

## CAOS Simulation Package 3.0: an IDL-based Tool for Adaptive Optics Systems Design and Simulations

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**Abstract.** The IDL-based simulation software Code for Adaptive Optics Systems (CAOS) was originally developed to simulate the behavior of generic adaptive optics systems. The modular structure of the software allows the simulation of a great variety of different systems and is particularly suited for the adoption of graphical techniques for the programming of applications. It is actually composed of a global user interface (the CAOS Application Builder – presented in Fini et al. 2001), and a set of specific modules: the CAOS Simulation Package. We present in this paper the last version (3.0) of the CAOS Simulation Package, together with an example of an application to the Large Binocular Telescope interferometer adaptive optics system.

### 1. Introduction

In the framework of the “Laser Guide Star for 8-m Class Telescopes” *Training and Mobility of Researchers* network funded by the European Union, an IDL-based software package has been developed to simulate generic adaptive optics (AO) systems. The structure of the software is modular. Each elementary physical process such as turbulence in atmospheric layers, propagation of light from source to observing telescope and through the turbulent layers, the wavefront sensor, is modeled in a specific module. The resulting software, called Code for Adaptive Optics Systems (CAOS), is composed of a global graphical user interface (GUI), the CAOS Application Builder (Fini et al. 2001), and a set of specific modules—the CAOS Simulation Package. A list of modules and brief descriptions are presented in Section 2. An example of an application to the Large Binocular Telescope (LBT) interferometer AO system is presented in Section 3. References to more information about CAOS are given in Section 4.

## 2. The Modules of CAOS Simulation Package 3.0

Table 1 shows a complete list, together with a very brief description, of the modules of CAOS Simulation Package 3.0.

Table 1. Descriptive list of the modules.

Module	Purpose
wavefront generation modules	
ATM - ATMosphere building	to simulate the turbulent atmosphere
SRC - SouRCe definition	to define the observed source
GPR - Geometrical PRopagation	to propagate the light
LGS-specific modules	
LAS - LASer generation	to define the projected laser beacon
NLS - Na-Layer Spot building	to simulate the 3D sodium LGS
wavefront correction modules	
TTM - Tip-Tilt Mirror	the tip-tilt correcting mirror
DMI - Deformable MIRROR	the deformable correcting mirror
wf sensing and reconstruction	
TCE - Tip-tilt CEntroiding	to reconstruct the tip-tilt
SHS - Shack-Hartmann Sensor	to simulate the Shack-Hartmann sensor spots formation
CEN - CENtroiding calculus	to compute the SH centroids
TFL - Time FiLtering	to emulate commands time-filtering
REC - REConstruction module	to reconstruct the wavefront
calibration-oriented modules	
CFB - Calibration FiBer	to define a calibration fiber
CSQ - Command SeQuencer	to generate calibration commands
MCA - Make CALibration data	to elaborate calibration data
other scientific modules	
IBC - Interf. Beam Combiner	to simulate co-phasing of two beams
IMG - IMager module	to simulate image formation
STF - STructure Function	to compute the structure function
WFA - WaveFront Adding	to linearly combine two wavefronts
BSP - Beam SPplitter	to emulate a beam-splitter device
utility modules	
PSG - Phase Screen Generation	to generate turbulent phase screens
DIS - data DISplay utility	to display any kind of input data
SAV - data SAVing utility	to save cubes of data (XDR format)
RST - data ReSTore utility	to restore XDR cubes of data

Using the CAOS Application Builder, a simulation can be built by connecting together the required occurrences of the desired modules, represented by the boxes of Figure 1. The only constraints are those imposed by input/output types. Each module comes with an individual GUI in order to set its own physical and numerical parameters, during the design step or independently at a

