Post-adaptive optics bispectral speckle imaging

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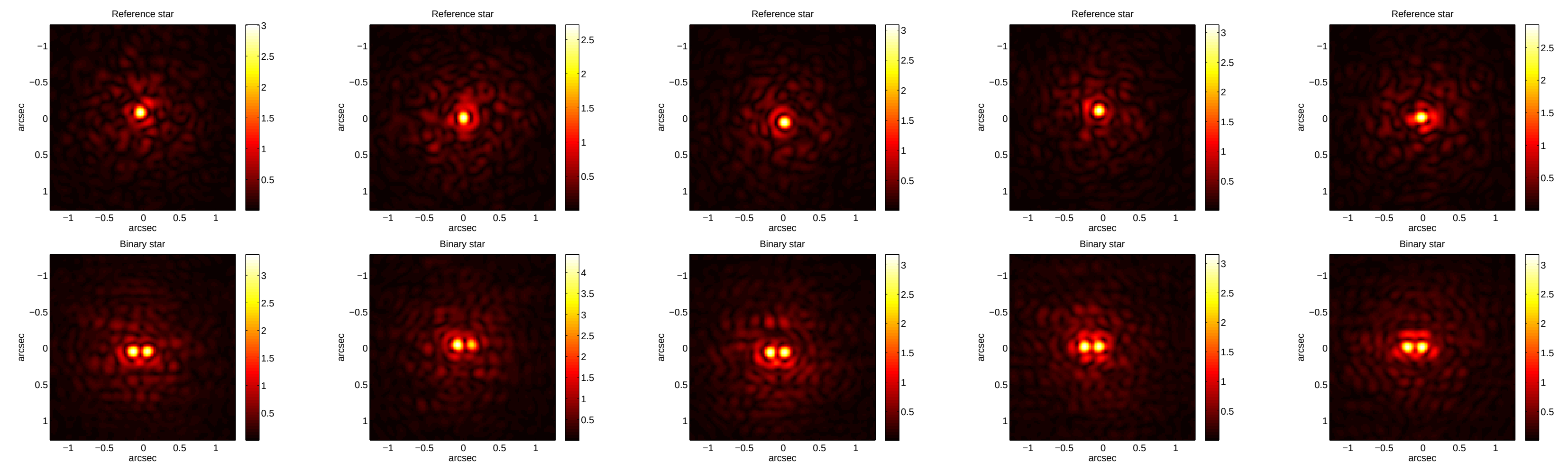
Abstract Adaptive Optics (AO) in the visible is more difficult with respect to near-infrared because of degraded spatial and temporal coherence of the turbulent atmosphere. Images are less corrected and generally contain a large amount of speckle residuals. Dedicated image processing techniques become necessary to reach the telescope theoretical resolution. We propose to apply the "Speckle Masking" method to post-AO partially corrected images to reconstruct objects at the diffraction limit of the telescope. We present here first results based on numerical simulation of binary stars, using the "Building Block" algorithm.

Data simulation

Partially AO-corrected images of a test-object were simulated by means of the `Software Package CAOS` [6] (part of the `CAOS Problem-Solving Environment` [5, 7, 9]) by considering the 1.04-m telescope C2PU [10] (plateau de Calern, Observatoire de la Côte d'Azur, France) equipped with its future AO system, with a Fried parameter of 10 cm (at 500 nm) and a partial correction on the first 44 Zernike modes (8th radial order) of the incident perturbated wavefronts. The test-object considered is a close binary star of separation $\rho = {}^{\prime\prime}\!\!.2$ ($\sim 2\,\lambda/D$ at λ=550 nm, i.e. 10 px with the chosen pixel scale, $0.\!\!^{\prime\prime}02$), and an intensity ratio between the two components of 2. An example of short-exposure images obtained is shown below (square-root scale), together with estimations of the point-spread function (PSF, images of a nearby reference star simulated here by means of a different random seed for the atmospheric turbulence), and corresponding to 73% correction of the Zernike modes considered (resulting average Strehl ratio $\simeq$ 0.2).



