The CAOS Problem-Solving Environment: tools for AO numerical modeling and post-AO deconvolution

Marcel Carbillet[a] and Andrea La Camera[b]

[a]Laboratoire Lagrange, Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Parc Valrose, 06100 Nice, France
[b]Dipartimento di Informatica, Bioingegneria, Robotica e Ingegneria dei Sistemi (DIBRIS), Università di Genova, Via Dodecaneso 35, 16145 Genova, Italy

ABSTRACT

The CAOS problem-solving environment (PSE) is an IDL-based tool developed for adaptive optics (AO) modeling and post-AO imaging. Two scientific packages enhance the CAOS PSE: the Software Package AIRY, a tool for deconvolution of post-AO images, and the eponymous Software Package CAOS, an end-to-end code for AO system simulations. In the first part of this paper we present the status and most recent developments concerning the whole CAOS PSE and its two presently developed scientific packages, while in the rest of the paper we provide two examples of application involving the Software Package AIRY: one tackling high-dynamic range images reconstruction, and the other one real data processing.

Keywords: Adaptive optics, modeling and numerical simulations, post-processing of AO data

1. THE CAOS PSE, THE SOFTWARE PACKAGE CAOS, AND THE SOFTWARE PACKAGE AIRY

Since its version 7.0, the **CAOS Problem Solving Environment (CAOS PSE)**[1–3] has a unique basic distribution containing its global user interface (the so-called CAOS Application Builder[4]), its library of routines, and a package Utilities containing utility modules (to display/save/read data). The scientific packages developed beside are presently the eponymous Software Package CAOS[5,6] and the Software Package AIRY.[7–9] An example of use of the global user interface of the CAOS PSE together with modules of the Software Package AIRY is shown in next section.

Within the global interface, the list of installed Software Packages is shown thanks to the pull-down menu Modules. From this list, and selecting one of installed package, its modules can be selected and placed into the so-called "worksheet" in order to compose a simulation project by combining together the modules and defining the corresponding data flow. As an example, the list of modules of package Utilities is shown in Fig. 1, while the Software Package CAOS and the Software Package AIRY are also shown as installed packages.

The IDL code implementing the simulation program is then automatically generated, at the end of the simulation project design step or at any moment, by pushing pull-down button File, and the whole structure of the simulation is saved as a project that can be restored for latter modifications and/or parameters upgrading. Last version of the CAOS PSE, 7.1, includes a number of debugging and enhancements of routines from the common library, the global user interface, and the display utility. Note that, together with their specific sets of example projects, the two scientific packages AIRY and CAOS are distributed separately.

The **Software Package CAOS** (Code for Adaptive Optics Systems) is dedicated to end-to-end AO simulations, and includes scientific modules for modeling optical turbulence, image formation, wavefront sensing (with both Shack-Hartman and pyramid wavefront sensors), wavefront reconstruction, loop control, wavefront correction, AO system calibration, laser guide stars (with upward/downward propagation and Sodium layer modeling), Fizeau interferometry, and coronagraphy. Wide-field AO is also developed, permitting ground-layer AO simulations and conjugation of deformable mirrors at different altitudes. The list of the modules of the Software Package CAOS is shown in Tab. 1.

Further author information:
M. C.: E-mail: marcel.carbillet@unice.fr
A. L. C.: E-mail: andrea.lacamera@unige.it

Table 1. The 31 modules of the `Software Package CAOS`, version 7.0.

