1 Introduction

The SOAR Adaptive Module (SAM) is a ground-layer adaptive optics system that will significantly improve seeing-limited resolution. The expected performance of SAM has been analyzed in detail [5, 6, 3]. In this document, various performance metrics are presented in a systematic way from the user perspective. Indeed, a future SAM user would like to know the delivered parameters of the SOAR+SAM combination, such as resolution, energy concentration etc., without learning the details of the instrument or the method used to compute these parameters.

The task of presenting performance of an AO system such as SAM is complex. Different observing programs require different performance metrics. These metrics, in turn, depend on several parameters related to the instrument and observing conditions. An example of performance prediction for the Gemini GLAO system is given by Andersen et al. [1]. In the following we try to present the multi-parametric predictions for SAM in an orderly manner.

2 Performance metrics

Resolution is characterized by the Full Width at Half Maximum (FWHM) $\epsilon$ of the Point Spread Function (PSF). If the shape of the PSF were Gaussian or seeing-limited, this parameter would be sufficient to predict all other metrics. Unfortunately, this is not the case for a GLAO-compensated PSF. Still, FWHM is the most important metric. It was shown in [1] that FWHM strongly correlates with the gain in observing efficiency and the diameter containing 50% of the PSF energy. The FWHM $\epsilon = (\epsilon_x + \epsilon_y)/2$, where $\epsilon_x$ and $\epsilon_y$ are the FWHM diameters of the PSF cuts in two orthogonal directions.

Ellipticity is a measure of the PSF elongation. The standard definition of ellipticity $\epsilon$ adopted in weak-lensing studies is $\epsilon = (a - b)/(a + b)$, where $a$ and $b$ are the major and minor axes of a 2-dimensional elliptical Gaussian function approximating the PSF. Considering that the PSF is not a Gaussian, the ellipticity depends on the details of the fitting procedure. The most relevant measure of the PSF asymmetry relates to its steep part around half-intensity, so here the ellipticity is calculated as $\epsilon = (\epsilon_x - \epsilon_y)/(\epsilon_x + \epsilon_y)$. The directions $x$ and $y$ coincide with the elongation axis and $\epsilon > 0$ corresponds to a radially-elongated PSF.

Energy concentration $E$ is a fraction of the energy collected in a circular or square aperture of a given size. We select as representative the energy fraction $E_{0.3}$ in a circular aperture of 0.3" diameter.
The SIFS integral-field spectrograph will have square apertures of 0.3" size, so $E_{03}$ will be a good proxy of the gain in the SIFS performance brought by the SAM.

**Strehl gain** is the increase of the central intensity of the PSF compared to the seeing-limited case. We express here the Strehl gain $G$ in stellar magnitudes, $G = 2.5 \log(S_{SAM}/S_{seeing})$, where $S$ are the respective Strehl ratios. This metric shows the gain in the magnitude limit of photometry in crowded (confusion-limited) fields, as demonstrated by Olsen et al. [2].

The performance of SAM is characterized here by the four above metrics, leaving aside other potentially useful metrics for clarity.

3 Parameters and conditions

![Figure 1: SAM field of view. The nominal science field is 3' x 3' square and the patrol field where guide stars can be found is 5' x 5' or slightly larger. The diagram shows the assumed locations of the two NGS tip-tilt stars and the 5 test points where the performance metrics were computed. The circle at the center shows a footprint of the defocused laser spot at its nominal 10 km range.](image)

**Wavelength** $\lambda$ is defined by the observing programs. SAM will not be useful in the UV where the laser light will contaminate the science beam. Thus we select representative wavelengths of 0.4, 0.5, 0.7, and 1.0 micron and compute performance metrics at these wavelengths.

**Observing conditions** can vary greatly, both in terms of seeing and in terms of the turbulence profile (more or less turbulence in the ground layer). Three model turbulence profiles were developed in [7] on the basis of measurements done at Cerro Pachón. It was shown that these *good*, *typical*, *bad* profiles represent best 25%, median, and 75% observing conditions at SOAR. The performance is computed for all three models. A SAM user may expect performance in the limits indicated by these models for 50% of time, the remaining time shared equally between better and worse performance.

**Field variation** of each performance metric is evaluated at 5 points, starting at the center of the field and going in the x-direction out to 2' radius (Fig. 1). The results depend on the configuration of the natural guide stars, assumed here to be located symmetrically at $\pm 2'$ radius in the y-direction. The *uncorrected* atmospheric PSF was also computed and its metrics are plotted at a distance of 2.5' from the center, for comparison with the SAM performance.

**Zenith distance** $\gamma$ depends on the target. It is strongly recommended to observe with AO and GLAO as close to zenith as possible, but astronomical objects tend to be located on the whole sky.
We select $\gamma = 45^\circ$ (air mass 1.41) as a representative case and compute performance only for this zenith distance. Some data for other $\gamma$ can be found in [5].

**LGS range** can be set between 7 km and 14 km, a higher LGS giving better resolution at the field center but worse uniformity. Here, only the nominal LGS range of 10 km is studied.

**Number of tip-tilt NGS** (one or two) and their location influence the PSF uniformity and other metrics. A representative case of two NGSs located symmetrically is chosen (Fig. 1). A NGS inside the science field can be selected, improving somewhat the on-axis SAM performance. However, NGS must be located outside the laser beam footprint (1.4' diameter at 10 km). Other NGS configurations were studied in [4].

**SAM parameters.** The method of the PSF calculation is detailed in [5]. The degradation resulting from the nominal instrument errors (e.g. ripple on the optics) is included as per error budget [6]. On the other hand, the un-corrected PSFs do not include the contributions from the telescope ripple (this effect is small) or aberrations. The atmospheric model with the finite turbulence outer scale $L_0 = 25$ m is used, hence the uncorrected PSFs are better than the standard (infinite-scale) "seeing".

### 4 Results

The results for 4 selected wavelengths are presented in Figs. 4 and 3. The solid, dashed and dash-dotted lines correspond to the good, typical and bad conditions, respectively. The un-corrected seeing-limited PSFs are plotted at 2.5' from the center, so the "jump" of the curves is artificial.

For selected field points in the x-direction, the ellipticity changes sign: the PSF at the center is elongated vertically due to the residual atmospheric tilts, while at the field edge the elongation is radial, caused by the under-compensated high-order aberrations. However, in the direction of the guide stars these two effects are additive, and the ellipticity is always positive (Fig. 2).

![Figure 2: Ellipticity of the PSF at 700 nm for test points on the vertical (y) axis (in the direction of the NGS). The solid, dashed and dash-dotted lines correspond to the good, typical and bad conditions, respectively.](image-url)
Figure 3: Parameters of the SAM PSF at 400 nm (top) and 500 nm (bottom) wavelengths. The solid, dashed and dash-dotted lines correspond to the good, typical and bad conditions, respectively. The un-corrected seeing-limited performance metrics are plotted at 2.5′ offset.
Figure 4: Parameters of the SAM PSF at 700 nm (top) and at 1 μm (bottom) wavelengths across the field. The solid, dashed and dash-dotted lines correspond to the good, typical and bad conditions, respectively. The un-corrected seeing-limited performance metrics are plotted at 2.5′ offset.
5 Discussion

SAM brings a sizable gain in all performance metrics under all observing conditions and at all wavelengths. The gain is largest at longer wavelengths and at good conditions, where a FWHM resolution of 0.15" can be reached at 1 μm. Under good conditions (low turbulence in the upper atmosphere) the PSF uniformity is also good.

The gain in the magnitude limit of crowded-field photometry is a function of wavelength, increasing from 0.5″ in the blue to 1″ and more in the red.

References