A visible-light AO system for the 4.2 m SOAR telescope

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ABSTRACT

Pushing the adaptive compensation of turbulence into the visible range remains a challenging task, despite the progress of AO technology. An AO system for SOAR, now under conceptual study, will be able to reach diffraction-limited resolution at 0.5-0.7 microns with natural guide stars as faint as magnitude 12, enabling studies of stellar vicinities for faint companions, nebulosity, etc. During the second stage of the project a Rayleigh laser guide star will be implemented. In this mode, only the lowest turbulent layers will be compensated. The angular resolution will be only two times better than natural seeing, but, in exchange, the uniformly compensated field will reach 2-3 arc-minutes, offering unique capabilities in crowded fields (clusters, nearby galaxies).

Keywords: Adaptive optics

1. DRIVERS FOR VISIBLE-LIGHT AO

The 4.2-m SOuthern Astrophysical Research (SOAR) telescope[1] is nearing completion at Cerro Pachón in Chile, sharing this mountain with the 8-m Gemini-S telescope. Although by modern standards SOAR is "medium-sized", it will have a well-defined and unique role in complementing wide-angle and near-IR telescopes in the visible range. Achieving high angular resolution in the visible is critical for the success of SOAR. As a first step, it will be optimized with respect to its optical quality and environment and will have tip-tilt compensation. Development of a visible-light adaptive optics (AO) system for SOAR has been started. Here we describe the scientific rationale for such a system, its expected performance, and the system concept.

Turbulence compensation in the visible is known to require relatively bright (hence rare) guide stars (GSs) and to be possible only in a small isoplanatic field of few arcseconds. Application of such an AO system in astronomy would be restricted to a small number of targets and not very compelling, considering the competition with the Hubble Space Telescope ($0.1''$ resolution over few arcmin field over the entire sky) and with interferometric image reconstruction that works well for bright stars. The GS problem will be solved with artificial laser guide stars (LGSs), but first in the near-IR. The compensated field will be enlarged by multi-conjugate AO (MCAO), now under development for Gemini-S[2] and other telescopes, but again in the IR. Can anything useful be done with AO in the more difficult visible range?

The diffraction-limited resolution of a 4-m aperture in the visible is 30 mas – 3 times better than at the HST. Compared to interferometry, AO offers the possibility to accumulate signal for a much longer time. This would permit increasing the spectral resolution and the investigation of astrophysics and kinematics close to bright stars with unprecedented detail. Applications include young stars with discs and jets, stellar ejectae and close binaries. Coupling of high spatial and spectral resolution will be a unique feature of the *high-resolution* mode of the proposed system. Astronomical applications require reaching GS magnitudes as faint as possible, so this mode will be most useful in periods of excellent seeing.

Ground-based observations of *faint* objects are strongly affected by seeing. When resolution improves, the amount of sky background in the seeing disk becomes less, thus increasing sensitivity for faint object detection. Moreover, better resolution reduces crowding in dense stellar fields (galaxies, clusters). A resolution gain of two would make SOAR competitive with 8-m class telescopes in the background-limited case. Such a gain over a

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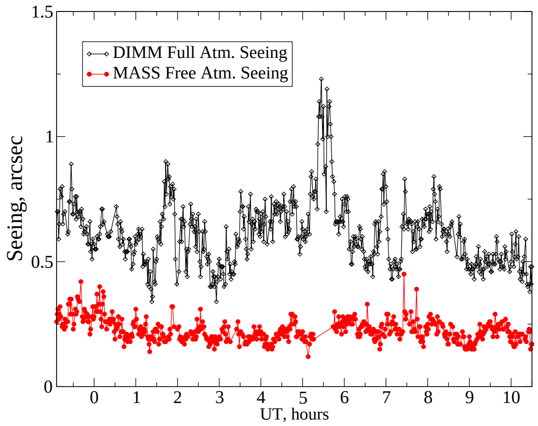


Figure 1. Seeing at Cerro Tololo on June 20 2002 as measured by a differential image motion monitor (upper curve) and without contribution of the first 0.5 km above ground (lower curve) as measured by the turbulence profiler, MASS.[8] The lower curve would correspond to ground layer compensated by AO.

relatively wide field can be achieved by compensating turbulence only in the ground layer using an LGS. The idea of such *enhanced seeing* AO was formulated already by Rigaut[3]; its implementation in the SOAR AO system is discussed below. Note that classical low-order AO also improves visible-light resolution (as demonstrated by the PUEO system[4]), but in a narrow field only, whereas ground layer compensation will correct a much larger field, because the aberrations corrected are located near the telescope aperture.

