Adaptive Optics Simulations for Imaging with the Large Binocular Telescope Interferometer: a First Application

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ABSTRACT

In this contribution we present a first application of the ongoing numerical simulations that are carried out in order to study the adaptive optics (AO) correction and the subsequent imaging post-processing when observing with the Large Binocular Telescope (LBT) interferometer. The simulation tool used as a starting point for this study is the software package CAOS 2.0 (Code for Adaptive Optics Systems, version 2.0), for its AO-simulation capabilities and its modular structure. It is used here in order to generate the turbulence-corrupted and subsequently adaptive-optics-corrected interferometric point-spread functions corresponding to the simultaneous observation of both a scientific object and a reference star, for three parallactic angles corresponding to three observation runs during the night. The obtained data are therefore used as the inputs of a multiple deconvolution method planned for imaging with the LBT interferometer. As an example, we have simulated the observation, in the R-band, of a Betelgeuse-like stellar object of 15th magnitude, 30mas diameter, and with a 3 mas bright spot, under two different conditions of turbulence and AO-correction (leading to Strehl ratios of \(\sim 0.15\) and \(\sim 0.45\), respectively). Final results are found to be very encouraging.

Keywords: Large Binocular Telescope, adaptive optics, interferometry, high-angular resolution imaging

1. INTRODUCTION

The Large Binocular Telescope (LBT) will consist of two 8.4 m primary mirrors on a common altitude-azimuth mount, with a total baseline of 22.8 m (14.4 m center-to-center).\(^1\)-\(^3\) It has been designed for optical/infrared interferometry that combines high sensitivity and high resolution. The LBT will be fitted out with an advanced adaptive optics (AO) system based, among other new techniques, on adaptive secondary mirrors. These correcting mirrors will have 918 actuators\(^4\) and Shack-Hartmann sensors will be used for the wavefront sensing. This AO system will be used to recover deep, long exposure diffraction-limited images. The behavior of the resulting interferometric point-spread function (PSF), that will be obtained after the AO correction made on the two adaptive secondary mirrors and the recombination of the beams, is a crucial point to study when implementing interferometric imaging techniques for the LBT.\(^5\)-\(^7\)

As a first application, we chose to simulate the observation of a 15th magnitude 30mas Betelgeuse-like stellar object, with AO-sensing and correction in the R-band by means of a natural guide star (NGS) off-axis from the scientific target, two conditions of turbulence and reconstruction (Fried parameter \(r_0 = 25.2\) cm and wavefront reconstruction of 105 Zernike orders for the first simulation series, \(r_0 = 30\) cm and wavefront reconstruction of 231 Zernike orders for the second simulation series), and eventually application of a multiple Lucy-Richardson-based deconvolution algorithm called ML-EM (maximum likelihood-expectation maximisation) as an attempt to retrieve the full high-angular resolution image.

CAOS2.0 (Code for Adaptive Optics Systems, version 2.0) is the simulator used in order to simulate the atmospheric turbulence corruption and subsequent adaptive correction made on the wavefronts coming from the astronomical objects onto both pupils of the LBT. CAOS 2.0 is a general AO software and is developed as one of the tasks of the Training and Mobility of Researchers (TMR) program “Laser Guide Star for 8m Class Telescopes”, funded by the European Union (EU). The software package is fully written in IDL and based on a library of functions that allows to accurately simulate an astronomical system with AO and possibly laser guide star (LGS) facility.

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The ML–EM method is used to perform aperture synthesis imaging. It is studied to allow the restoration of a full angular resolution image from several LBT interferograms. It actually does a simultaneous deconvolution of a set of frames per parallactic angle, and yields the common maximum-likelihood estimate from the full data set.\(^8\)\(^9\)

The paper is organized as follow. The main features of the simulation package CAOS 2.0 are reminded in Sect. 2. The simulations performed for imaging with the LBT are detailed in Sect. 3, where the interferometric PSFs obtained are presented and analyzed. The results of the multiple deconvolution process applied to the Betelgeuse-like object are briefly described in Sect. 4. Finally, a conclusion and prospects about this ongoing work are given in Sect. 5.