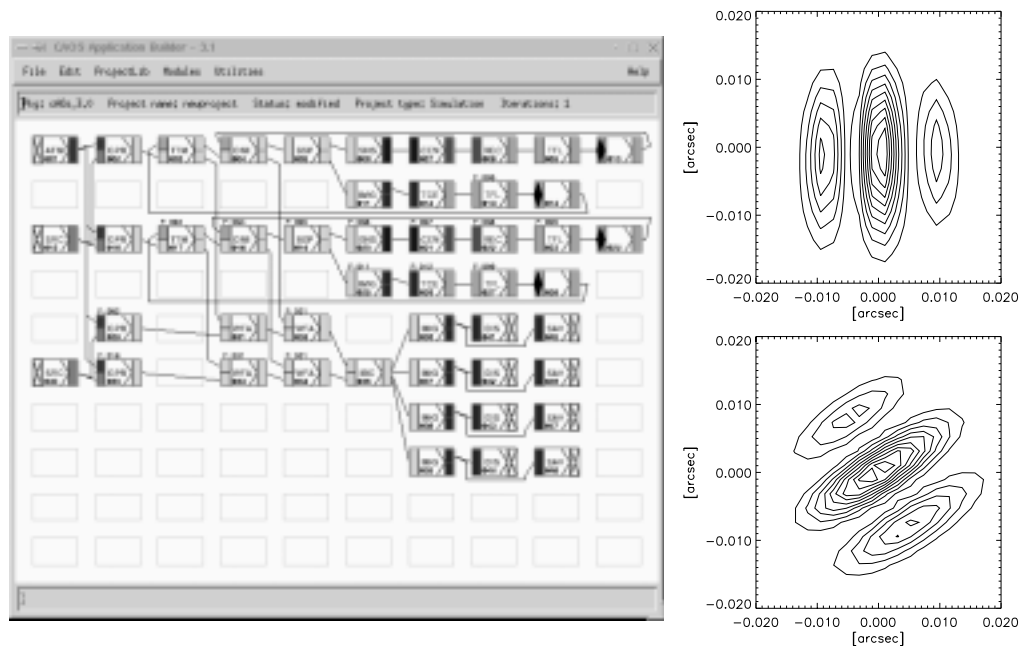


Figure 1. The CAOS worksheet corresponding to the LBT interferometer (left), together with the contour plots of two of the obtained PSFs: R-band,  $1''$  off-axis, parallactic angle of  $0^\circ$  (up), and  $120^\circ$  (down).

later time. The whole structure of a simulation can be saved as a “project” that can be restored for later modifications and/or parameters upgrading. The IDL code, corresponding to the designed simulation, is written down during the saving of a project, and it can be modified “by hand” in order to be completed with additional tasks not supported by the CAOS package.

### 3. An Example of an Application to the LBT Interferometer

Let’s assume that we would like to simulate high-angular-resolution observations in the red and near-infrared wavelength bands<sup>1</sup>, with the LBT interferometer<sup>2</sup> and with AO correction. Figure 1 (left) shows the whole project designed for such a purpose, with a natural guide star (NGS) of  $10^{th}$  magnitude for the AO sensing, either on-axis or  $1''$  off-axis with respect to the astronomical object. The turbulent atmosphere is modeled with two layers: a ground layer evolving along the baseline and weighted with 30% of the total turbulent energy, and an upper layer (at 10 km altitude) evolving orthogonally to the baseline and weighted with 70% of the total turbulent energy. For both layers the wind speed is 5 m/s. The total Fried parameter  $r_0$  is 20 cm (at 500 nm), and the wavefront outer-scale  $L_0$  is 40 m. Each pupil of the LBT interferometer has its

<sup>1</sup>namely R (700±110 nm), J (1250±150 nm), H (1650±175 nm), and K (2200±200 nm)

<sup>2</sup>2×8.25 m with a 14.4 m baseline

own AO system made of a tip-tilt (TT) correction loop, and a high-orders (HO) correction loop. The HO loop is made of: a  $34 \times 34$  Shack-Hartmann lenslet array with  $8 \times 8$  pixels/sub-aperture and  $0.15''$ /pixel for the sensing, a modal rejection of the Zernike modes over number 231 ( $20^{th}$  radial order) during the wavefront reconstruction, and a  $35 \times 35$  actuators deformable mirror (that corresponds to a projected inter-actuator distance of  $\sim 23.5$  cm on the primary mirror) for the correction. The TT loop contains a quad-cell detector (with  $0.25''$ /cell). Both sensings are performed in R, the light from the NGS being split 95% for the HO loop and 5% for the TT loop, assuming an overall efficiency of 60% and a read-out noise of  $3 e^{-rms}$ . The time-filtering acts in each loop as a pure integrator, and the differential piston is supposed to be perfectly corrected. The scientific CCD – on which the point-spread function (PSF) corresponding to the astronomical object is formed – make  $128 \times 128$  pixels images<sup>3</sup>. The total temporal history of each simulation run – one per value ( $0^\circ$ ,  $60^\circ$ , and  $120^\circ$ ) of the parallactic angle – is 2.075 s (corresponding to 415 iterations of 5 ms each), but the resulting interferometric PSFs (one per band (four) and per off-axis (two) considered) are integrated over the last 2 s for sake of AO stability. For each of the simulation run, a different realization of the turbulent atmosphere was considered (since each parallactic angle corresponds to a different period of the observing run). Figure 1 (right) shows two of the  $3 \times 4 \times 2$  obtained PSFs, while Table 2 synthesizes the quality of all the 24 AO-corrected interferometric PSFs obtained in terms of Strehl ratio.

Table 2. Strehl ratios obtained for each of the interferometric PSF.

$0''$	R	J	H	K	$1''$	R	J	H	K
$0^\circ$	.606	.851	.907	.946	$0^\circ$	.554	.827	.893	.938
$60^\circ$	.581	.836	.897	.939	$60^\circ$	.522	.809	.881	.929
$120^\circ$	.557	.816	.878	.921	$120^\circ$	.504	.791	.864	.912

#### 4. More Information...

For more information and references on the CAOS Simulation Package and the CAOS Application Builder, see <http://www.arcetri.astro.it/caos>. See also Correia et al. (2001) for a description of the CAOS-compatible simulation package AIRY (Astronomical Image Restoration in interferometry).

#### References

- Fini, L., Carbillet, M., Riccardi, A. 2001, this volume, 253  
 Correia, S., Carbillet, M., Fini, L., et al. 2001, this volume, 404

<sup>3</sup>with  $\sim 2.1$  mas/pixel in R,  $\sim 3.8$  mas/pixel in J,  $\sim 5.0$  mas/pixel in H, and  $\sim 6.7$  mas/pixel in K