SOAR AO system: simulation results

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1 Simulation tools and general conditions

Initial estimates of the SOAR AO performance were done with the modal covariance code, developed by the author and programmed in IDL. This analysis is based on second-order statistical formulas and ignores many aspects of real systems: WFS architecture and readout noise, time lag, etc. The goal of this study is to confirm the results with another, complementary simulation code based on Monte-Carlo emulation of an AO system. The code `simul.pro` was written by F.Rigaut (version of March 2001) and was recuperated from the Gemini web site `www.gemini.edu`.

Specific goal of this study is the choice of WFS concept between curvature and Shack-Hartmann (S-H). In SOAR AO project, achievement of the diffraction-limited resolution *in the visible* with the faintest natural guide stars is one of the primary goals. The behavior of these two WFSs at low light levels can be significantly different. First, S-H is usually associated with CCD detectors and, hence, with some readout noise (RON). What level of RON can be tolerated and to what extent is it critical for achieving faint GS magnitudes? Secondly, noise propagation properties of S-H and curvature WFSs are different: curvature systems produce more noise at low spatial frequencies (low-order modes like tip-tilt) which may destroy the coherence of compensated wavefronts at the scale of aperture, leading to an enlargement of the central peak in the compensated image. On the other hand, curvature systems are more effective at high spatial frequencies, and thus the compensated wavefronts can be more smooth, with a better coherence at short spatial scales and better concentration of energy in the compensated image.

Our atmospheric model corresponds to the median seeing conditions at Cerro Pachón: $r_0 = 0.15$ m at 500 nm. Imaging wavelength is fixed to 700 nm, or $D/r_0 = 18.9$ for telescope diameter $D = 4.25$ m. Vertical distribution of turbulence and its time constant are not changed with respect to the original Rigaut's code: 5 layers at altitudes of 0, 1.6, 3.6, 6.3, and 11.6 km above telescope, relative intensities 0.18, 0.28, 0.18, 0.19, 0.17, wind speeds 3, 10, 15, 25, 15 m/s. Only time constant is relevant here, because we do not study anisoplanatism.

Calculation of stellar flux assumes that the total number of photons per second detected by WFS from the whole telescope aperture is equal to $Fe^{-0.5m}$, where m is the R-magnitude of the GS, and F is the zero point. We take F= 1.36000e+11, assuming a total efficiency of 40% and spectral bandpass of 300 nm, as recommended in the Roddier book. The last assumption is probably optimistic, because we must share stellar photons between WFS and scientific channel. Real magnitude limits may thus be some 1 mag. brighter.

The command matrix used in the code is obtained by a simple SVD inversion of the interaction matrix. Better results would be achieved with optimized command matrix that automatically reduces compensation order for faint GSs while trying to minimize the residual phase variance. Optimization will improve limiting magnitudes, but it was not yet tried.

The code computes Strehl ratio (SR) for long-exposure compensated image after a certain number of loop iterations (we chose 150 iterations, the first 20 are skipped). Also, a short-exposure SR is computed as an average of instantaneous SRs. This second parameter is higher, being insensitive to residual image motion and also being enhanced by the speckle structure of the stellar image. We use the short-exposure SR only for comparison with "real" long-exposure SR.

2 Shack-Hartmann system

We suppose that the DM is capable of compensating 66 Zernike modes. This is an approximation to the yet-unspecified curvature DM. Using Noll formulas, theoretical residual phase would be 1.04 rad^2, or Strehl ratio (SR) of 0.35 (here and below all values are given for the imaging wavelength of 700 nm). If the efficiency of AO system (in the sense of Roddier) is not ideal, and instead of order 10 it compensates only up to the order 8 (45 modes), the expected residual would be 1.46 rad^2, SR=0.23. These estimates do not take into account WFS noise and time lag.

We assume a geometry of 10x10 square apertures across pupil diameter, or 72 useful apertures inside pupil. Several modes are rejected in the inversion of the interaction matrix. Our basic choice is a S-H with 2x2 pixels per sub-aperture working in a quad-cell mode. This is motivated by reduction of RON, and is the solution adopted in Keck and Gemini AO systems. We found that even with a short loop time of 1 ms and bright GS of 5 mag. (no influence of RON), the SR of only 0.15 could be achieved, and some residual motion of the compensated image was apparent. The reason must be related to the quadrant S-H mode which has an inherent noise related to the changing image structure at individual sub-apertures. When an artificial source blur was introduced, we obtained SR=0.20. Finally, with a S-H of 9x9 pixels per sub-aperture (pixel size 0.26$''$) we obtained SR=0.24. Increasing loop time to 2 ms leads to SR=0.17.