2. CAOS 2.0

CAOS 2.0 is a software package with a modular structure which results in a set of specific modules where each module represents an elementary physical process (e.g. the evolution of the turbulent atmosphere, the propagation of the light from a source to the observing telescope and through the turbulent layers of the atmosphere, or a piece of hardware like a deformable mirror). This implies that CAOS 2.0 is more likely a code that makes possible to simulate a wide variety of configurations that an optimized code for a given configuration of the simulated system.

The software package is provided with an application builder (AB) that allows to build any simulation project as an ensemble of occurrences of modules logically linked together. Each module is in practice defined by a standard group of function calls, a collection of parameters, and a typed definition of input(s) and output(s). It can support up to two inputs and up to two outputs, and it is represented within the AB as a rectangular box with colored input handles (on its left side), and output ones (on its right side). Each color describes one of the pre-defined type of input/output: wavefront, image, commands, etc. CAOS 2.0 also contains a library of utilities, as well as an on-line help and a set of examples.

A global description of the first version of the software (called LA³OS\(^2\) – Laser-Aided Astronomical Adaptive Optics Systems Simulator) was already presented.\(^10\) In the present section we will only remind its essential features and briefly underline the main new ones.

2.1. From LA³OS\(^2\) to CAOS 2.0

While the previous version of the software performed an automatic calibration step, the present one treats the calibration of a given module (e.g. the high-orders wavefront reconstruction module) as a separate and independent simulation project. This allows more flexibility and precision when designing a given system, and results in a dramatic simplification of the whole software structure. The calibration data obtained within a calibration project are then read by the concerned module within the main simulation project.

The second main new feature is that the correcting mirrors (e.g. the deformable mirror module or the tip-tilt mirror module) do not need to be artificially duplicated when performing simultaneous observations of more sources (e.g. a guide star and a scientific object). This feature yields to a considerable gain in memory usage, computational time, and clarity of the simulation projects designed within the AB. This is done by simply outputting both the corrected wavefront (i.e. the sum of the perturbed wavefront from the guide star and the correcting mirror shape resulting from the sensing and reconstruction process), and the correcting mirror shape itself, that can be so used to correct the wavefronts coming from other sources than the concerned guide star.

2.2. Simulation Capabilities of CAOS 2.0

Table 1 shows a complete list, together with a very brief description, of the modules present in the modules library of CAOS 2.0. A short and simplified list of the most relevant physical parameters corresponding to each module is also given.