| Module	Purpose
Optical turbulence & image formation	
`ATM - ATMosphere building`	-builds the turbulent atmosphere (FFT+subharmonics, Zernike)
	(see also utility PSG - Phase Screen Generation)
`SRC - SouRCe definition`	-characterizes the guide star/observed object
`GPR - Geometrical PRopagator`	-propagates light from source to telescope through atmosphere
`IMG - IMaGing device`	-forms an image of the observed object (+detector noises)
Wavefront sensing	
`PYR - PYRamid wavefront sensor`	-simulates the pyramid wavefront sensor
`SLO - SLOpe computation`	-computes the slopes from the pyramid signals
`SWS - Shack-Hartman Wavefront Sensor`	-simulates the Shack-Hartmann (SH) wavefront sensor
`BQC - Barycentre/Quad-cell Centroiding`	-compute the signals from the SH spots centroiding calculus
`IWS - Ideal Wavefront Sensing`	-applies "ideal" wavefront sensing (see text)
`TCE - Tip-tilt CEntroiding`	-computes and reconstructs tip-tilt
Wavefront reconstruction, control & correction	
`REC - wavefront REConstruction`	-reconstructs the wavefront
`TFL - Time-FiLtering`	-applies time-filtering after wavefront reconstruction
`SSC - State-Space Control`	-applies state-space control
`DMI - Deformable MIrror`	-simulates the behavior of a deformable mirror (DM)
`TTM - Tip-Tilt Mirror`	-simulates the behavior of a tip-tilt mirror
Calibration	
`CFB - Calibration FiBer characterization`	-defines a fiber to be used for calibration purpose
`MDS - Mirror Deformation Sequencer`	-generates a sequence of DM modes or influence functions
`SCD - Save Calibration Data`	-saves the calibration data (interaction matrix+set of deformates)
Wide-field AO	
`AVE - signals AVEraging`	-averages measurements from various wavefront sensors
`COM - COMbine measurements`	-combines measurements from various wavefront sensors
`DMC - Deformable Mirror Conjugated`	-corrects at different conjugated altitudes
Other modelling modules	
`LAS - LASer characterization`	-defines laser projector characteristics
`NLS - Na-Layer Spot definition`	-characterizes the Sodium-layer behavior
`IBC - Interferometric Beam Combiner`	-combines the light from two apertures
`COR - CORonagraphic module`	-simulates various coronagraphs (Lyot, Roddier&Roddier, FQPM)
`AIC - Achromatic Interfero-Coronagraph`	-simulates the Achromatic Interfero-Coronagraph
`BSP - Beam SPlitter`	-splits the light beam
Other utility modules	
`WFA - WaveFront Adding`	-adds or combines together wavefronts
`ATA - ATmosphere Adding`	-adds or combines together atmospheres
`IMA - IMage Adding`	-adds or combines together images
`STF - STructure Function`	-calculates the structure function and compares to theory
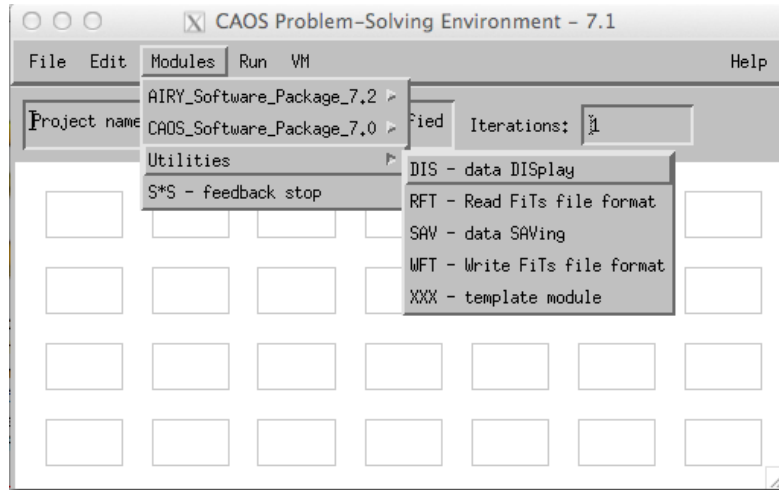
Figure 1. The global user interface of the `CAOS PSE`, within which the pull-down menu `Modules` shows the installed packages. In particular, the lists of modules of the utility package `Utilities` is shown.

The **Software Package AIRY** (Astronomical Image Restoration with or without interferometrY) now reached version 7.2, and is a complete tool for simulation and deconvolution of astronomical data (either a post-AO image from a single-dish telescope or multiple images from a Fizeau interferometer). The list of the modules of the `Software Package AIRY` is shown in Tab. 2.