Bispectral speckle imaging & the building block algorithm

Speckle techniques were introduced in the early 1970's [1] to attain diffraction-limited resolution by means of post-processing of short-exposure images. Turbulence effetcs are described by a telescope+atmosphere random instantaneous PSF, whose statistical properties are estimated on a nearby reference star. The present study focus on the bispectral technique introduced by Weigelt in 1977 [2]. It is based on the bispectrum $B_I(\vec{u},\vec{v}) = \hat{I}(\vec{u})\hat{I}(\vec{v})\hat{I}(\vec{u}+\vec{v})^*$ of the intensity distribution $I(\vec{x})$. $\hat{I}(\vec{u})$ denotes the Fourier trasform of $I(\vec{x})$ at the spatial frequency vector $\vec{u}$. For an astronomical object with ideal brightness distribution $O(\vec{x})$ blurred by a random PSF $S(\vec{x})$, the bispectrum of the object can be recovered by the relation:

$$B_O(\vec{u},\vec{v}) = \frac{\langle B_I(\vec{u},\vec{v})\rangle}{\langle B_S(\vec{u},\vec{v})\rangle}\ ,$$

where $\langle\rangle$ denotes ensemble average of a large number of instantaneous images. The PSF bispectrum B_S is computed from images of a nearby star. The object's intensity is then reconstructed from its bispectrum using an iterative least-square algorithm based upon the accumulation of ideal Airy discs (building block method [3]). The bispectrum is a four dimensionnal quantity quite complex to handle. For simple objects such as binary stars, it can be reduced to two dimensions, without loss of information, by fixing a value for the spatial frequency $\vec{v}$ (see [4] for a review of the bispectrum properties). The module (left) and phase (right) of B_O are shown below (square-root scale), for $\vec{v}$=1 frequel (0.4 arcsec^{-1}) in the horizontal direction.