Taking advantage from the AB of CAOS 2.0, a simulation can be built by putting and connecting together the required occurrences of the desired modules. During this step, or independently in a later moment, the physical and numerical parameters of each module present in the simulation project can be set by clicking on the module box and then complete the widget fields of the module graphical user interface. After this simulation design step is completed, the block diagram is analyzed by the AB and the IDL code implementing the simulation program is generated. The whole structure of the simulation can be saved as a project that can be restored for later modifications and/or parameters upgrading. Beside the main simulation project one or more calibration project(s) might be necessarily designed and ran.
<table>
<thead>
<tr>
<th>Module</th>
<th>Purpose (and main physical parameters)</th>
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| wavefront generation modules               | - to simulate the turbulent layers of the atmosphere  
| ATM -- ATMsphere building                   | ($C_n^2$, outer scale, winds velocities, layers’ altitudes)                                            |
| SRC -- SouRCe definition                   | - to define the observed object characteristics  
|                                            | (point-like/2D object, natural object/LGS, magnitude)                                                   |
| GPR -- Geometrical PRopagation             | - to propagate light geometrically (pupil diameter, position)                                           |
| LGS-specific modules                       |                                                                                                                                                          |
| LAS -- LAser generation                    | - to define the laser used for LGS creation (power, beam shape, pointing direction, focusing distance) |
| NLS -- Na-Layer Spot building              | - to simulate the 3D LGS formation within the sodium layer (vertical profile, width, altitude)        |
| wavefront correction modules               |                                                                                                                                                          |
| TTM -- Tip-Tilt Mirror                     | - to simulate the tip-tilt correcting mirror behavior                                                 |
| DMI -- Deformable Mirror                   | - to simulate the deformable mirror behavior (actuators distribution, maximal stroke)              |
| wavefront sensing, reconstruction, and filtering modules | - to compute the tip-tilt centroid and generate the ad hoc commands for subsequent correction  
| TCE -- Tip-tilt CEntroiding                | - to compute the Shack-Hartmann centroids                                                             |
| CEN -- CEntroiding calculus                | - to simulate the Shack-Hartmann sensor spots creation (sensor geometry, spectral sensitivity, integration time, delay time, noises) |
| SHS -- Shack-Hartmann Sensor               |                                                                                                       |
| TFL -- Time Filtering                      | - to emulate time-filtering of the commands                                                           |
| REC -- REConstruction module               | - to reconstruct the wavefront and generate the ad hoc commands for subsequent correction (type of reconstructor, possible modal rejection) |
| calibration-oriented modules               | - to define the output wavefront characteristics of a (calibration) fiber (number of photons/s/m², FWHM) |
| CFB -- Calibration FiBer                   | - to generate a sequence of commands for correcting mirrors                                           |
| CSQ -- Command SeQuencer                   | - to elaborate and save the needed calibration data                                                   |
| MCA -- Make Calibratlon data               |                                                                                                                                                          |
| other scientific modules                   | - to simulate the beams co-phasing from two pupils                                                   |
| IBC -- Interferometric Beam Combiner       | - to simulate image formation from the input wavefront and object (pixels Ω-ν, spectral sensitivity, integration time, delay time, noises) |
| IMG -- IMager module                       | - to compute the structure function from wavefronts                                                  |
| STF -- STructure Function calculus         | - to linearly combine two wavefronts (e.g. a corrupted one and the correcting shape of a deformable mirror)    |
| WFA -- WaveFront Adding                    | - to emulate a beam-splitter device                                                                  |
| BSP -- Beam SPLitter                       |                                                                                                                                                          |
| utility modules                            | - to generate turbulent phase screens (suitable for ATM)                                              |
| PSG -- Phase Screen Generation             | - to display any kind of input data                                                                  |
| DIS -- data DISplay utility                | - to save cubes of data in XDR format                                                                |
| SAV -- data SAVing utility                 | - to restore cubes of data saved using the module SAV                                                 |
| RST -- data ReStOre utility                |                                                                                                                                                          |
Figure 1. The LBT interferometric AO-corrected PSF simulation projects as they appear using the AB of CAOS 2.0. The main window contains the actual simulation project (labelled lbt_simul), while the two smaller ones contain the tip-tilt calibration project (labelled tt_calib) and the high-orders-reconstruction calibration project (labelled lbt_calib).
3. LBT INTERFEROMETRIC AO-CORRECTED PSF COMPUTATION

Our goal is to simulate high-resolution observations with the LBT interferometer and with AO correction, in order to use them for further testing of restoration methods. We chose for this purpose to simulate the data corresponding to the observation of a 15th magnitude stellar object in the r-band ($\lambda = 700$nm, $\Delta \lambda = 220$nm), together with the data corresponding to a brighter point-like reference star to be used during the deconvolution process.

For sake of simplicity, we consider a unique off-axis star as our NGS for both tip-tilt and high-orders sensing, and as our imaging reference star. This unresolved object is so chosen to be a 9.25-magnitude star 0.3 arcsec away from the scientific target. Considering the light to be splitted such as half goes to the AO loops and half to the scientific camera, this becomes equivalent to consider in one hand a tenth magnitude off-axis NGS and in the other hand a tenth magnitude off-axis reference star.

