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SAM – THE SOAR ADAPTIVE MODULE

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Abstract. SOAR, located on Cerro Pachón in Chile, is a recently completed 4.1m telescope, dedicated to high angular resolution. To complement the other two larger telescopes, Gemini on Cerro Pachón and the Blanco telescope on Cerro Tololo, SOAR's niche is high resolution, imaging in the visible and spectroscopy, which calls for the development of an adaptive optics (AO) module. This instrument will provide improved seeing over a wide field, for visible wavelengths. In this paper, I briefly describe which kind of science can be carried out with this type of AO and compare its performance with other ground-based and space-based telescopes. Then, the ground layer compensation principle and its application for Pachón atmospheric conditions are presented. Most of the nights, the perturbations are located close to the ground; thus a partial correction of the first kilometer of the atmosphere will be efficient to improve the seeing significantly (by a factor of 2 or more). Finally, technical details on the instrument itself including the deformable mirror, the wavefront sensor, the laser and the turbulence simulator are given.

1 Introduction and science motivations

The SOuthern Astronomical Research (SOAR) telescope is located on Cerro Pachón in Chile, close to the 4m Blanco telescope and next to the 8m Gemini, forcing it to find its own niche. Gemini is optimized for infrared observations and the Blanco currently provides wide field of view (30 arcmin) and seeing-limited imaging, leaving for SOAR high spatial resolution optical imaging. This will be further enhanced by the SOAR Adaptive Module (SAM). SAM is an adaptive optics (AO) system positioned between the telescope focal plane and one of several instruments. It will provide a factor of 2 improvement of the image quality – both in the infrared (IR) and in the visible. Figure 1 shows the location of SAM's niche on the image quality and field of view (FOV) map, compared with several other telescopes.

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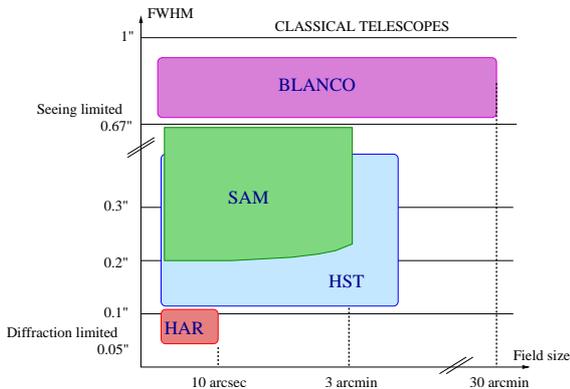


Fig. 1. Image quality and field of view of SAM compared to other facilities in the visible. The diffraction-limited resolution corresponds to a 4m in the IR. (HAR=High Angular Resolution).

The Hubble Space Telescope (HST) has produced very good images over a large bandwidth of wavelengths and a large field of view. However, HST with its 2.4m aperture is smaller than SOAR. This disadvantage was compensated by the location of this telescope in space, which leads to diffraction-limited resolution in the near IR as well as in the visible. Nowadays, large telescopes equipped with AO systems reach comparable image quality in the near IR, over a small FOV (HAR on figure 1). Observations in the visible from the ground, though, remain seeing-limited. As shown in figure 1, SAM will cover a large part of HST capabilities, including the visible range of wavelengths and a wide FOV. The timing for SAM is also favorable since HST is now at the end of its life.

High spatial resolution, larger field of view than typical AO systems and visible wavelengths are the unique features of SAM. As an AO system, it will increase the sensitivity and the efficiency of SOAR. Instruments combined with SAM will have less difficulties with crowding and with the confusion limit. Spectroscopic and imaging observations with SAM will better detect fine spatial structures.

With its novel characteristics, SAM enables original and forefront science. For instance, from high-resolution maps of radial velocities obtained with SAM, it will be possible to study the kinematics and dynamics of nearby galaxies. Moreover, interesting science on the stellar populations in nearby galaxies and on clusters in galaxies and galactic nebulae (Planetary nebulae, HII regions, reflection nebulae etc...) will be possible. Photometry of distant supernovae and imaging of the morphology of lensed galaxies are considered. A more detailed example concerning planetary and symbiotic nebulae is shown in figure 2.