Table 2. The 11 modules of `AIRY` version 7.2, divided in three subsets, depending on the goal of each module.

Module	Purpose
Simulation	
OBJ – OBJect definition	-defines the astronomical object to be convolved
CNV – CoNVolution	-convolves object and psf
ADN – ADd Noise	-adds noise perturbation to the image
Deconvolution	
PRE – PREprocessing data	-defines the background and other preprocessing data
DEC – DEConvolution	-standard module for deconvolution
MCD – Multi-Component Deconvolution	-special algorithm for the deconvolution of HDR images
CBD – Constrained Blind Deconvolution	-for blind reconstruction, if the psf is not known
PEX – Psf extraction and EXtrapolation	-extracts the psf from an image
RTI – RoTate Image	-utility module, for (de)rotation of images
Data Analysis	
ANB – ANalysis Binary	-analyses reconstructed image
FSM – Find Stars Module	-analyses reconstructed image

The `Software Package AIRY` implements several methods for reconstructing images considering Gaussian or Poisson statistics: Richardson-Lucy (RL), Ordered-Subset Expectation Maximisation (OSEM), and the Scaled Gradient Projection (SGP) method,[10] with a number of regularization capabilities and a multi-component (MC) deconvolution module.[9] Remarkable features of `AIRY` include also a super-resolution method,[11,12] Strehl-constrained blind deconvolution,[13,14] and high dynamic range (HDR) capabilities.[15–17]

An example of application of these HDR capabilities of the `Software Package AIRY` is detailed in next section, while an example of application on real SPHERE/VLT data of a Wolf-Rayet star in the near-infrared domain is shown in Section 3, using the SGP method with an edge-preserving regularization. Finally, foreseen developments of the whole tool are described in Section 4.
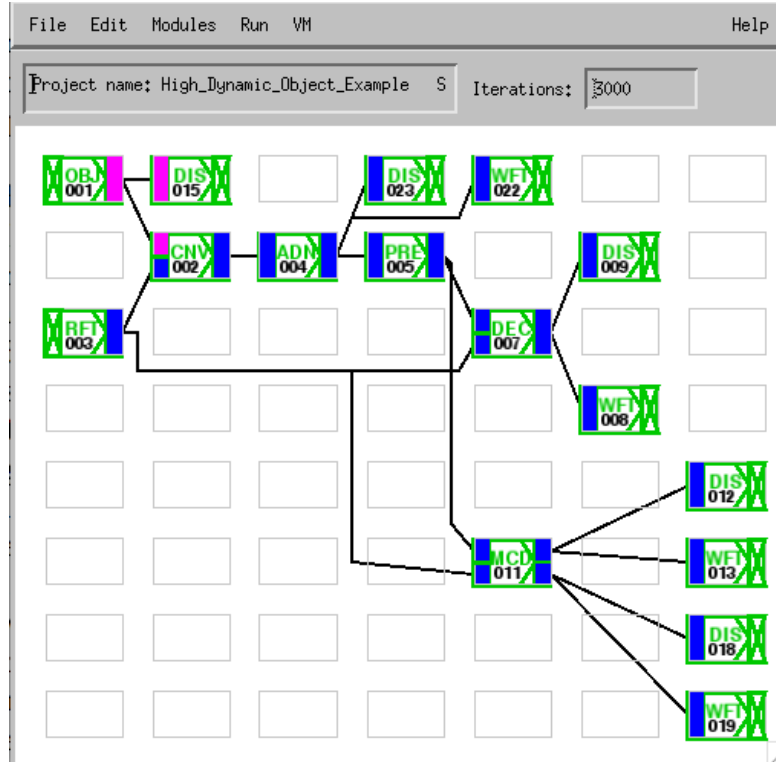
Figure 2. The `AIRY` project as represented within the `CAOS PSE` global interface.

