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PSF RECONSTRUCTION FOR NAOS-CONICA

Y. Clénet[1], M. Kasper[2], E. Gendron[1], T. Fusco[3], G. Rousset[1], D. Gratadour[4], C. Lidman[5], O. Marco[5], N. Ageorges[5] and S. Egner[6]

Abstract. In the framework of PSF reconstruction for NACO, we first introduce 2 new algorithms that prevent the use of the so-called "U_{ij} functions" and hence (1) avoid the storage of a large amount of data, (2) shorten the PSF reconstruction computation time, (3) can provide an estimation of the PSF variability. We then identify and explain issues in the exploitation of real-time Shack-Hartmann data for PSF reconstruction, emphasising the large impact of thresholding in the accuracy of the phase residual estimation. Finally, we present the PSF reconstruction algorithms we are developing for NAOS and the NAOS data used for this purpose (the data presently available as well as two NAOS software modifications that would provide new data to increase the accuracy of the PSF reconstruction).

1 New algorithms for adaptive optics PSF reconstruction

In their adaptive optics (AO) PSF reconstruction algorithm, Véran et al. (1997) make use of the "U_{ij} functions" to compute the mean residual phase structure function: $\bar{D}_{\phi_{\epsilon_\parallel}}(\vec{\rho}) = \sum_{i=1}^{N}\sum_{j=1}^{N}\langle\epsilon_{\parallel i}\epsilon_{\parallel j}\rangle\, U_{ij}(\vec{\rho})$, where N is the number of modes and $\epsilon_{\parallel i}$ the decomposition of the residual phase on the basis of the mirror modes $M_i(\vec{x})$ ($\phi_{\epsilon_\parallel}(\vec{x},t) = \sum_{i=1}^{N}\epsilon_{\parallel i}(t)\, M_i(\vec{x})$). The residual phase covariance matrix $\langle\epsilon_\parallel {\epsilon_\parallel}^t\rangle$ is the basic entry point of the PSF reconstruction software, from which are deduced successively $\bar{D}_{\phi_{\epsilon_\parallel}}(\vec{\rho})$, the mean residual phase Optical Transfer Function (OTF) $\langle OTF_{\phi_{\epsilon_\parallel}}(\vec{\rho}/\lambda)\rangle$, and then, after a Fourier transform, the corresponding PSF. Additionally, one has to compute, store once for all, and also read during the reconstruction process the $U_{ij}(\vec{\rho})$ functions. There are $N\times(N+1)/2$ "useful" $U_{ij}(\vec{\rho})$ functions. This large number of $U_{ij}(\vec{\rho})$ represents, depending on the array size and data type, several gigabytes of data to compute, store and read. This leads to a heavy PSF reconstruction process, which will turn out to be impossible to handle in the future since next AO systems are expected to have a largely increased number of modes.

We propose 2 new algorithms to prevent the use of the $U_{ij}(\vec{\rho})$. Using the basis that diagonalizes $\langle\epsilon_\parallel {\epsilon_\parallel}^t\rangle$ ($\Lambda = B^t\langle\epsilon_\parallel {\epsilon_\parallel}^t\rangle B$), $\bar{D}_{\phi_{\epsilon_\parallel}}(\vec{\rho})$ reduces to: $\bar{D}_{\phi_{\epsilon_\parallel}}(\vec{\rho}) = \sum_{i=1}^{N}\langle\eta_i\eta_i\rangle\, V_{ii}(\vec{\rho}) = \sum_{i=1}^{N}\lambda_i\, V_{ii}(\vec{\rho})$, where $\eta = B^t\epsilon_\parallel$ represents $\phi_{\epsilon_\parallel}(\vec{x},t)$ in the new basis and $\{\lambda_i\}_{i=1\ldots N}$ are the eigenvalues. The $V_{ij}(\vec{\rho})$ functions are equivalent in the new basis to the $U_{ij}(\vec{\rho})$ functions. This V_{ii} algorithm mathematically produces the same result as the U_{ij} one. It requires only the computation on the fly of N $V_{ii}(\vec{\rho})$ functions, is much faster, and thus preferred.

In the second algorithm, we generate vectors η whose coefficients are independent Gaussian random variables with zero mean and variance equal to the eigenvalue λ_i, i.e. $\langle\eta\eta^t\rangle = \Lambda$. From $\beta = B\eta$, whose covariance matrix is $\langle\epsilon_\parallel {\epsilon_\parallel}^t\rangle$, we build the corresponding phases $\phi(\vec{x},t) = \sum_{i=1}^{N}\beta_i(t)\, M_i(\vec{x})$ and "instantaneous" PSFs $PSF_\parallel(\vec{x},t) = \left\|\mathcal{FFT}\big(\exp(i\phi(\vec{x},t))\big)\right\|^2$ that, in average, converge to the long-exposure PSF of the mirror space (which does not include the uncorrected part of the phase). Despite the slow convergence and the larger error compared to U_{ij} algorithm, this "instantaneous PSF" algorithm can provide an estimation about the variability of the OTF, that can help a lot in some deconvolution algorithms (see Gendron et al. 2006).