SAM will not only allow the astronomical community to continue to broaden their observational and science possibilities, but it is also a technical achievement. The combination of SAM and SOAR will yield the unique capability of improving image quality at visible wavelengths over a large field of view. The characteristics *visible* and *wide field* in *high* resolution observations require technical innovation. Atmospheric turbulence is represented by the Fried parameter r_0 , defined by $r_0 = 0.98\lambda/\sigma_{turb}$, where λ is the wavelength in m and σ_{turb} is the seeing angle.

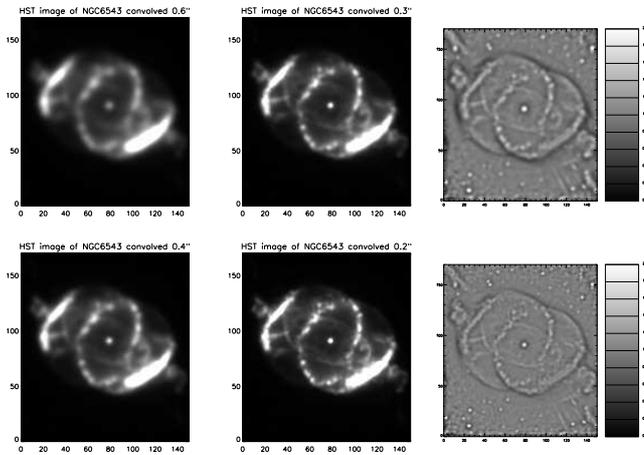


Fig. 2. Influence of resolution on the recovery of the structure of the planetary nebula NGC 6543 in the N[I] emission line. A HST image was convolved with the PSF corresponding to median and good seeing at SOAR (left) and to its 2-fold improvement with GLAO (center). The right panels show the difference of those image pairs that reveal how much high-frequency details would be recovered by SAM.

For the same atmospheric conditions, since $r_0 \propto \lambda^{6/5}$, r_0 is smaller (the seeing is poorer) in the visible than in the infrared. Consequently, compensating the turbulence in the visible is not as simple and straightforward as in the infrared. Moreover, it requires brighter guide stars and the diameter of compensated field (isoplanatic angle) is smaller - few arcseconds. Another complication is the number of actuators N needed. For a given number of N , the residual phase variance σ_ϕ^2 in AO compensated wavefronts is $\sigma_\phi^2 = 0.3N(\lambda)^{-5/6}(D/r_0(\lambda))^{5/3}$, leading to $N(\lambda) = [0.3/\sigma_\phi^2(\lambda)]^{6/5}[D/r_0(\lambda)]^2$. For a given value of σ_ϕ , $N(\lambda) \propto \lambda^{-12/5}$. In the visible, the ratio D/r_0 is larger than in the IR, thus to reach comparable performance of the AO system, many more actuators are needed. For example, going from $1.6\mu\text{m}$ to $0.7\mu\text{m}$ leads to a number of actuators $(0.7/1.6)^{-12/5} = \mathbf{7.3}$ times larger. This makes the deformable mirror (key component of an AO) prohibitively expensive. One of the challenges for SAM is to build a non-expensive, reliable and powerful system.

2 Application of a new concept: ground layer compensation

A large part of atmospheric turbulence is usually located near the ground, in the first kilometer. Therefore, correcting only partially the turbulence in the ground layer is an attractive way to improve the image quality. The correction will not be

as complete as in usual adaptive optics systems and will never reach high Strehl ratios. However, the improvement of the resolution or the increase of the quantity of light going through a narrow slit of a spectrograph is significant and can reach a factor of 2 to 5. The small resolution gain of Ground Layer Adaptive Optics (GLAO) compared to a regular AO system is compensated by a correction over a wider field of view, at shorter wavelengths.