2. DECONVOLUTION OF HIGH-DYNAMIC RANGE IMAGES WITH AIRY

In this example* we show two different approaches to the problem of deconvolution of high dynamic range images. The first one, already present in the previous versions of this example project, is based on a regularization version of the OSEM algorithm called HDR and introduced by Anconelli *et al.* in 2006.[18] The new one is the multi-component method based on the Split Gradient Projection[10] algorithm (in short MC-SGP), available in `AIRY` since version 7.0 thanks to module `MCD` (which stands for Multi-Component Deconvolution). The method was recently described by La Camera *et al.*[9,16] We recall here that MC-SGP is able to reconstruct separately the unknown object assuming that it is composed of two parts: a point-like part and a diffuse part. An astronomical object made of (bright or very-bright) star(s) surrounded by a diffuse nebula is a perfect example of the input image that `MCD` is able to reconstruct.

The input object, the point-spread functions (PSFs) and all the parameters used in this simulation and all the parameters of the HDR regularization are described by Anconelli *et al.*[18] In Fig. 2 the example project is shown within the `CAOS PSE` global interface. In Fig. 3 we show the three PSFs and the corresponding images, while in the first panel of Fig. 4 the original object (also known as *ground truth*) is shown.

Considering the multi-component method, the MCD module needs two parameters for the regularization function, and one supplementary image, the so-called *mask*, which contains information about the positions of the point-like components. The first parameter (δ) can be estimated by computing the mean value of the modulus of the gradient on the blurred and noisy image ($\bar{\delta}$). Since the regularization is applied only to the diffuse part (fainter, in general) we consider one order of magnitude less than the value of $\bar{\delta}$: we hence assume here $\delta = 5 \times 10^4$. The second parameter is the regularization parameter β that can be chosen in the range of $0.1 \div 0.001$, even if larger or smaller values sometimes must be assumed. In this case we choose $\beta = 0.03$. The input mask is given by assuming that the positions of the two stars are perfectly known. In real cases this information can be obtained with a first deconvolution of the image which provides a "sharp" version of the object and permits to identify the centroids of the stars with good precision. We point out that we define a broader region (3×3 instead of the single pixel of the true object) in order to leave to the algorithm the possibility of reconstructing the centroid of each star in any position around the central pixel.

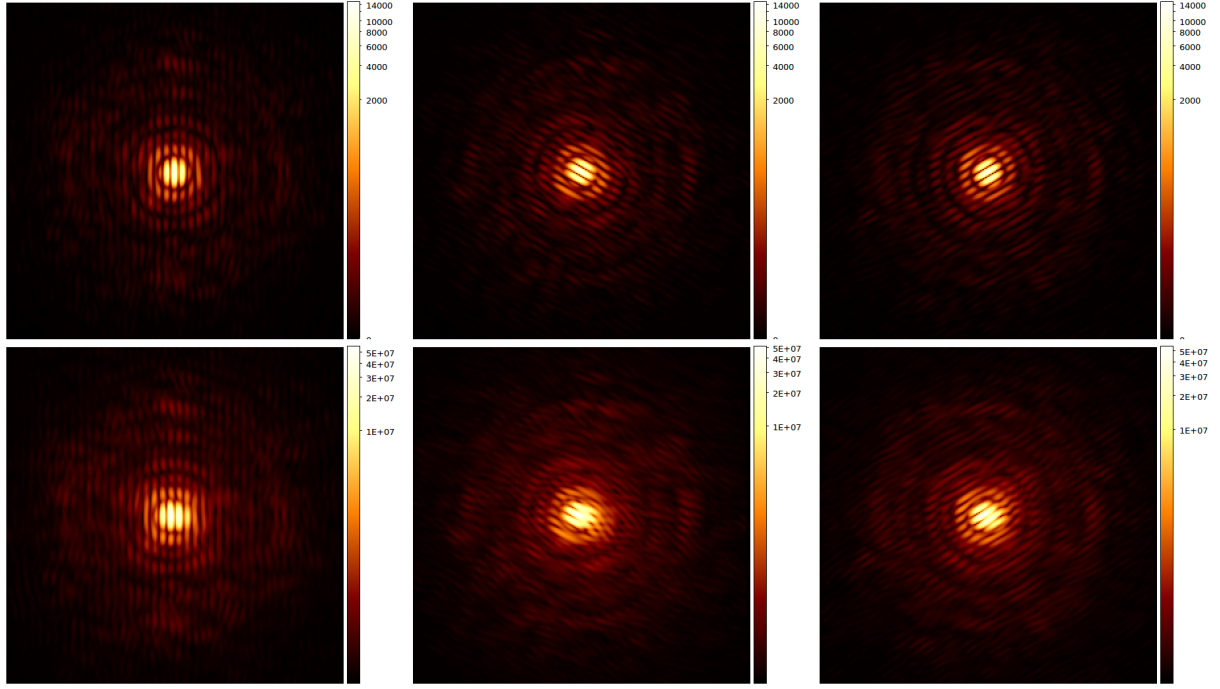*The example project here described is distributed together with the `Software Package AIRY`.