As data from the scientific object we chose to compute both short exposure and long exposure interferometric PSFs, as well as the long exposure images (i.e. the interferograms), in order to be able to use the PSFs for Strehl ratio computation and easier analysis of the AO-correction quality, and the interferograms as the useful data for the deconvolution tests.

3.1. Simulation Design

Figure 1 shows the three simulation projects that are necessary for this work. They show together the whole set of modules used, and the corresponding data flows defined by the links between the modules.

Let’s first describe the main simulation project (labelled lbt_sim1). The upper part simulates the propagating of the light from the NGS/reference star (defined within module SRC number 037), through the turbulent atmosphere (module ATM), and to the two pupils of the LBT interferometer. The two propagation paths are performed by means of the geometrical propagator (module GPR), followed by the adaptive correction loops. Let’s follow the upper path (let’s say the west pupil of the LBT). The two correcting mirror modules (tip-tilt mirror TTM and deformable mirror DMI) pass the corrected wavefront to a sequence of two beam-splitters (BSF). The first one distributes the light between the scientific camera and the AO-loops while the second one distributes it again between the tip-tilt loop and the high-orders loop. The tip-tilt loop is made of an imager module IMG emulating the tip-tilt sensor, a tip-tilt centroiding TCE module, and a time-filtering of the commands (module TFL). The loop is then closed by a dedicated module (numbered 010), to TTM. The high-orders loop is defined by the sequence of a Shack-Hartmann module SHS, a centroiding module CEN, a reconstructor module REC, and a TFL module, before to be closed to DMI. The same scheme is repeated for the east pupil of the LBT. Note that the second output of both types of correcting mirrors (the bottom output) is the correcting shape of the mirror. After the AO-correction step of both telescopes, the two resulting wavefronts are sent to the module IBC (number 030) in order to be co-phased. The output of this operation is then sent to a module IMG that computes the final interferometric PSF corresponding to the reference star data, eventually displayed (module DIS) and saved to the disk (module SAV).

Let’s now follow the bottom part that corresponds to the scientific object: after encountering the two pupils of the LBT, the wavefronts from the scientific object are summed with the correcting shapes from the two correcting mirrors of each pupil by means of the four occurrences of the module WFA. The corrected wavefronts are then co-phased within the module IBC (number 042) and the results is sent to an IMG module in order to obtain the interferometric PSF corresponding to the scientific object. The same is also applied to each of the PSFs corresponding to each of the single pupils of the LBT; these last data being used for individual pupil Strehl ratio computations.

As stated in Sect. 2, the module REC needs to be calibrated (when used in closed loop), as well as the module TCE (at least when using a Quad-Cell as tip-tilt sensor). The bottom part of Fig. 1 shows both calibration projects associated to the actual simulation project. The modules DMI, SHS, CEN, and REC occurrences are identical to those present in the main project, while the modules CSQ, CBF, and MCA are necessary only for this calibration procedure. The data flow is simple: a sequence of commands (from CSQ) is sent to the correcting mirror, iteration after iteration, together with the wavefront from a calibration fiber (module CBF), the correcting mirror acts in function of each of these commands, and sends the resulting wavefront to the the rest of the adaptive loop. The calibration data are built during the running of the calibration project with the help of the ad hoc module MCA.
3.2. Main Physical and Numerical Parameters of the Two Simulation Series

Two series of simulation runs are reported here, leading a priori to two different quality of AO-correction. Both series result in two sets of three long exposure AO-corrected images: one set for the reference star, and one for the scientific object. The three interferometric images correspond to three parallactic angles: 0°, 60°, and 120°, i.e. to three different observation runs during the night.