In short, we propose an astronomy-driven concept of AO system. Our goal and ambition is to maximize the impact of AO on the science done at SOAR by addressing the visible band with unique enhancement in performance. The SOAR AO will work in two complementary modes:

- **HR** – high-resolution mode with natural GSs and narrow field.
- **LR** – low-resolution or seeing-improvement mode with Rayleigh LGS and wide compensated field.

2. PERFORMANCE ESTIMATES

The performance of the proposed AO system was estimated using the modal simulation code,[5] augmented by Point Spread Function (PSF) calculations by the method of Véran et al.[6] These simulations include all main wave-front errors except time lag and readout noise in the wave-front sensor (WFS).

Table 1. Performance of tip-tilt and two AO modes under median seeing

Option	Zernike compens.	Sub-apert., m	Guide stars	FoV	FWHM (0.5 μm)
Tip-tilt	3	4.2	1 NGS	$2' - 3'$	$0.''50$
High resolution AO	66	0.4	1 NGS	$10''$	$0.''03$
Low resolution AO	66	0.4	1 LGS at 10 km	$3'$	$0.''35$

We infer from the Gemini site-testing campaign[7] that the median seeing at SOAR will be $0.67''$ ($r_0 = 15$ cm at 0.5 μm) while good (first-quartile) seeing corresponds to $r_0 = 20$ cm (or $0.5''$ seeing). Compared to the standard optical atmospheric propagation theory, we take into account the finite outer scale of turbulence, assuming its typical value to be 25 m. The mean vertical turbulence profile was approximated by 7 layers at altitudes from 0 to 15.8 km, with the ground layer containing 65% of the total turbulent energy; the same model was used for the Gemini MCAO simulations.[2] However, the turbulence profile is in fact highly variable. In May 2002 we started regular monitoring of the turbulence profiles at the adjacent mountain Cerro Tololo, using the new single-star turbulence profiler, MASS.[8] During periods of stable atmosphere like the night shown

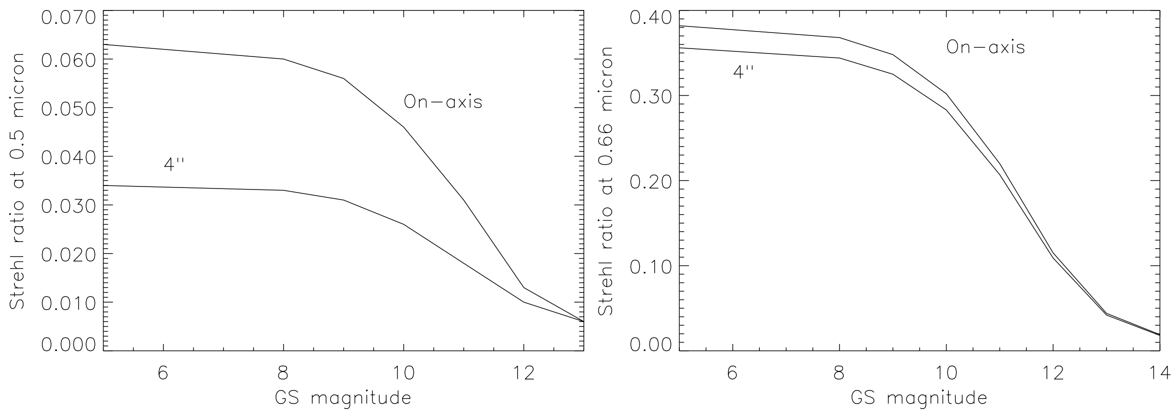
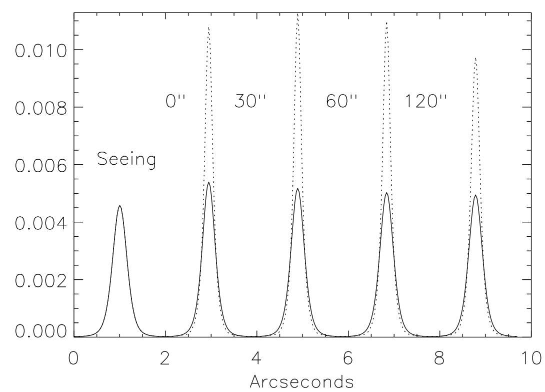