Figure 3. Top panels: the three PSFs of the Fizeau interferometer considered in the simulation. Bottom panels: the corresponding blurred and noisy images. All images are shown in logarithmic scale.
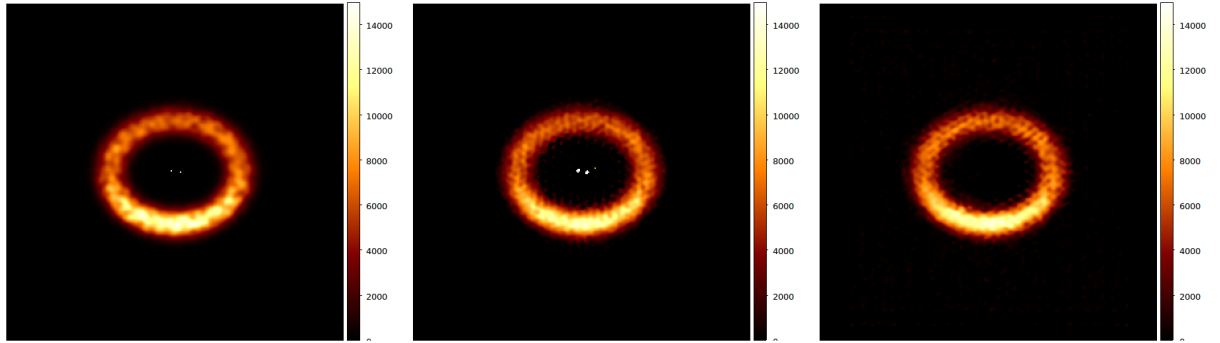

Figure 4. Left panel: the *ground truth* object made of two bright stars (here saturated) and a circumstellar ring. Middle panel: the reconstruction obtained by the OSEM method with the HDR regularization. Right panel: the diffuse component of the reconstruction obtained by the MC-SGP method. The point-like part is not shown. All images are shown in linear scale.

The total number of iterations is fixed to 5000 for both the methods and it is set up on the worksheet of the CAOS PSE. In Fig. 4 we show the object and the two reconstructions obtained by using the two different methods.

We evaluate the quality of the reconstructed objects thanks to two different figures of merit. For the two stars, we compute the reconstructed flux in a 3×3 pixel region, we call it F_n ($n = 1, 2$) and we divide this flux by the true flux F_n^* of each star. Concerning the diffuse part of the object we compute the so-called *restoration error*, defined as