We have considered a turbulent atmosphere made of two turbulent layers situated at 0 and 10 km above the LBT, with perpendicular winds of speed \( v = 5 \text{ m/s} \) (the ground layer evolves along the baseline while the upper one evolves orthogonally to it). The associated Fried parameter \( r_0 \) is 25.2 cm (at 700 nm) for the first simulation series, and 30 cm for the second simulation series. The wavefront outer-scale \( L_0 \) is for both 60 m (von Kármán model is assumed). These two sets of parameters lead to a typical evolution time of turbulence of \( \sim 18 \text{ ms} \) and \( \sim 22 \text{ ms} \), respectively, and an isoplanatic angle of \( \sim 3.7 \text{ arcsec} \) and \( \sim 4.4 \text{ arcsec} \), respectively. The turbulent layers are numerically simulated by means of the classical fast-Fourier-transform-based method, with addition of subharmonics in order to compensate from the associated lack of low-frequencies.\(^\text{11} \) The time-lag chosen for the elementary shift (Taylor hypothesis is assumed) of the atmosphere layers is 5 ms. This is in practice the time-base for the whole simulation. Each of the three runs is associated to independent realizations of the two turbulent layers.

In order to simulate the behavior of the secondary mirrors that will equip the LBT, we set the parameters of the deformable mirrors in order to have an inter-actuators distance of \( \sim 25.5 \text{ mm} \) on the secondary mirrors, corresponding to \( \sim 23.5 \text{ cm} \) on the primary mirrors\(^* \). The first beam splitter sends 50\% of the light to the scientific camera, and the other 50\% to the AO-branch. Within the AO-branch 0.5\% of the remaining light is sent to the tip-tilt sensing loop, and the other 99.5\% to the high-orders sensing loop. The tip-tilt sensor is a Quad-Cell and the associated efficiency (optics and detector) is 60\%, the read-out noise is \( 3 \sigma^{\text{rms}} \), and the integration time is 5 ms. The sensing is performed in the r-band. The high-orders sensing is performed in the same conditions with the help of a \( 34 \times 34 \) Shack-Hartmann sensor, with \( 8 \times 8 \) pixels per subaperture and a pixel size of 0.15 arcsec per pixel. The zonal reconstructor applies a rejection of the Zernike modes over number 105\(^\dagger \) (that corresponds to the completion of the 13th radial order) for the first simulation series, and over number 231 (20th radial order) for the second simulation series.

For both adaptive loops, the time-filtering is set to work as a pure integrator. The differential piston is supposed here to be perfectly corrected. The scientific cameras for both the reference star and the scientific object make \( 128 \times 128 \) pixels images, with a pixel size of \( \sim 2.13 \text{ mas} \) (that yields to a sampling of 3 pixels per FWHM of the fringes), and are characterized by a read-out noise of \( 2 \sigma^{\text{rms}} \) and an overall efficiency (optics and detector) of 30\%. The single-telescope PSFs data are made with the same parameters, but a pixel size of 5 mas per pixel (that yields to a sampling of \( \sim 3.5 \) pixels per speckle). Each simulation run has a temporal history of \( 2.8 \text{ s} \) (560 iterations of 5 ms each), but the resulting interferometric PSFs are integrated over the last 2.5 s in order to fully benefit from the AO correction.

3.3. Expected Strehl ratios

From the parameters given previously one can compute an a priori expectation value for the attainable Strehl ratio for each of the two simulation series. For this purpose, we must first evaluate the compensated mean square phase error. Let’s review the four main error contributions in the present case:

- the fitting error \( \sigma_{fit} \) due to the finite sampling and therefore the finite number of compensated modes,
- the time decorrelation error \( \sigma_{TD} \) due to the time-lag between sensing and correction of the wavefront,
- the measurement error \( \sigma_{MEAS} \) due to the finite number of photons from the guide star,
- the anisoplanatism error \( \sigma_{AO} \) due to the off-axis between the guide star and the observed object.

\(^* \text{Note that the effective diameter of the primary mirrors is actually } 8.25 \text{ m} \) and then the effective maximum baseline of the LBT is 22.65 m – since the secondary mirrors are undersized to serve as aperture stops of the system for sake of minimum thermal background.

