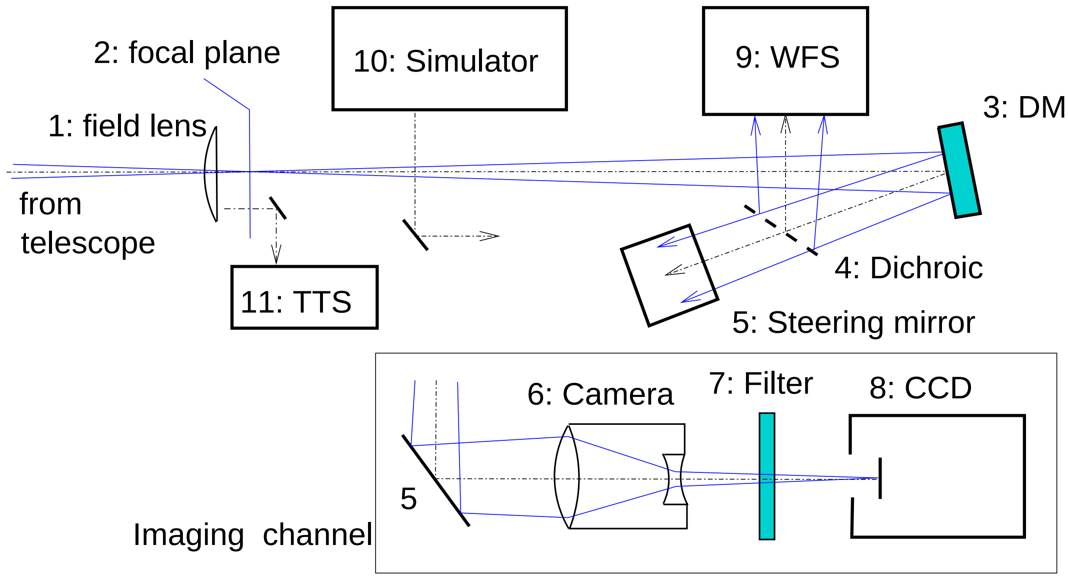

Figure 6: Optical concept of a high order AO system with small deformable mirror (DM).

once per loop cycle, as in the S-H WFS. A provision will be made to work with only one extra-focal image, to further reduce the readout noise on faint objects.

Several interchangeable dichroics will be provided, to be selected according to the imaging wavelength of the scientific channel. The light path from the telescope focus to the WFS includes a minimal number of elements, assuring highly efficient use of stellar or laser photons.

The turbulence simulator (10) with artificial star is permanently installed within the AO module and is switched into the beam for testing and adjustment. Turbulence is simulated by means of rotating phase screens, giving perfectly reproducible and well characterized distortions. The strength of simulated turbulence is selected by changing the distance of the phase screen from the artificial light source.

When the AO system is upgraded with a Rayleigh LGS for the seeing improved mode, one to three small pick off mirrors or prisms will be deployed close to the focal plane (2) to direct the light of 1-3 NGSs into the tip-tilt sensors (11). The tip-tilt compensation is achieved by the telescope tertiary mirror; hence, there is no need to locate the sensors after the DM, as in other AO systems. We prefer to use three NGSs instead of one, whenever possible, to get uniform compensation over the field. The guide probes must be small to avoid occulting a large fraction of the field. The WFS will be translated to accommodate for a severe defocusing of Rayleigh LGS, compared to high resolution (NGS) mode.

Lasers for Rayleigh guide stars are currently a factor of 10 cheaper than sodium lasers. Reliable solid state lasers are commercially available, being used in many industrial applications. Furthermore, the ultraviolet radiation of these lasers is invisible and does not penetrate aircraft and satellite windows, so operational constraints are relaxed, leading to high efficiency (Gemini has estimated that aircraft and satellite avoidance constraints may limit the duty cycle for Sodium laser work to only $\sim 50\%$ typically broken into short fragments). Rayleigh LGS is insensitive to sodium layer variations and less vulnerable to thin clouds.