$$\rho(k) = \frac{||f(k) - f||}{||f||}$$

where $f(k)$ is the reconstructed object at $k - th$ iteration, f is the original object and $|| \cdot ||$ is the euclidean norm. In the case of HDR reconstruction, we masked the two stars by setting to zero the 3×3 region around each star; while in the MCD reconstruction, as said above, we have the diffuse part separately reconstructed and this operation is not necessary.
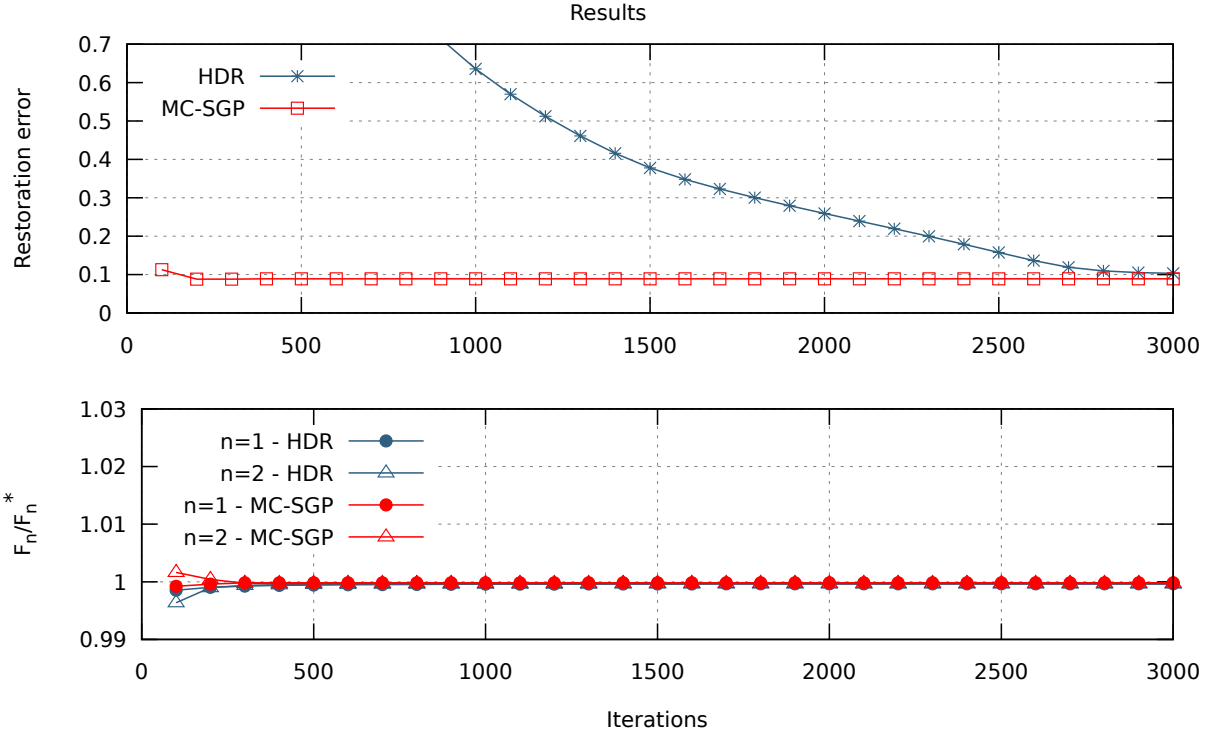
Figure 5. Top panel: the restoration error of the two reconstructions (see text). Bottom panel: the error of the fluxes as functions of the number of iterations.

Figure 5 shows the two errors as functions of the number of iterations. Concerning the first plot (top panel), we can see a different velocity in terms of convergence: as it is well-known, SGP (and therefore MC-SGP) is a faster algorithm with respect to OSEM. Moreover, the reconstruction provided by the MCD module has a smaller error (about 8.9% with respect to 10.3% of the other method). The stars are reconstructed with excellent precision (the errors on the fluxes are smaller than 1%), and the two algorithms go rapidly here to convergence.

3. DECONVOLUTION OF REAL DATA: WR 104 AS SEEN BY SPHERE/VLT

A preliminary deconvolution using SGP together with an edge-preserving regularization of real data of the Wolf-Rayet star WR 104 taken in the near-infrared domain with the help of the instrument IRDIS of the planet-finder SPHERE equipping the VLT (data courtesy of A. Soulain *et al.*) is briefly presented here. Also thanks that SPHERE permits rather high Strehl ratios, which is the case for the K-band data presented in Fig. 6 (left panel for the image, middle panel for the associated PSF), the reconstruction performed very clearly reveals the spirale shape of the observed object (see right panel).