Our basic 2x2 pixel mode with 2 ms loop time gives thus sub-optimal performance for bright GSs. We still adopt these parameters for the study of limiting magnitudes. A curve of SR versus R-magnitude is given in Fig. 1 left.

3 Curvature system

For the curvature system, we adopted the DM geometry of a 79-actuator electrostatic DM from Okotech. We did not attempt any optimization of geometry at this stage and assumed that the pupil border is projected at the inner radius of the last ring of electrodes. Taking this radius as 1, the relative radii of the rings are 0.19, 0.40, 0.59, 0.79, 1.0, 1.26. Corresponding numbers of electrodes are 1, 7, 14, 21, 28, 8. Telescope central obscuration is 0.15. The WFS geometry is matched to the DM geometry.

The value of defocusing l (stroke of membrane mirror) is a critical parameter, to be adapted to stellar magnitude and seeing. In the simulation code, a beam f-ratio of F/D =1:60 is always assumed. The formula 5.12 of the minimum l from Roddier (1999) book is

$$l > \left(\frac{F}{D}\right)^2 \frac{D}{d} D\theta_B, \qquad (1)$$

where $d = 0.4$ m is sub-aperture diameter and $\theta_B = 0.5''$ is the beam blur. This leads to $l > 0.37$ m. We tried values of 0.15 (originally in the code example, adopted for PUEO), 0.2 and 0.3. All works for bright GSs, and with $l = 0.15$ we obtained SR=0.21 for a 5 mag. GS. On the other hand, with l this small the loop is not closed for a 13-mag star, whereas better results are obtained with $l = 0.2$. We adopted $l = 0.3$ for our simulations reported below.

There is no penalty in fast loop, because RON is zero for curvature systems. Loop time was set to 1 ms.

4 Comparison of the two systems

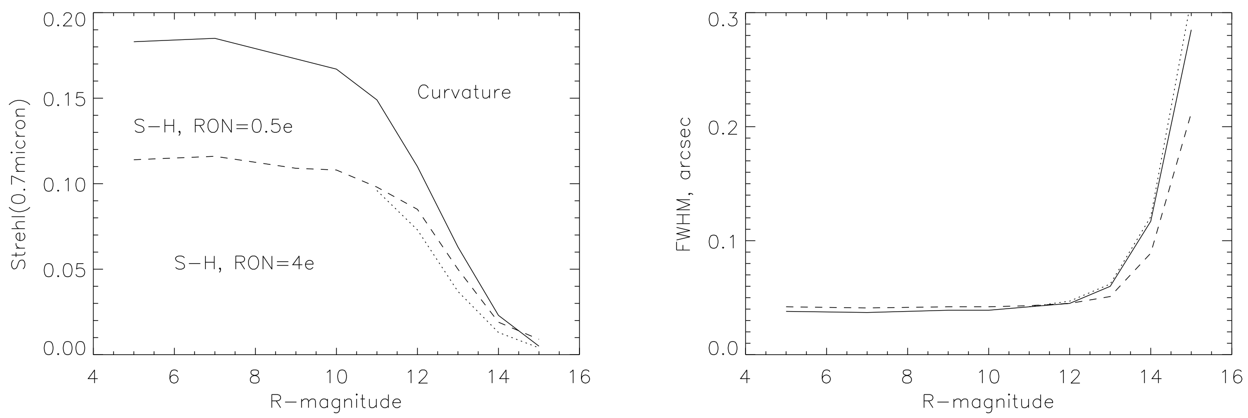

Figure 1: Strehl ratio (left) and FWHM (right) against guide star R-magnitude. Full line: curvature system, 1 ms loop. Dashed line: S-H system, 2 ms loop, 2x2 pixel/subap. WFS, RON=0.5e. Dotted: same, RON=4e.

Fig. 1 gives the comparison of the S-H and curvature systems. It is seen that the S-H system gives lower SR for bright stars. However, this is due to a longer loop time and additional noise in a 2x2 WFS, as explained above. If these two defects are corrected, we obtain SR=0.24 and FWHM of 35 mas - slightly better than for a curvature system.

As for the limiting magnitude, both systems show a very similar performance. Pending the optimization of the command matrix and of the S-H centroid computation (thresholding), it is difficult to name a winner. Considering that S-H is conceptually simple, will work with an extended pulsed source (LGS), is cheaper and easier to maintain, we tentatively select this WFS concept for further study.

Conclusions: 1. It seems reasonable to expect diffraction-limited resolution with a S-H WFS with 4e RON and a GS of R=12...13, even without optimization of the command matrix. 2. In order to reach the Strehl ratio limited by compensation order, we need a loop time of 1 ms and a S-H design with more than 2 pixels per sub-aperture.