[1] LESIA, Observatoire de Paris, 5 place Jules Janssen, 92195 Meudon cedex, France
[2] ESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany
[3] ONERA, BP52, 29 avenue de la Division Leclerc, 92320 Chatillon Cedex, France
[4] Gemini Observatory, Gemini Observatory, Hilo, HI 96720, USA
[5] ESO, Alonso de Cordova, Casilla 3107, Vitacura, Casilla 19001, Santiago 19, Chile
[6] MPIA, Königstuhl 17, D-69117 Heidelberg, Germany

2 Issues in the exploitation of real-time Shack-Hartmann data for PSF reconstruction

Testing the algorithms introduced in Sect. 1 with 2 different end-to-end Shack-Hartmann (SH) simulation softwares (Rigaut 2005; Conan et al. 2004), we have observed that the Strehl ratios of the PSF obtained from the real-time wavefront data were systematically overestimated. These unexpected high values are related to the correlation between the error and the turbulence signal: an improper threshold level may bias the wavefront data, leading to a wrong estimation of the noise and of the phase residuals (see Clénet et al. 2006 for details).

3 PSF reconstruction algorithms/data for NAOS-CONICA

The delivery of wavefront-related data to estimate the PSF has been among the main specifications of NAOS to maximise its scientific returns: with its NACO FITS files, the observer gets (1) attached to the images: the 2 covariance matrices of the modal coefficients deduced from the residual slopes ($C_{\epsilon\epsilon}$) and the voltages (C_{vv}), the 2 means of the modal coefficients deduced from the slopes ($\bar{\epsilon}$) and the voltages ($\bar{v}$); (2) written in the image FITS header: turbulence parameters (r_0, L_0) and AO loop parameters such as the Zernike mean noise $\overline{n_z^2}$.

Following Véran et al. (1997), the long-exposure AO-corrected OTF is the product of the mean residual phase OTF $\langle OTF_{\phi_{\epsilon_\parallel}}(\vec{\rho}/\lambda)\rangle$, the mean perpendicular phase OTF $\langle OTF_{\phi_{\epsilon_\perp}}(\vec{\rho}/\lambda)\rangle$ and the telescope OTF $OTF_{\mathrm{tel}}(\vec{\rho}/\lambda)$.

3.1 Computation of the mean residual phase OTF

The WFS measurement can be decomposed into the sum of the residual phase, the noise and the aliasing in the basis of the miror modes ($\hat{\epsilon}_\parallel = \epsilon_\parallel + n + r$), leading to $\langle \epsilon_\parallel {\epsilon_\parallel}^t\rangle = \langle \hat{\epsilon}_\parallel \hat{\epsilon}_\parallel^t\rangle - \langle nn^t\rangle + \langle rr^t\rangle$ (assuming a high temporal bandwidth, Véran et al. 1997). We then derive $\bar{D}_{\phi_{\epsilon_\parallel}}(\vec{\rho})$ and $\langle OTF_{\phi_{\epsilon_\parallel}}(\vec{\rho}/\lambda)\rangle$. In our PSF reconstruction software for NAOS-CONICA:

– $\langle \hat{\epsilon}_\parallel \hat{\epsilon}_\parallel^t\rangle$ is directly obtained from the NAOS data: $\langle \hat{\epsilon}_\parallel \hat{\epsilon}_\parallel^t\rangle = C_{\epsilon\epsilon} - \langle \bar{\epsilon}\bar{\epsilon}^t\rangle$

– $\langle rr^t\rangle$ is in a first step neglected. In the future, it will be computed with a SH simulation of NAOS

– $\langle nn^t\rangle$ was contemplated to be computed from $\overline{n_z^2}$, with strong assumptions (noise uncorrelated from a subpupil to another, $\overline{n_z^2}$ equally distributed over all the Zernike modes). In Clénet et al. (2006), we introduce 2 different modifications of the NAOS RTC software that would provide either the whole vector of variance noises $n_{z_i}^2$ for all considered Zernikes or the vector of variance noises n_i^2 for all considered mirror modes. Using one of these vectors would decrease the uncertainties in the PSF estimation (see Clénet et al. 2006 for details).

3.2 Computation of the mean perpendicular phase OTF

$\langle OTF_{\phi_{\epsilon_\perp}}(\vec{\rho}/\lambda)\rangle$ can be derived from simulated phases screens, computed at $D/r_0 = 1$ and scaled at the proper D/r_0 value. The r_0 value of the observations can be either directly read in the image FITS header or derived from $\bar{v}$ and C_{vv} that are attached to the CONICA image FITS file. In our PSF reconstruction software for NAOS-CONICA, we have chosen the former solution. In Clénet et al. (2006), we describe 2 algorithms to compute $\langle OTF_{\phi_{\epsilon_\perp}}(\vec{\rho}/\lambda)\rangle$ from these scaled perpendicular phase screens: a "PSF-like" algorithm, that averages the "instantaneous perpendicular PSFs" obtained from these phase screens, and a "U_{ij}-like" algorithm, which is similar to the procedure used for the computation of the U_{ij} functions (see Clénet et al. 2006 for details).

4 Future work

The decision to proceed with the NAOS RTC software modification is in discussion with ESO. Though, tests of the software with the present NAOS RTC data have just begun and more will be accumulated before a release to the community.

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