With the pipeline-reduced data used here, we attempt a preliminary reconstruction involving the SGP deconvolution method together with an edge-reserving regularization. As shown in Fig. 6, the result is very convincing, clearly revealing the spirale shape of the circumstellar environment of WR 104. More refined reconstructions for various wavelength bands and analysis details will be given in a forthcoming paper currently under preparation.[19]

4. CURRENT APPLICATIONS AND FURTHER DEVELOPMENTS

Concerning the `Software Package CAOS`, it will next include (for its version 7.1) an updated simple embedment of the semi-analytic AO code `PAOLA`.[20] New modules for wide-field AO modeling will hopefully be finalized, in order to permit to consider multiple sources and multiple sensors within single modules, and hence an easier modeling of GLAO systems, as well as layer-oriented and star-oriented multi-conjugate AO systems. For its part, the `Software`
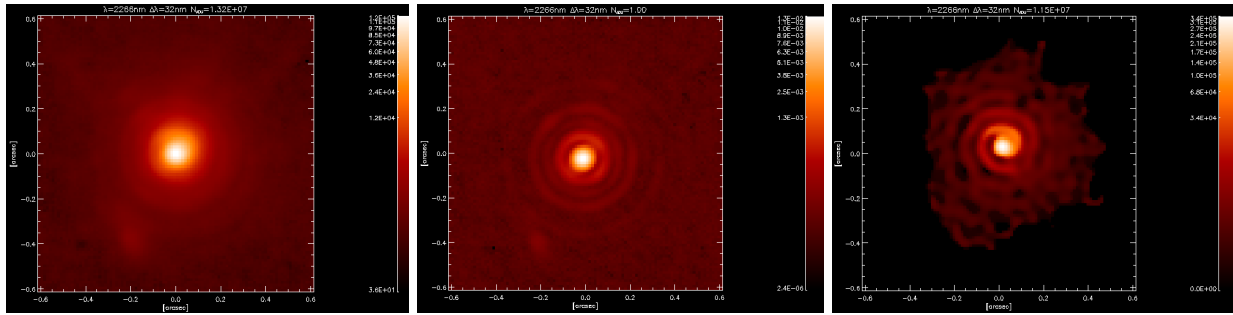
Figure 6. Left panel: observed object (K band). Middle panel: associated PSF. Right panel: reconstruction with SGP and an edge-preserving regularization (data: courtesy A. Soulain *et al.*, more details to be given in a forthcoming paper[19]).

`Package AIRY` is being used in a number of astrophysical applications involving post-AO images obtained from various instruments (NACO/VLT, SPHERE/VLT, LMIRcam/LBTI, NIRC2/Keck-II).

> Freely download the `CAOS PSE`, together with the `Software Package CAOS` and/or the `Software Package AIRY` from http://lagrange.oca.eu/caos .

REFERENCES

[1] Carbillet, M., Vérinaud, C., Guarracino, M., Fini, L., Lardière, O., Roux, B. L., Puglisi, A. T., Femenía, B., Anconelli, A. R. B., Bertero, M., and Boccacci, P., "CAOS – a numerical simulation tool for astronomical adaptive optics (and beyond)," in [*Advancements in Adaptive Optics*], Bonaccini, D., Ellerbroek, B., and Ragazzoni, R., eds., *Proc. SPIE* **5490 (2)**, 550 (2004).

[2] Carbillet, M., Desiderà, G., Augier, E., La Camera, A., Riccardi, A., Boccaletti, A., Jolissaint, L., and Kadir, D. A., "The CAOS problem-solving environment: recent developments," in [*Adaptive Optics Systems II*], Ellerbroek, B., Hart, M., Hubin, N., and Wizinowich, P. L., eds., *Proc. SPIE* **7736**, 773644 (2010).

[3] "The `CAOS PSE` website." http://lagrange.oca.eu/caos. (last visited: October 12, 2017).

[4] Fini, L., Carbillet, M., and Riccardi, A., "The CAOS Application Builder," *Astronomical Data Analysis Software and Systems X* **238**, 253 (2001).