SAM uses GLAO principle by focusing a Rayleigh laser guide star at an altitude of $H_{RI} = 10\text{km}$ above the ground (Tokovinin 2003). The Rayleigh scattering occurs continuously at all altitudes less than 20km approximatively, diffusing some photons back toward the telescope. Only photons coming from the altitude H_{RI} will be selected by a range gate system (Pockels Cell or other type of fast shutter) to be measured by the wavefront sensor (cf. Section 3, laser system). The wavefront sensor will measure the aberrations due to those H_{RI} first kilometers of the atmosphere only and will send a signal to the deformable mirror which is conjugated to the ground layer. The DM will then be able to partially correct the low altitude perturbations.

Seeing at Cerro Pachón

The Gemini site characterization campaign in 1998 measured the turbulence profiles and the seeing at Cerro Pachón. The model used in AO simulations has 7 layers at altitudes from 0 to 15.8km. The main results are that the total median seeing corresponds to $r_0 = 15\text{ cm}$ at $0.5\ \mu\text{m}$ and that 65% of the perturbations come from the ground layer (Vernin et al. 2000 and Ellerbroek et al. 2000).

Another campaign carried out with the new low-resolution turbulence profiler in 2002 at Cerro Tololo confirmed those results (Tokovinin et al. 2003). From a median seeing of 0."95 (which happens 50% of the nights), ground layer turbulence accounts for 60% (about 0."66) while the free-atmosphere gives a median seeing of about 0."55. For a calm night, the free-atmosphere median seeing reaches 0."2. The graphs on figure 3 illustrate the results.

Sensing and correcting only the lower layers of the atmosphere will enhance the image quality significantly.

Simulation: system parameters and performance

Tokovinin et al. (2003) compared different techniques of seeing compensation (tip/tilt, outer scale or high resolution compensation) at wavelengths from $0.4\ \mu\text{m}$ to $1.3\ \mu\text{m}$, and showed that GLAO is efficient. For a number of corrected Zernike modes equal to 66, the improvement of the seeing can be a factor of two on average to five for the best conditions (rare but possible), over a field of view of 3 arcmin. For example, for a median seeing of 0."95, the corrected Full Width at Half Max (FWHM) can reach 0."35 at $0.5\ \mu\text{m}$. Figure 4 shows seeing compensation results using GLAO for different fields of view, at $\lambda = 0.7\ \mu\text{m}$. It is possible to forecast the best conditions.

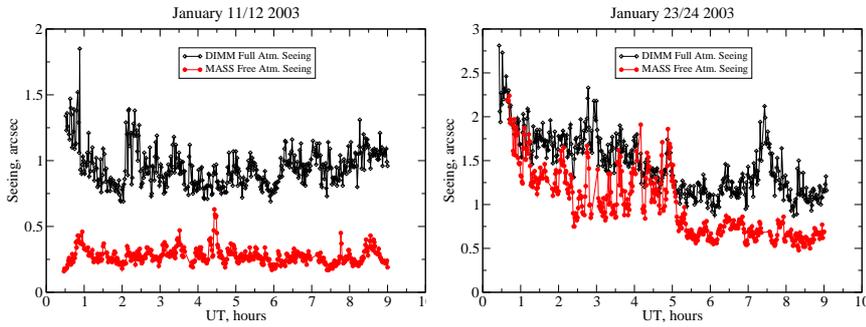


Fig. 3. Seeing as a function of time at Cerro Pachón: comparison between a calm night (left) and a bad night (right). On each graph, the upper curve is the seeing measured with DIMM (Differential Image Motion Monitor) and corresponds to the turbulence integrated over all altitudes. The lower curve shows the seeing after full suppression of the turbulence of the first 0.5 km above the ground, as measured with MASS (Multi-Aperture Scintillation Sensor by Tokovinin et al. (2003)). For a calm night, the improvement can reach 5 times.