Figure 2. Strehl ratio on-axis and at 4″ offset as a function of NGS R magnitude in HR mode. Left: 0.5 micron, median seeing. Right: 0.66 micron, good seeing.

Figure 3. Stacked PSFs for the case of good seeing and imaging at 0.66 micron. Left: uncompensated atmospheric PSF. Full line: PSFs for tip-tilt compensation at distances of 0, 30, 60, and 120 arcsecond from guide star. Dotted line: PSFs at the same distances from the Rayleigh LGS in low-resolution (enhanced seeing) AO mode.



in Fig. 1, the gain from ground-layer compensation will be significantly higher than on the average, while the uniformly compensated field of view will be larger.

The parameters of AO and performance of SOAR with and without AO are summarized in Table 1. We suppose that the AO compensation order is equivalent to 66 Zernike modes (radial order 10), with a deformable mirror (DM) conjugated to the telescope pupil. Thus the size of the sub-apertures is around 0.4 m.

SOAR AO with natural GSs in HR mode is a well-studied case. Compensation order is too low to achieve high Strehl ratios in the visible. However, even with Strehls of few percent the diffraction-limited core dominates the PSF and ensures diffraction-limited FWHM (Full Width at Half Maximum) resolution in a field of a few arcseconds around the GS. Quantitative results for this mode are plotted in Fig. 2. They were confirmed by direct Monte-Carlo simulations using the IDL code of F. Rigaut `simul.pro`. This code takes into account both servo time lag error (500 Hz frame rate assumed) and readout noise in a S-H WFS which was assumed to be 4 electrons. A Strehl ratio of 0.08 at 700 nm wavelength was obtained with guide star as faint as R=12 under median seeing, which roughly agrees with Fig. 2. For an R=14 guide star the on-axis FWHM is no longer diffraction-limited but still quite good, 0.15″.

In the LR (enhanced seeing) mode we shall use a Rayleigh LGS placed deliberately at a low altitude of about 10 km. The WFS signal will contain information mostly on low turbulent layers. Upper layers will be left uncompensated, enlarging the PSF to well above the diffraction limit. However, the uniformity of the PSF over the field will be much better than for classical AO, as shown in Fig. 3.

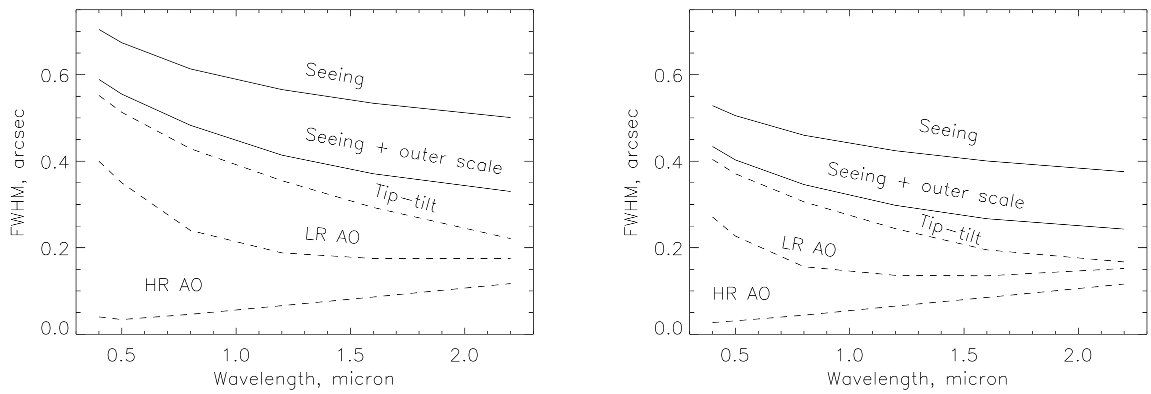


Figure 4. The on-axis FWHM resolution under median (left) and good (right) seeing conditions as a function of wavelength. Full curves: without turbulence compensation (standard theory and with outer-scale of 25 m); dashed curves: with tip-tilt compensation, LR and HR adaptive optics.