In addition to the cost and operational advantages, Rayleigh LGS is not sensitive to high-altitude turbulence, hence makes it possible to trade the compensation quality against PSF uniformity over the field. When field is of no importance, the LGS height will be increased to 20 km to get the maximum resolution gain. it might be thought that the use of a sodium LGS would increase the sky coverage possible in high resolution mode. However, our preliminary estimates indicate that the compensation quality will be limited by residual tip-tilt errors (both photon noise and atmospheric anisoplanatism) unless a bright natutral guide star is available quite close to the science target. So the gain in sky coverage to be had through use of a sodium LGS will be modest at best.

After the dichroic, a steering mirror (5) directs the light beam to one of the scientific instruments mounted on the AO module. One of the instruments (shown in Fig. 6) is a dedicated CCD imager. It consists of a camera lens (6) (zoom lens), filter block (7) and 2Kx2K red sensitive CCD (8) in a dewar. Small motions of the steering mirror enable some image scanning. The zoom lens will be interchangeable: in the high resolution mode, the pixel size will be $0\farcs015$, while in improved seeing mode the pixels will be about $0\farcs1$, covering a $3'$ field.

A second instrument that can be rapidly switched in by a steering mirror is the SOAR IFU spectrograph. The IFU fibers will be detached from their regular location and mounted on the AO module which will provide an image with a suitable scale for diffraction limited resolution. The third available instrument port will be left free and reserved for possible future upgrades.

The AO module with its instruments will operate at the Nasmyth focus of SOAR, attached to one of the side ports of the optical ISB. The module can be permanently maintained in a ready state and activated rapidly when seeing improves. In turn, the instruments attached to the AO module can be interchanged rapidly by switching the steering mirror. Thus, the AO system will be fully adapted to queue scheduled operation as planned for all SOAR instruments.

This concept lends itself to progressive upgrades. As a first step, only the high resolution (NGS) mode will be implemented. At the second stage, a Rayleigh LGS and tip-tilt sensors will be added, accompanied by the wide field re-imaging lens to change the CCD plate scale. In the future a sodium LGS could be be envisaged if and when sodium laser technology matures sufficiently and new instruments can be added. The AO module can be quickly upgraded in the event of any new revolutionary advances in the field of adaptive optics (e.g. new principles of wave front sensing).

5 Tentative implementation plan and resources

Year 2001. Refinement of the concept and scientific case. Simulation of WFS and selection of definitive WFS concept. Interaction with SOAR community.

Year 2002. Purchase and study of the DM. Fabrication and characterization of the turbulence simulator. Closed loop laboratory simulator of the AO system using available or loaned equipment (optical table, cheap CCD imager). By the end of the year, experience with AO will be gained, parts of the AO hardware and software will be prototyped, and refined performance estimates will be available.

In parallel, conceptual design studies will be pursued. By the end of 2002, a conceptual design will be ready, including cost estimates. The decision to actually build the AO system will be taken after the CoDR.

Risk assessment of this concept will be addressed at the CoD phase. Not all current AO systems achieve their theoretically expected performance, especially in the visible range. For SOAR AO this match will be critical. We shall study the characteristics of the actual DM and shall perform detailed modeling (or even prototyping) of the WFS in order to get reliable limiting magnitude estimates. As for the Rayleigh LGS, we shall summarize the experience of other groups which use this technology and collect technical information on modern UV lasers.

Year 2003. Final design and fabrication of the AO system. Design of the Rayleigh LGS upgrade.

Year 2004. Integration, testing and commissioning. By mid 2004, only a year after the SOAR dedication, first light of the AO system is expected. Only the high resolution mode with NGS will be implemented at this first stage.

Year 2005. Upgrade with Rayleigh LGS and the implementation of the improved seeing mode.

The work on conceptual design and prototyping will be supported by the internal NOAO resources. By the end of 2002, funding of the AO instrument should be defined. We expect that the total project budget will be suitably constrained at below ($500K?).

The challenge of the SOAR AO project lies not in the blind cloning of existing AO systems, but in creating a truly useful and efficient instrument that can be scheduled a significant fraction of the time and can serve a wide range of astronomical programs. Being a second generation AO system, it must take full advantage of all previous experience and improved and/or cheaper technology. The cost must be kept to a reasonable proportion of the overall cost of the SOAR project; SOAR is a 4m class telescope, not a Keck, VLT or Gemini.

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