\(^\dagger \text{following Noll’s ordering} \)
We can neglect here $\sigma_{\text{MEAS}}$ assuming that we are dealing with a relatively bright NGS, as well as $\sigma_{\text{SOY}}$, since the angle between the NGS and the scientific target is much smaller than the isoplanatic angle (0.3arcsec vs. ~3.7 arcsec and ~4.4 arcsec, for the first and the second simulations series, respectively). The fitting error is, in a modal approach (e.g. using Zernike polynomials), equal to the contribution of the uncompensated modes.\(^1\) Its expression is then:\(^1\)

$$\sigma_{\text{fit}}^2 = \frac{2944}{n_z} \left( \frac{D}{r_0} \right)^2 \simeq 1.75 \text{ rd}^2 \text{ for the first simulation series},$$

$$\simeq 0.66 \text{ rd}^2 \text{ for the second simulation series},$$

where $n_z$ is the number of corrected Zernike modes, $D$ is the effective pupil diameter, and $r_0$ is the considered Fried parameter. Finally, the time-decorrelation error is:\(^1\)

$$\sigma_{\tau_0}^2 = \left( \frac{\Delta t}{\tau_0} \right)^2 \simeq 0.12 \text{ rd}^2 \text{ for the first simulation series},$$

$$\simeq 0.09 \text{ rd}^2 \text{ for the second simulation series},$$

where $\Delta t$ is the time-lag of the system, and $\tau_0$ is the evolution time of the atmospheric turbulence. A first-order estimation of the expected Strehl ratio $S$ is then,\(^1\) for the two cases:

$$S \simeq \exp \left( -\sigma_{\text{fit}}^2 - \sigma_{\tau_0}^2 \right) \simeq 0.15 \text{ for the first simulation series},$$

$$\simeq 0.45 \text{ for the second simulation series}.$$

Note that these expected values of the Strehl ratio are assuming a single pupil of the LBT, but since we are considering here to take advantage of a perfect correction from differential piston, this is expected to be roughly the same value for the interferometric mode. Let’s now analyze the results from the simulation series.

### 3.4. Resulting PSFs

Figure 2 shows (top row) a sample of the resulting single-pupil PSFs and the associated interferometric PSF, corresponding to the first simulation series and the observation of the scientific object (0.3 arcsec away from the NGS), with the parallactic angle 120 deg. Note that the pixel size is 5 mas for the single-pupil PSFs and ~2.13 mas for the interferometric PSF. Figure 2 also shows (bottom row) the strehl-ratio temporal evolutions (with increasing integrating time) for both the west- and the east-pupil PSF, as well as for the resulting interferometric PSF. The sampling time for these Strehl plots is 5 ms, and the total temporal history (2.8 s) is represented. The attained Strehl ratio, considering the interferometric PSFs integrated over the last 2.5 ms, is ~0.16 (averaging over the values resulting from the three scientific-object PSFs), that is in good agreement with the expected value previously computed. The first 0.3 s of the simulation temporal history were skipped for the following since they only describe the transient regime of AO-correction from the speckle initial pattern to the more stable (partially) corrected image.

Figure 3 shows the same plots as Fig. 2, but for the second simulation series, and with the parallactic angle 0 deg. The attained Strehl ratio is here ~0.44, that is also in good agreement with the expected value. One can notice by comparing this last result with the one of Fig. 2 that the Strehl temporal evolution shows a behavior that is much more stable after the first tenths of second and converges rapidly to its final value. Moreover, the PSFs contour plots also show a better definition of the expected morphologies for both the single-pupils PSFs and the interferometric PSF.
4. EXAMPLE OF DECONVOLUTION PROCESS