Table 2. Main characteristics of the AO instruments

Mode	Focal length, m	Pixel size μm	Pixel size mas	Field, arcsec
CCD, low resolution	40.0	15	77	158x158
CCD, high resolution	206.2	15	15	30x30
IFU spectrograph	13750	1000	15	0.45x0.75

In Fig. 4 the resolution achievable without compensation, with tip-tilt compensation and in the two proposed AO modes is plotted as a function of wavelength. It can be seen that the influence of turbulence outer scale on un-compensated imaging is significant. It mostly reduces the image motion, so the gain from tip-tilt compensation is also less compared to infinite-scale predictions. In the HR mode we should achieve the diffraction limit at all wavelengths. In the LR mode the FWHM resolution at an astrophysically important wavelength of 0.66 micron (Hα) can reach $0.25''$ even under median seeing. Under special conditions like those in Fig. 1 the resolution gain will be even higher. The gain in energy concentration brought by AO is slightly lower than in FWHM, because the PSF becomes more peaked compared to the un-compensated atmospheric PSF and hence contains less energy in its narrow core.

3. SYSTEM CONCEPT

Conceptual studies of the SOAR AO are underway. In this section, only preliminary considerations are presented. The AO system concept is driven by science requirements and the desire to make it as cheap as feasible without sacrificing performance.

3.1. Scientific instruments

The AO system will be equipped with its own dedicated scientific instruments (Table 2). A 2048^2 pixel CCD camera would be adequate for imaging in the visible and not expensive. Two pixel scales must be provided, 15 mas/pixel for diffraction-limited sampling and 80 mas/pixel for improved-seeing imaging. Spectroscopic capability, critical for the success of the proposed system, will be provided by the Integral Field Unit (IFU) spectrograph already being developed for SOAR; the input of this imaging spectrograph (a lenslet array with fiber bundle) will be re-located to the AO module which will supply it with a pixel scale suitable to sample the

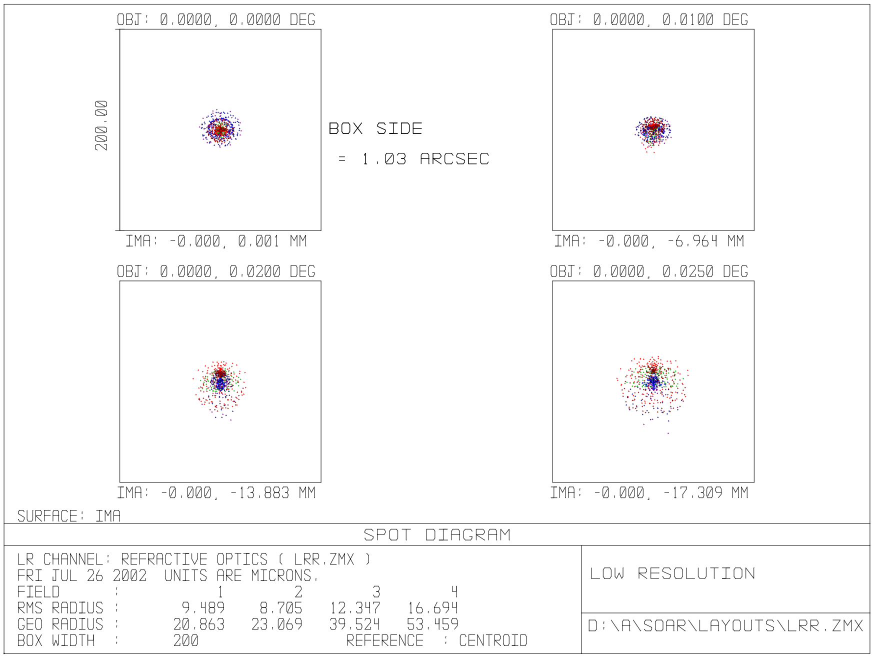


Figure 5. The polychromatic spot diagrams for SOAR AO in the LR mode.

diffraction-limited PSF. Providing a second, coarser pixel scale for the IFU is under consideration. The AO module will have an additional output port where a third small instrument can be mounted in the future.