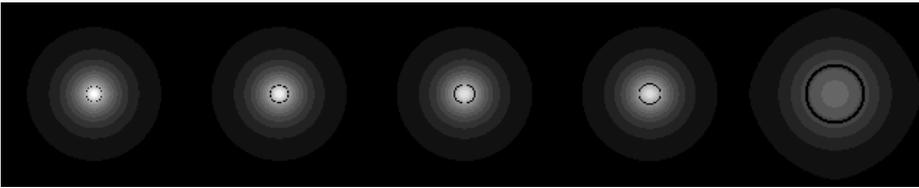


Fig. 4. Mosaic of simulated PSF for GLAO with a Rayleigh guide star at a 4m telescope. From the left to the right are the correction on axis, at 1', at 2', at 3' and no correction for a median turbulence at Cerro Pachón. $\lambda = 0.7\mu m$.

3 Technical aspects

The need for SAM to be low cost, compact and robust, led to some changes from the original concept presented in Tokovinin et al. (2003). Here is a summary of the current concept.

The deformable mirror: The deformable mirror (DM) is a key component because not only it defines the size of the AO instrument, but also because it partly defines the quality of the correction. It is also one of the most expensive elements. The electrostatic OKOtech mirror, initially considered, appeared to be too fragile and with a saturation just acceptable for a 4m telescope. The “winner” is a bimorph DM from Cilas because it is robust and it does not saturate for a 4m telescope, although its pupil diameter is slightly larger (50mm instead of 35mm)

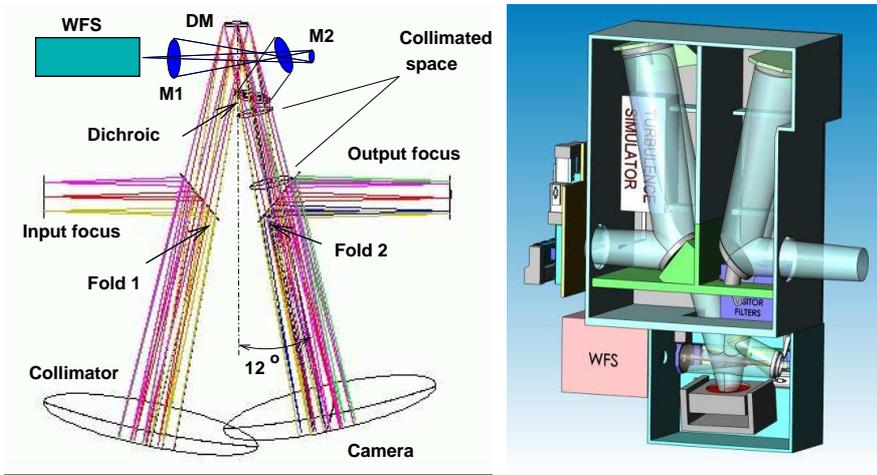


Fig. 5. Left: Optical design. right: SAM global mechanical view.

and it is more expensive.

Mechanical and optical designs: The optical design is presented in figure 5 (left). The optics are all reflective, based on two off-axis paraboloids, leading to excellent optical properties over a wide field. Moreover, the magnification of the system is 1, maintaining the scale and the focal ratio of SOAR for SAM. This allows the use of regular SOAR instruments with SAM, making the instrument a truly “adaptive module”!

An overview of the mechanical design is presented in figure 5 (right). It is compact and modular.

The wavefront sensor: The wavefront sensor (WFS) contains three important elements: the lenslet array, the CCD and the elements such as Pockels Cell for the range gating when using the Rayleigh laser guide star.

The number of elements in a lenslet array must be large enough to sample well the wavefront and small enough to limit the complexity. Moreover, the WFS sampling needs to be only slightly better than the DM correction sampling - oversampling would be a waste. For SAM, the DM order used is 60. Consequently, we will use 10x10 microlenses which correspond to about 80 useful subapertures across the pupil.

The camera will be a CCD-39 with a pixel size of $24\mu\text{m}$ and a readout noise of 4 electrons approximately.