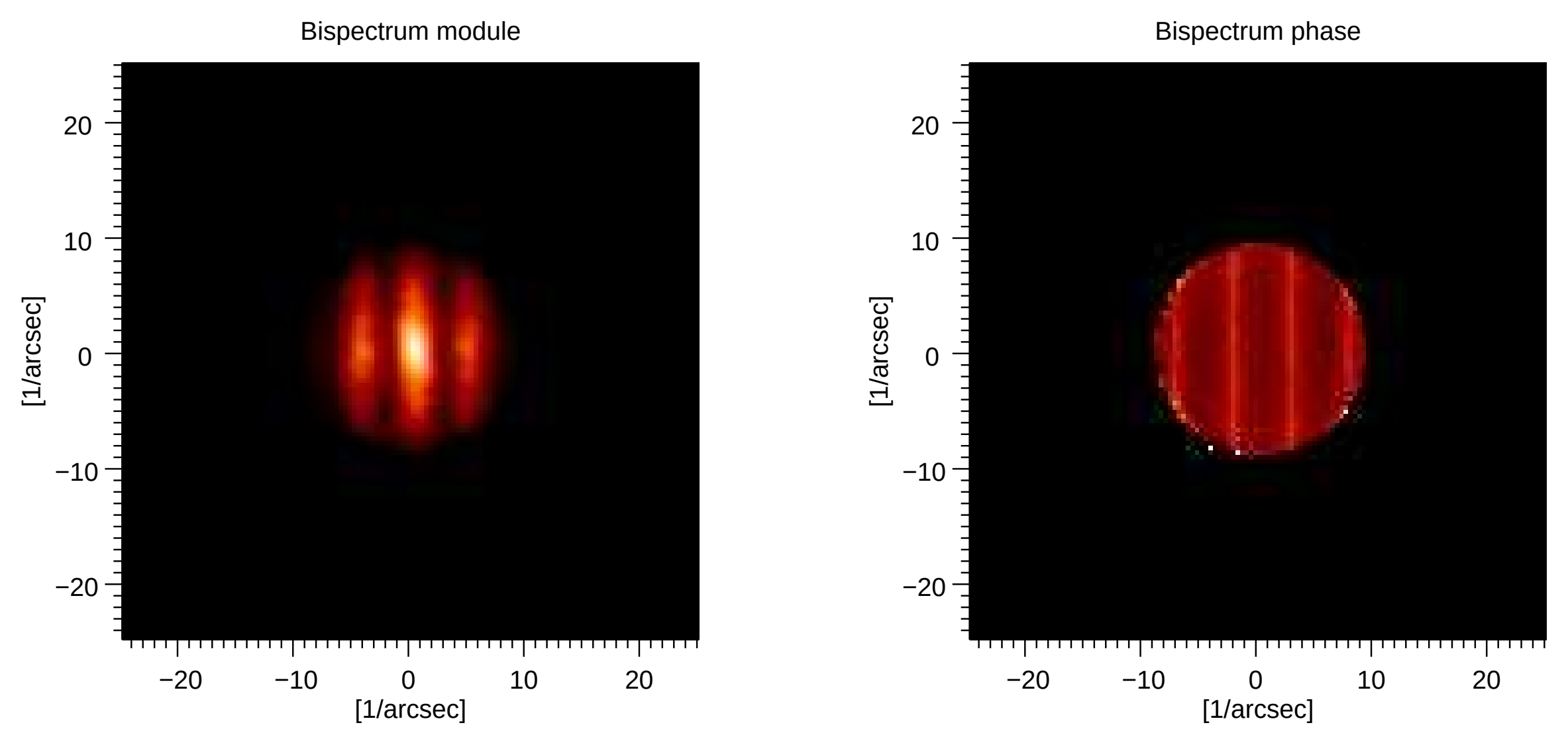
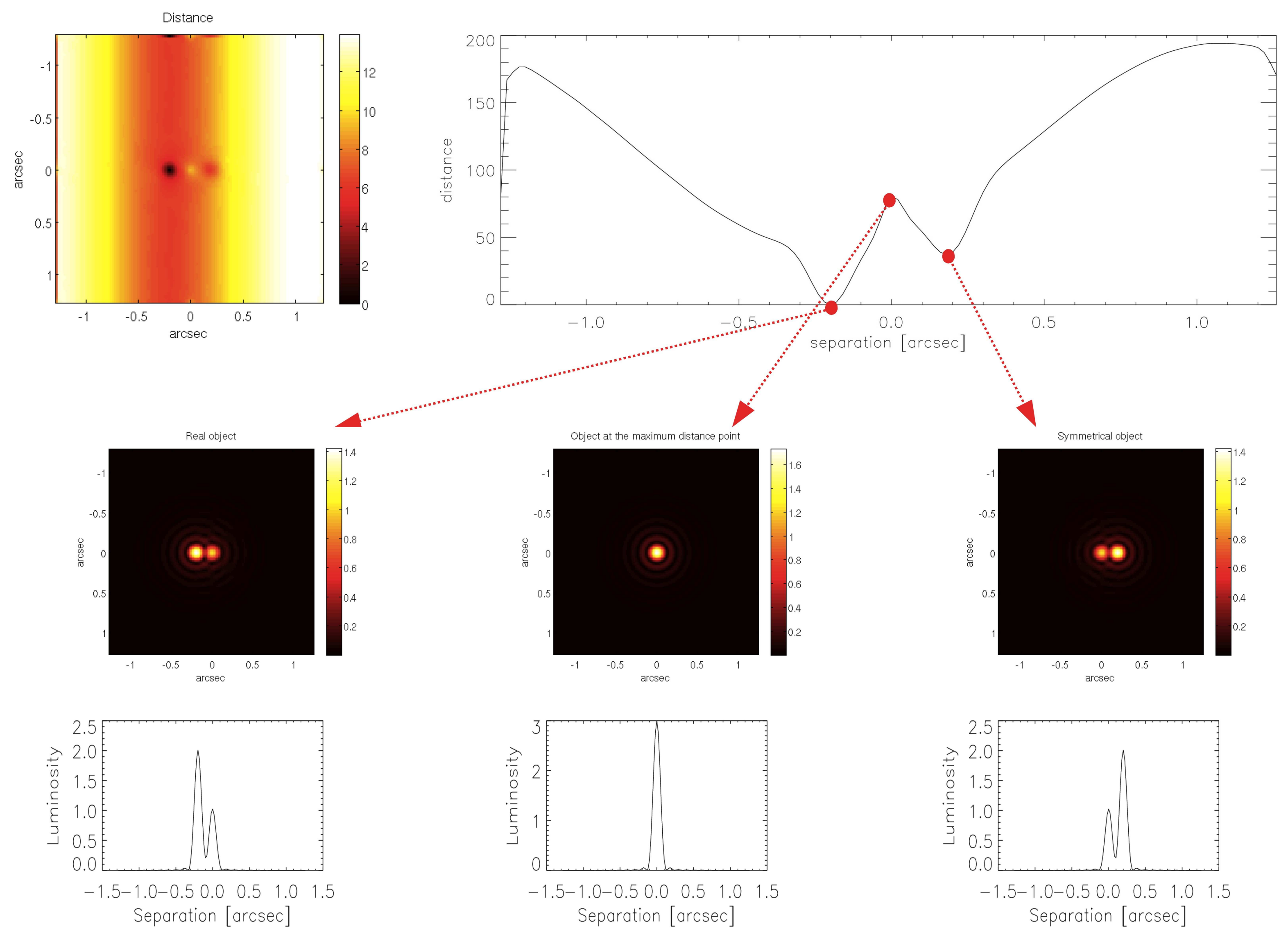