The AO will need flexible scheduling to take advantage of the good-seeing periods. It means that the AO module must be permanently installed at the telescope and always ready for work.

3.2. Deformable mirror

Originally, an adaptive secondary seemed attractive, permitting to supply AO compensation to regular scientific instruments. However, none of the instruments currently planned for SOAR (with the exception of IR imager) has a pixel scale fine enough to take advantage of diffraction-limited images. Moreover, an adaptive secondary can not work unless we incorporate a WFS into each of the instruments. The technology of thin-membrane adaptive secondaries as pioneered at Multi-Mirror Telescope[9] is complex and expensive. All this made us decide in favor of a more traditional approach with a small DM and re-imaging optics.

We base our design on a small electrostatic DM from Flexible Optical (Okotech, `http://www.okotech.com`). This will be a curvature DM with 70-119 actuators and an active membrane area of 35 mm diameter. A similar 37-element electrostatic DM has been purchased and studied in the laboratory using a Wavescope sensor from Adaptive Optics Associates (`http://www.aoainc.com`). It was found that when a voltage of 210V is applied to all electrodes, the peak-to-valley defocus corresponds to a 7 μm DM displacement. The stroke of higher-order modes is smaller, being inversely proportional to the square of the spatial frequency of deformation. Intrinsic aberrations of the 37-element DM, mostly astigmatism and coma, are tolerably small ($\sim$0.3 μm of peak-to-peak DM surface deflection). In the normal state the DM will biased with a nominal 25 m curvature radius of its concave surface.

Extrapolating to a 35-mm DM, we find that the stroke will be more than sufficient to compensate 66 modes on a 4.2 m telescope under 1$''$ seeing. The stroke calculations assume that a 35-mm useful surface of the DM can