[5] Carbillet, M., Vérinaud, C., Femenía, B., Riccardi, A., and Fini, L., "Modelling astronomical adaptive optics - I. The software package CAOS," *Monthly Notices of the Royal Astronomical Society* **356**(4), 1263–1275 (2005).

[6] Carbillet, M., La Camera, A., and et al., "The Software Package CAOS 7.0: enhanced modelling of astronomical adaptive optics systems," in [*Adaptive Optics Systems V*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9909**, 9909–319 (2016).

[7] Correia, S., Carbillet, M., Boccacci, P., Bertero, M., and Fini, L., "Restoration of interferometric images: I. the software package AIRY," *Astron. Astrophys.* **387**, 733–743 (2002).

[8] "The AIRY project website." http://www.airyproject.eu. (last visited: October 12, 2017).

[9] La Camera, A., Carbillet, M., Prato, M., Boccacci, P., and Bertero, M., "The software package AIRY 7.0: new efficient deconvolution methods for post-adaptive optics data," 99097T, International Society for Optics and Photonics (jul 2016).

[10] Bonettini, S., Zanella, R., and Zanni, L., "A scaled gradient projection method for constrained image deblurring," *Inverse Probl.* **25**(1), 015002 (2009).

[11] Anconelli, B., Bertero, M., Boccacci, P., and Carbillet, M., "Restoration of interferometric images. IV. An algorithm for super-resolution of stellar systems," *Astron. Astroph.* **431**, 747–755 (2005).

[12] Carbillet, M., La Camera, A., Chesneau, O., Millour, F., Girard, J., and Prato, M., "Deconvolution-based super resolution for post-AO data," in [*Proceedings of the Third AO4ELT Conference. Firenze*], 104 (2013).

[13] Desiderà, G. and Carbillet, M., "Strehl-constrained iterative blind deconvolution for post-adaptive-optics data," *Astron. Astrophys.* **507**(3), 1759–1762 (2009).

[14] Carbillet, M., La Camera, A., Deguignet, J., Prato, M., Bertero, M., Aristidi, E., and Boccacci, P., "Strehl-constrained reconstruction of post-adaptive optics data and the Software Package AIRY, v. 6.1," in [*Adaptive Optics Systems IV*], Marchetti, E., Close, L. M., and Véran, J.-P., eds., *Proc. SPIE* **9148**, 91484U (2014).

[15] La Camera, A., Antonucci, S., Bertero, M., Boccacci, P., Lorenzetti, D., and Nisini, B., "Image reconstruction for observations with a high dynamic range: LINC-NIRVANA simulations of a stellar jet," in [*Optical and Infrared Interferometry III*], Delplancke, F., Rajagopal, F. J. K., and Malbet, F., eds., *Proc. SPIE* **8455**, 84553D (2012).

[16] La Camera, A., Antoniucci, S., Bertero, M., Boccacci, P., Lorenzetti, D., Nisini, B., and Arcidiacono, C., "Reconstruction of high dynamic range images: Simulations of lbt observations of a stellar jet, a pathfinder study for future ao-assisted giant telescopes," *Publications of the Astronomical Society of the Pacific* **126**(936), pp. 180–193 (2014).

[17] Antoniucci, S., La Camera, A., Nisini, B., Giannini, T., Lorenzetti, D., Paris, D., and Sani, E., "The HH34 outflow as seen in [Fe II] 1.64 μm by LBT-LUCI," *Astron. Astrophys.* **566**, A129 (jun 2014).

[18] Anconelli, B., Bertero, M., Boccacci, P., Desiderà, G., Carbillet, M., and Lantéri, H., "Deconvolution of multiple images with high dynamic range and an application to LBT LINC-NIRVANA," *Astron. Astrophys.* **460**(1), 349–355 (2006).

[19] Soulain, A. *et al. in preparation* (2017).

[20] Jolissaint, L., "Synthetic modeling of astronomical closed loop adaptive optics," *J. of the European Opt. Soc. - Rapid Pub.* **5**, 10055–10070 (2010).