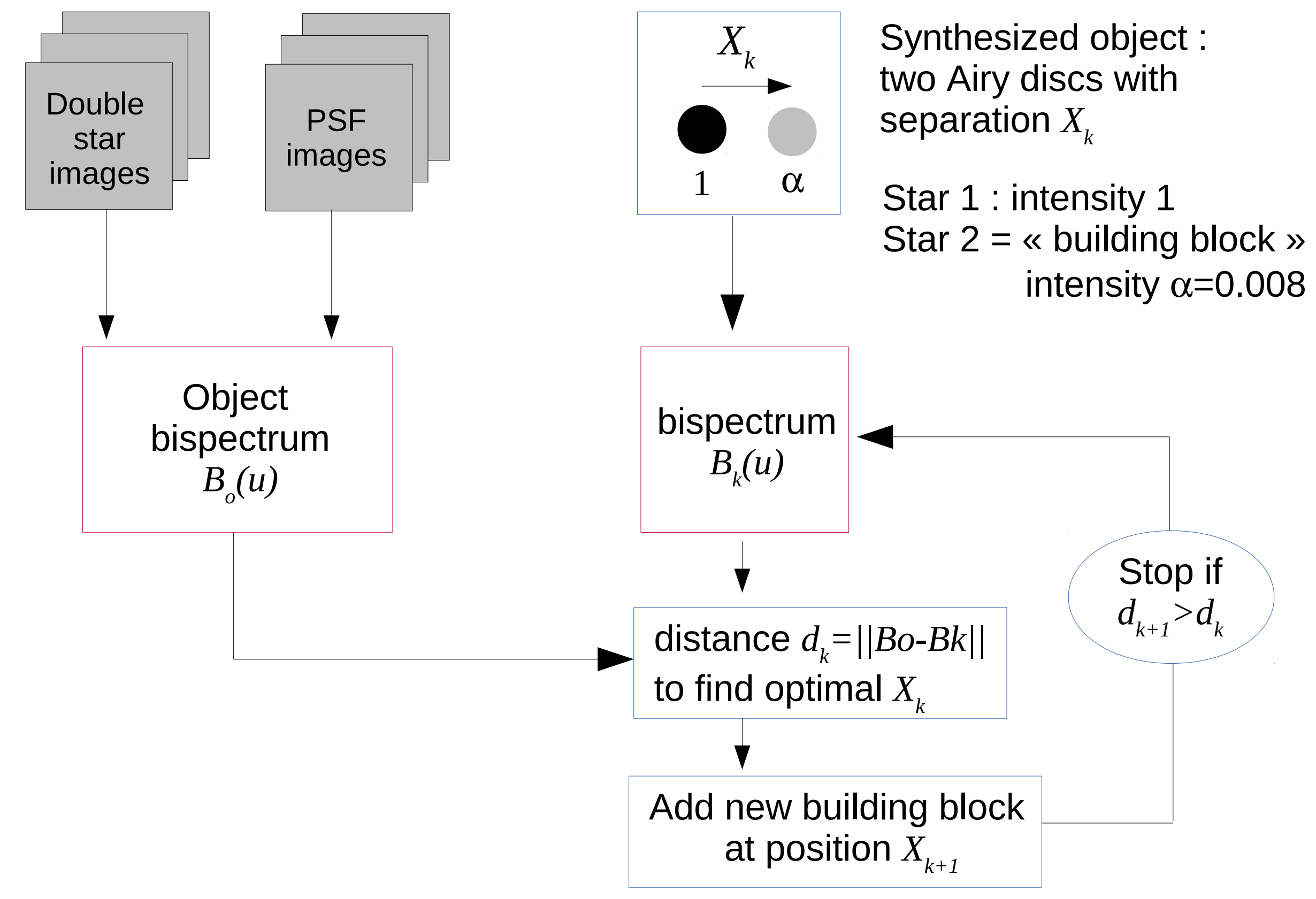