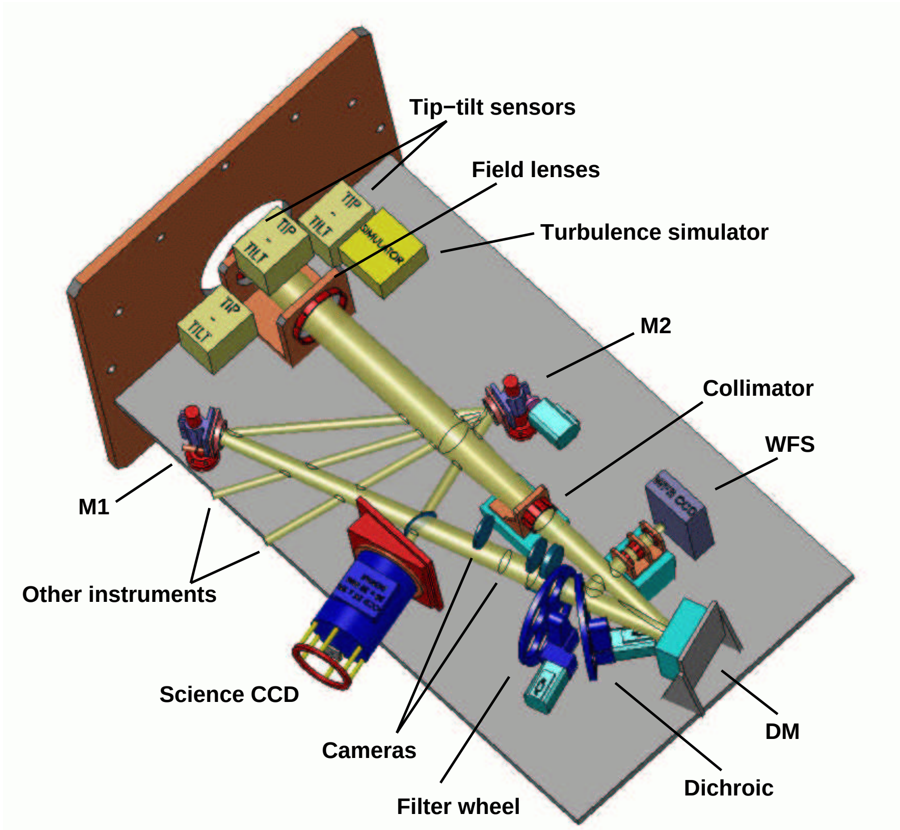


Figure 6. Tentative opto-mechanical layout of the SOAR AO system. The optical table size is 1.16x0.61 m.

have a defocus displacement of ± 12 μm, or a curvature radius from 12 m to infinity. Atmospheric defocus under $1''$ seeing, according to Noll's formulae, would correspond to a 0.48 μm rms displacement of the DM surface. For the Kolmogorov turbulence spectrum the curvature amplitude of higher-order modes will be similar to that of defocus. Hence, a sum of 66 independent modal signals would have an rms variation of curvature (and electrode voltages) of $\sqrt{66} = 8.1$ times higher than pure defocus, but the saturation limit will still be $12/(8.1 \cdot 0.48) = 3$ times higher than the rms signal. Of course, part of the dynamic range will be used to compensate the intrinsic aberrations of the DM, telescope and optics, but the available margin is sufficient, especially if we recall that the AO system will mostly operate under good seeing conditions.

3.3. Optical design

Having a small DM is good for reducing instrument cost, size and weight. However, the optical design of the re-imaging optics becomes non-trivial. Unlike other AO systems, the field of view in LR mode is relatively wide, 3 arcminutes (60 mm in the focal plane of SOAR), which means that angles of incidence in the AO module become significant. Although we do not require diffraction-limited image quality in this mode (it must only be better than $0.2''$ in order not to degrade the compensated PSF), a classical AO optical scheme with two identical off-axis parabolas is not satisfactory (remember also that we need two distinct pixel scales at the CCD).

A reflective optical design that satisfies our requirements has been developed. It involves however fast off-axis aspherical mirrors that would be difficult and expensive to manufacture. This is why an alternative and more practical *refractive* optical design has been adopted. In the most difficult LR mode it was possible to achieve a FWHM of better than $0.1''$ over the whole 3 arcmin diameter field and $0.025''$ at the center of field (Fig. 5). In the HR mode the image quality is diffraction-limited with a Strehl ratio of over 0.9. No refocusing is required in the nominal wavelength range of 0.4 to 1.0 micron. The transmission of all channels is better than 0.82. Even at the laser wavelength of 0.355 nm the WFS transmission is 0.74. Reflections from lenses that increase instrument background in the infrared are not important for a visible-light system.

In Fig. 6 a possible opto-mechanical layout is shown. The AO module will be attached to the Instrument Selector Box of the SOAR telescope. This box receives light from the Nasmyth focus and also contains an atmospheric dispersion corrector. A two-component positive field lens diminishes the beam divergence on a refractive collimator which forms a 35 mm diameter pupil image on the DM. The beam after the "collimator" is in fact slightly converging. The tip-tilt compensation can be achieved by rocking this lightweight DM, but we hope that the fast tip-tilt tertiary mirror of SOAR will be sufficient to off-load most of the tilt from the DM.

Upon reflection from the DM, the beam is divided between science and WFS channels by a dichroic. A set of several selectable dichroics will be provided to optimally distribute photons depending on the science wavelength. In the LR mode the dichroic will reflect only the UV laser light. The transmitted beam is focused by a 3-lens camera on a CCD. The two cameras for LR and HR modes are interchangeable, while the CCD remains fixed; the LR camera is inserted into the beam with its 45° mirror that deflects the image to the CCD. The beam in HR mode is folded by mirrors M1 and M2 before it strikes the CCD; additionally, M2 is used to direct the HR beam to alternative instruments. One of those will be an IFU spectrometer with a pixel (lenslet element) size of 1 mm; the required extension of the focal length will be achieved by a microscope objective or a small lens in the IFU beam.