As mentioned above, the atmosphere scatters light at all altitudes. A Pockels Cell will be used as a range gating system, to control the information arriving on the WFS by selecting the light coming only from one altitude. A Pockels Cell is an electro-optics crystal which acts as a high-speed shutter by changing its optical properties when applying a voltage V (for more detailed description, see

Bass 1995). The efficiency of a Pockels Cell as a shutter depends strongly on the incidence angle of the beam: the bigger the angle, the worse the efficiency. The application of the Pockels cells is still under investigation as the cell will be placed in a diverging beam. Another option under investigation would be the use of gated CCDs.

Laser guide star (LGS) system: The correction of the wave-front will be achieved using a low-altitude (10km) Rayleigh laser guide star, created by a frequency-tripled Nd:YAG solid-state laser. The nominal average optical power of this laser beam will be 8W, its wavelength 355nm and its pulse frequency 10kHz. The launch telescope, 25 cm diameter, will be located behind the SOAR secondary mirror and the laser will be placed at the telescope elevation ring. The UV laser beam will be aircraft-safe.

In parallel to the laser, SAM will get signals for tip-tilt correction from one to three guide stars located in a circular field of 5' diameter around the science field. The magnitude limit will be $R < 18$, ensuring 90% sky coverage at Galactic pole. It will be possible to use bright ($R < 10$) natural stars instead of a LGS if available – in this mode the resolution will be higher, but the uniformly-corrected field will be smaller.

TURSIM, the turbulence simulator: To test and calibrate an AO, a physical turbulence simulator is needed. TURSIM is the turbulence simulator developed for SAM. We have discovered that a phase plate of reasonable characteristics can be fabricated by depositing multiple layers of ordinary hair spray onto a glass substrate.

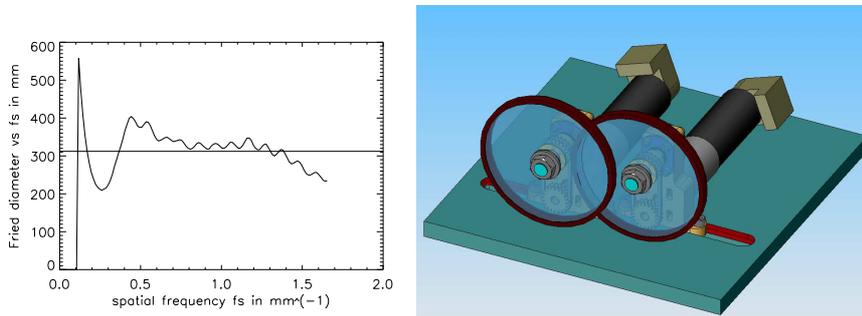


Fig. 6. **Left:** Characteristics of one of the phase screens made with the hair spray; plot of r_0 versus the spatial frequency calculated from the power spectrum. **Right:** View of the discs. Each disc has its own DC (direct current) motor with variable speed.

Figure 6 (left) displays the characteristics of one of the phase screens made with the hair spray. It shows the Fried parameter r_0 as a function of the spatial frequency calculated from the power spectrum of the measured phase distribution. The curve obtained is close to a straight line, which lets us conclude that the spatial spectrum of those phase perturbations is a reasonable match to the Kolmogorov

law. Two of those phase screens will be installed in an optical system simulating the SOAR telescope, placed inside SAM. We use two voltage regulated motors to rotate the discs independently permitting us to simulate various directions and speeds of the turbulence. A better sampling of the turbulence statistic is obtained by averaging random combination of two screens. The disks with motors are attached to a small rigid platform as shown in figure 6 (right).

Instruments: SAM will incorporate an integrated CCD imager covering the 3' field with an adequate sampling (not defined yet). On the visitor port of SAM, other instruments such as the SOAR Integrated Field Unit Spectrograph (SIFS), provide by our Brazilian partners can be mounted. A flip mirror will assure fast switching between the CCD and such visitor instruments.

4 Conclusions

In this paper, I showed why SAM is a very promising instrument both from a scientific point of view as well as a technical point of view. Improving the seeing at visible wavelengths over a wide angle is a real progress. Moreover, the choice of the DM and other components has been inspired by the need of simplicity, robustness and low cost.

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