The object we took as an example of application of the multiple deconvolution process is a synthetic image of a Betelgeuse-like stellar object, i.e. a star resolved by the LBT and presenting a bright spot feature on its surface (see the interferometric observations of Buscher et al.,18 or the speckle ones of Klückers et al.19). The angular diameter of the star is 30mas (that corresponds to ~14 px on the scientific camera, i.e. roughly four times 1.22\frac{\lambda}{D}, where B is the baseline of the LBT), with an axial ratio of 0.9. The object itself was computed by applying an arbitrary center-to-limb variation (to simulate limb darkening) from a uniform disc, while the bright spot has a Gaussian-like shape with 3mas FWHM (that corresponds to a bit more than 1 px on the scientific camera, i.e. less than half of 1.22\frac{\lambda}{D}). The light from the bright spot gives 5% of the total observed flux. The high-resolution informations to retrieve for such an object are basically: the angular diameter of the star and the relative position of the bright spot, from an astrometric point of view, as well as the limb-darkening of the star and relative intensity of the bright spot with respect to the rest of the star surface, from a photometric point of view. We applied the ML–EM algorithm with 200 iterations to the obtained interferograms in order to retrieve these informations. In the following we will only have a qualitative evaluation of the reconstruction results.

Figure 4 shows the complete set of data corresponding to the first simulation series, with the three parallactic angles 0, 60, and 120deg. The degradation due to the partial AO-correction is clearly visible from these contour plots, in particular the asymmetry of the fringes linked to the residual tip-tilt errors on both single pupils that creates a bad superimposing of the two envelopes.

Figure 5 shows the result of the reconstruction method applied to the data shown on Fig. 4, together with and
directly comparable to the original object and the incoherent sum of the three interferograms. The gain in resolution from the application of the deconvolution method is clear from these contour plots: while we could not detect any particular feature from the incoherent sum of the three interferograms, the reconstruction reveals the presence of a bright spot. The relative astrometry of the object seems so to be satisfactorily retrieved with a Strehl ratio as low as 0.16, but the actual relative photometry still suffers from a bad rendering.

The set of interferometric data resulting from the second simulation series is shown in Fig. 6, directly comparable to the data of Fig. 4. The better quality of these data is manifest. The gain is obvious by analyzing Fig. 7, where the reconstruction method clearly succeed in retrieving both relative astrometry and relative photometry of the observed stellar object, although some ghost features appear as well.

These two results can also be visually compared to the one obtained by Bertero et al.9 by applying an enhanced version of the algorithm with an ideal reference PSF. A detailed discussion based on this kind of comparison between partially AO-corrected PSFs and ideal ones, with applications to other stellar objects of interest and quantitative analysis of the results is presented by Correia et al.7

5. CONCLUSION

We have shown first results of our simulations for the LBT with AO correction. The behavior of the interferometric PSF was successfully simulated, and the restoration method proved to permit high-resolution imaging even for partial AO-correction.

Prospects about this ongoing work include, from a practical point of view, the implementation of the deconvolution methods within the software architecture of CAOS2.0, by means of different modules (mainly pre-processing and deconvolution), but also improving of the AO-simulation capabilities by means of an enhanced modelisation of the adaptive secondary behavior, and implementation of multiconjugate AO solutions. A better modelisation of the
Figure 4. AO-corrected interferometric PSFs and interferograms for the first simulation series. Contour plots of, from top to bottom: the reference star, and the Betelgeuse-like object, for the parallactic angles, from left to right: 0, 60, and 120deg. The six images are normalized and contour levels are from 10% to 100% of each of the maxima.

Figure 5. Reconstruction of a Betelgeuse-like object for the first simulation series. Contour plots of, from left to right: the original object, the incoherent sum of the interferograms corresponding to the three parallactic angles, and the restoration result. The three images are normalized to the same integral and contour levels are from 10% to 100% of the maximum of the original object.
Figure 6. Same as Fig. 4, but for the second simulation series.

Figure 7. Same as Fig. 5, but for the second simulation series.
atmosphere above the LBT will also be provided as soon as site measurements will be available (value of the Fried parameter \(r_0\), \(C_n^2\) profile, winds velocities and direction, wavefront outer-scale).

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