3.4. Wave-front sensor

The WFS will be of a Shack-Hartmann type, with 10x10 elements over the aperture in a square pattern (72 useful sub-apertures). Its design will follow standard practice, with a CCD-39 as a most likely choice for the detector. We assume that the readout noise will be 4 electrons. For faint GSs the WFS will work in a quadrant mode, with 2x2 pixels per sub-aperture (with 4x binning). The nominal frame rate will be set to 2 ms. With the usual assumptions (like 40% overall quantum efficiency) we estimate the photon flux from an R=12 star to be 60 photelectrons per 2 ms per sub-aperture. For brighter stars and a LGS we shall work with 8x8 pixels per sub-aperture (i.e. full-frame readout) in order to obtain good centroiding and hence a better Strehl ratio.

In the LR mode the WFS channel will be re-focused and supplemented with a fast electro-optical shutter for range-gating the laser pulses. Use of dynamic re-focusing to increase the photon flux[10] is under consideration: we have to balance the increased complexity of this solution against the cost of a more powerful laser.

Unlike other AO systems, we do not plan to implement relative offsets between the WFS and science fields. The reason is that in the HR mode the narrow isoplanatic field around the GS is entirely imaged by the CCD. In the LR mode the LGS will be centered in the field as well.

In the LR mode, tip-tilt signals must be obtained from natural GSs because an LGS does not contain this information. However, we can not use only one GS as in other laser-assisted AO systems because the tilt anisoplanatism over a 3 arcmin field will be significant. Instead, only tilts produced by the lowest atmospheric layers and telescope wind shake must be retrieved by averaging the signals from several tip-tilt GSs. We plan to implement 4 tip-tilt sensors based on APDs (e.g. like STRAP[11]). These will be located in the first focal plane (before the DM) because the compensating element (the SOAR tertiary mirror) is upstream in the beam. Any small residual high-frequency tilts will be corrected by the DM in the open loop. The stars for tip-tilt sensing in the LR mode will be selected outside the science field. These stars can be fainter than usually assumed because we do not aim at diffraction-limited resolution in this mode; moreover, averaging of the signals from several stars helps to reduce the noise. For this reason we expect the sky coverage of the SOAR AO in the LR mode to be complete.

3.5. Laser guide star

As explained above, we need a low-altitude Rayleigh guide star to measure turbulence selectively in low atmospheric layers. The best choice seems to be a UV solid-state Nd:YAG laser at 355 nm with an average power of a few Watts and a pulse repetition rate of 10 kHz (distance between successive pulses 30 km). The UV radiation is well scattered by air, does not present hazards to airplane pilots and does not contaminate the dark environment of an astronomical observatory. Compact pulsed lasers of sufficient power with diffraction-limited beam quality can now be purchased at a reasonable price. Thus, the beam-launching telescope can be of small size (∼20 cm diameter) and the laser can be located on the telescope tube. A steering mirror in the beam-feeding path will be needed to center the LGS in the WFS.

A low-altitude LGS should be relatively easy to implement. Starting from the numbers given in Ref. 12, we estimate return flux as $8.8 \cdot 10^6$ ph m^{-2} J^{-1} for an LGS at 10 km with 1 km range gating. Assuming an overall transmission of 0.25 and 0.4x0.4 m^2 square sub-apertures, a 8 W laser would give about 3000 photons per millisecond in each sub-aperture – likely over-kill for a sensitive WFS. However, the same laser focused at 20 km will give only 200 photons per sub-aperture. With higher LGS, a higher angular resolution in a smaller field will be achieved, thus bridging the gap between LR and HR modes.

4. CONCLUSIONS

Adaptive optics has now reached the state of a mature technology. The concept of a "second-generation" AO system for SOAR takes advantage of recent technological advances (small and cheap DMs, reliable solid-state UV lasers) and good seeing conditions at SOAR to push turbulence compensation into the visible at moderate cost. The two proposed operational modes with matched scientific instruments will provide the users of SOAR with unique observing capabilities that complement or even rival those of larger telescopes.

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