Figure below displays the least-square distance between bispectra of simulated data and synthesized binary stars at diffraction limit, with the same intensity ratio and varying separations. The bottom panel shows 3 examples of such binary stars for different separations. Note the main minimum of the distance when the separation is the actual one $\vec{\rho}$, and a secondary one for $-\vec{\rho}$, as expected.



The building block algorithm is schematized below, together with the distance permitting to find iteratively the binary intensity ratio (bottom left) and the final reconstructed image obtained (bottom right).


Double star images

PSF images

X_k

1 α

Synthesized object : two Airy discs with separation X_k

Star 1 : intensity 1
Star 2 = « building block » : intensity α=0.008

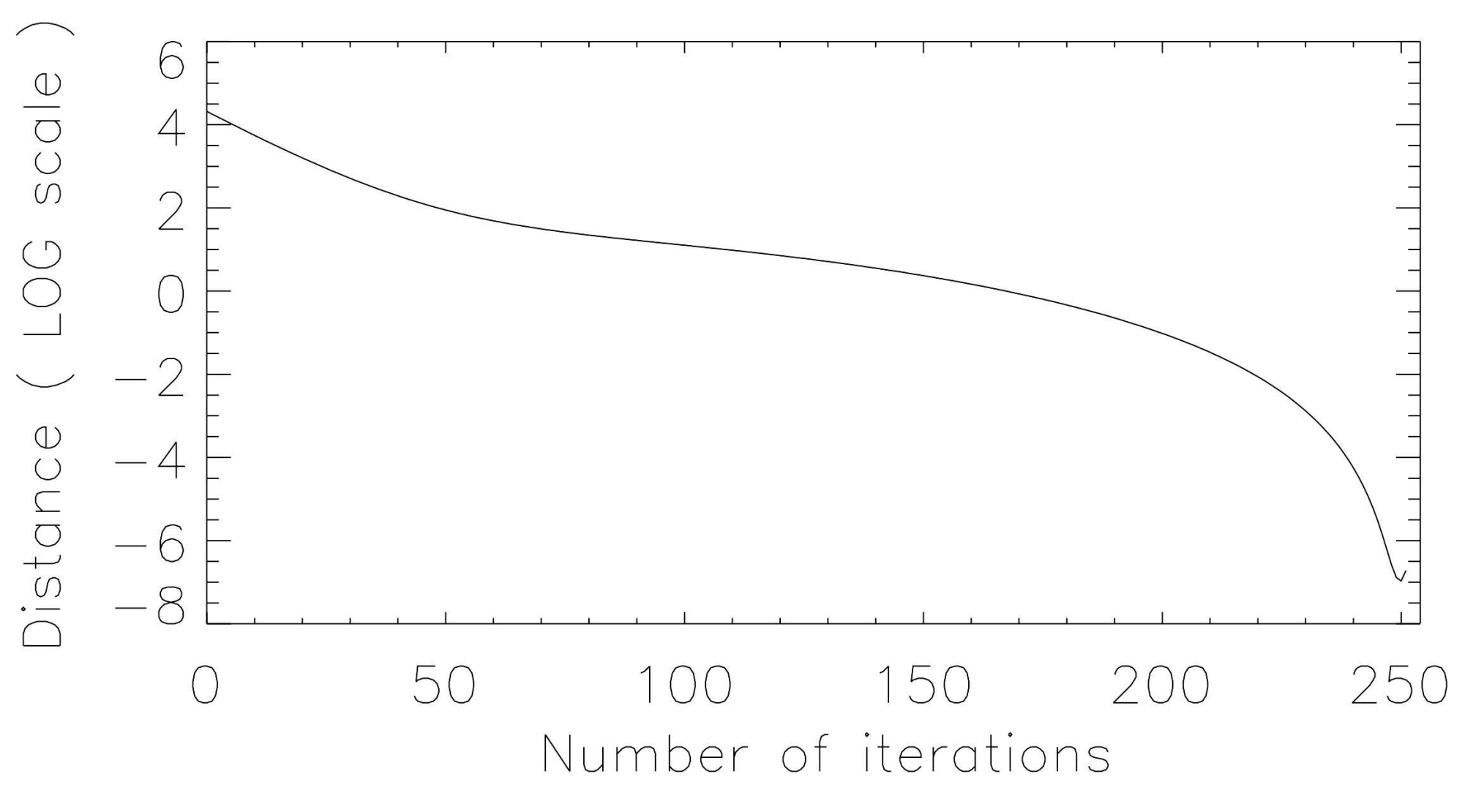
Object bispectrum $B_o(u)$

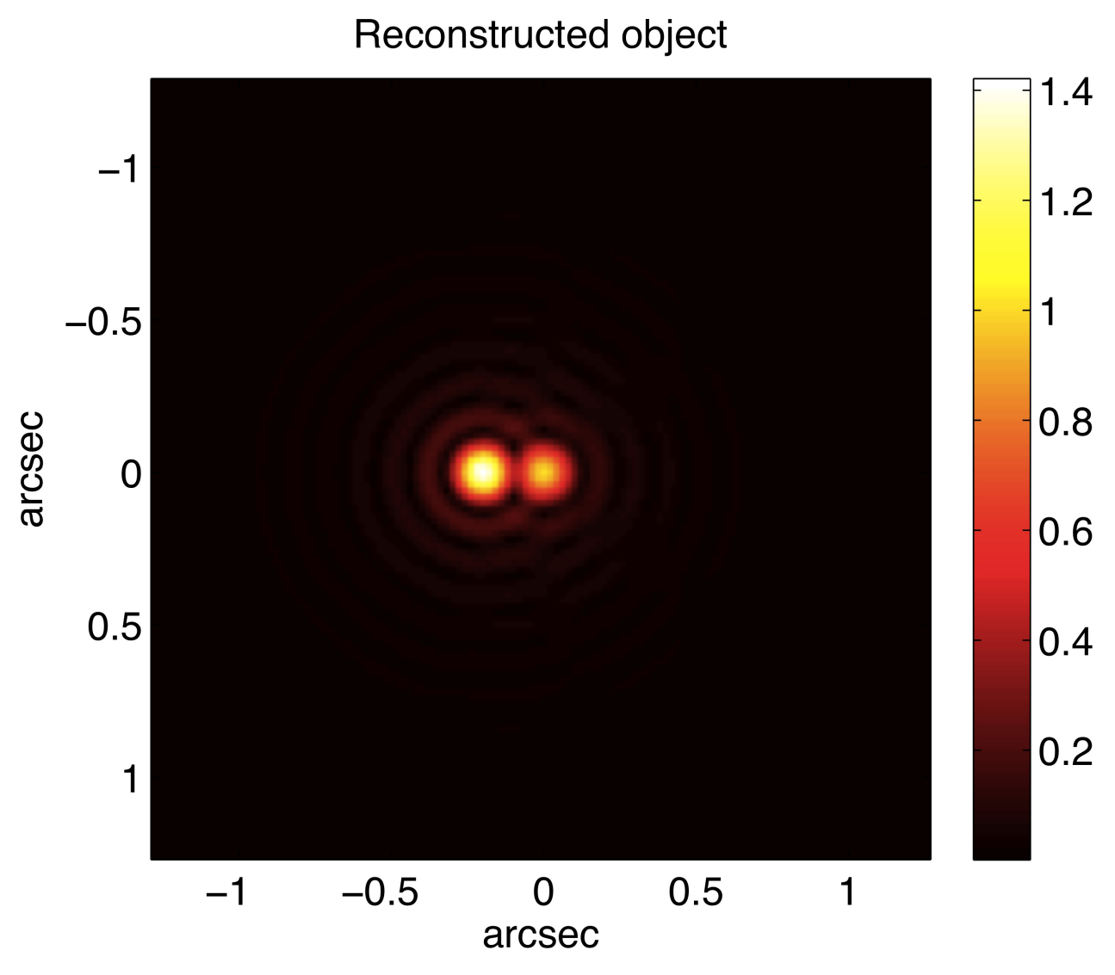
bispectrum $B_k(u)$

distance $d_k=||Bo\text{-}Bk||$ to find optimal X_k

Stop if $d_{k+1}>d_k$

Add new building block at position X_{k+1}





Conclusion and perspectives

This preliminary result is definitely encouraging with respect to the pertinence of the method. Further work will concern consideration of extended objects instead of binaries, as well as study of the precision of the method in function of the AO-correction **and** the level of detector noise. Comparison with long-exposure deconvolution techniques [8] will then be tackled.

References

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