MCAO PSF reconstruction

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1. Introduction

As in any AO system, the correction provided by a MCAO system is not perfect, due to various errors such as fitting, servo-lag, WFS noise, spatial aliasing, incomplete tomography, etc. The amplitude of these errors can vary drastically from one science exposure to the next. It follows that the PSF can change significantly from one science exposure to the next. Unless these changes are known, they can prevent the quantitative interpretation of the science images (astrometry, photometry, etc).

The PSF of a science exposure can be estimated if the image contains some point sources across the field of view. Then the image of the point sources gives the PSF in that direction and the PSF in any position in the field can be inferred by interpolation. Many science exposures however do not contain any point source. In addition, even if they do, these point sources may be so crowded that it becomes impossible to extract any PSF information.

The standard empirical method to determine the PSF in a classical AO system is to image a point source shortly before and/or after the science exposure. The drawbacks are however obvious: even if the observing conditions remain stable between the science and the calibration exposures, spending AO time to observe an unresolved point source is indeed a terrible loss of time. Most of the time, the conditions change between science and calibration exposures, inducing an error on the determination of the PSF that is hard to quantify.

An alternative approach is to determine the PSF from the data processed by the AO system during the science exposure. This approach is very appealing because it involves no observing time loss and because the PSF estimation is based on data exactly synchronous with the science acquisition. This method has been developed for a classical AO system based on a curvature WFS and has been successfully implemented on PUEO, the CFHT AO system [1]. This document reports on a very preliminary study on how this approach could be generalized to a MCAO system such as the one envisioned for Gemini South.

2. Outline of a MCAO PSF reconstruction method

The long exposure optical transfer function (OTF) in a direction q is expressed as the product of two contributions:

$$OTF(\mathbf{f},q) = OTF_{stat}(\mathbf{f},q)OTF_{atm}(\mathbf{f},q)$$

OTF_{stat} is the residual static OTF. It contains the diffraction pattern from the telescope, as well as any uncorrected static aberrations such as uncalibrated non-common path errors, high frequency primary mirror ripples, etc. OTF_{stat} can be measured, usually by imaging a point source at some point during the night (e.g. photometric standard star) or more often if there is any suspicion that the "static" aberrations might be changing.

OTF_{atm} is the contribution of the turbulence that is left uncorrected by the AO system. OTF_{atm} changes all the time, as the observing conditions (seeing, wind speed, magnitude of the GS, etc) change, and must be estimated for each science exposure in order to be able to retrieve the long exposure PSF. We are now suggesting ideas on how to estimate OTF_{atm} of a MCAO system.

The reasoning starts by supposing that we have ideal WFS's (independent of the actual WFS that drive the MCAO loop) that can perfectly measure the residual wave-front in the direction of each of our five LGSs. Because these ideal WFS's have no error, we would then be able to perfectly reconstruct the residual wave-front on the meta-pupil associated to each of the three DM's at each instant. From that, we could derive an instantaneous PSF in any direction on the sky. By averaging these instantaneous PSF, we would then obtain a long exposure PSF. However, even though the WFS measurements would be perfect, the long exposure PSF would not be perfectly accurate in any direction of the sky. This is because the residual phase cannot be fully reconstructed in 3 dimensions, but rather only at 3 discrete altitudes (the DM's). It is in fact exactly for the same reason that a MCAO system can not achieve an optimal correction everywhere in the field of view: since there is a finite (small) number of guide stars, the tomography can not be complete. Since the PSF estimation scheme is based on information from the same GS that are used to drive the MCAO system, we conclude that the field dependence of the MCAO PSF cannot be fully retrieved by an estimation scheme based on the MCAO loop data. This is a fundamental limitation of the proposed PSF estimation scheme. It could be argued that with 5 GS, one might in theory be able to do a bit more than reconstructing the phase at only 3 different altitudes. This argument is not very good though: if it were possible to do much better than that, then more than 3 DM's could be used during the correction in the first place, or less than 5 GS could be used to drive the three DM's, which is not the case. It might well be though that this fundamental field dependent error in PSF estimation is very small, especially considering that the field dependence of the MCAO PSF is quite weak by definition. However, the amplitude of this error remains to be quantified.

We now forget about the above field dependent error, and focus on the fact that we do not have ideal WFS to measure the residual wave-front in the first place. The first limitation of our WFS's is that they measure the wave-fronts only up to some spatial frequencies. Since the WFS's are matched to the DM, it is equivalent to say that only the DM component of the phase can be measured. So on each of the three DM's, the residual phase can be decomposed into:

$$j = j_p + j_o$$

Where only j_p, the component parallel to the DM space can be reconstructed. However, since j_o is also untouched by the AO system, its contribution can be estimated in a statistical sense by assuming a Kolmogorov model for the turbulence. In order to use this statistical information, we need to express the long exposure atmospheric OTF as a function of the second order moment of the residual phase. It can be shown that under certain conditions that should be also verified for a MCAO system, we can write:

$$OTF_{atm}(\mathbf{?}/l, q) = \exp\left[-\frac{1}{2} D_j\ (\mathbf{?}/l, q)\right]$$

Where D_j is the structure function of the residual phase. It is interesting to note here that by expressing the atmospheric OTF as a function of the second moment of the residual phase, we assume an infinite integration time. This means that we have removed all dependency on partially averaged atmospheric effects, such as speckle noise. This is a second fundamental limitation of using loop data to reconstruct the PSF: the residual speckle noise cannot be reconstructed. But this is in fact not surprising.

Since j_p is corrected by the AO system whereas j_o is not, we can write:

$$D_j\ (\mathbf{?}/l, q) = D_{j_p}(\mathbf{?}/l, q) + D_{j_o}(\mathbf{?}/l, q)$$

And $D_{j_o}(r, q)$ can be readily computed as a function of D/r_0 using the Kolmogorov model.

We now need to compute $D_{j_p}(\mathbf{?}/l, q)$ from the WFS measurements. Following the approach of reference [1], we should be able to show that $D_{j_p}(r, q)$ can be expressed as:

$$D_{j_p}(r, q) = \sum_{i,j,k,l} \langle a_{ik} a_{jl} \rangle U_{ij}(r, q)$$

where $a_{ik}(t)$ is the ith coefficient of the modal decomposition of the phase on the DM number *k* and $U_{ij}(r, q)$ depends only on the geometry of the system.

The problem is then to determine the covariance matrix $\langle a_{ik} a_{jl} \rangle$ from the WFS measurement. We can here use an approach similar to the classical AO case, that is we can compute the empirical covariance matrix $\langle \hat{a}_{ik} \hat{a}_{jl} \rangle$, and, recognizing that the WFS measurement are corrupted by noise and aliasing errors, we can “subtract” the statistical contribution of these errors. At this point, we also need to take into account the fact that tip, tilt and tilt anisoplanatism modes are not given by the LGS’s but rather by the NGS’s. A very interesting approach to estimating the covariance of the tilt anisoplanatism modes in the residual phase of an MCAO system is presented in reference [2] and it is likely that this work will lead the way to the full PSF reconstruction as outlined here.

3. Problems and current issues

PSF reconstruction based on AO loop data has so far been successfully implemented on PUEO, the Canada-France-Hawaii Telescope AO system. While implementation on any other curvature based AO system would be straightforward, the generalization of this scheme to a Shack-Hartmann based system remains problematic, even in the case of a classical AO system [3]. The main issue has to do with the estimation of the noise in the SH WFS. There are however good reasons to believe that no fundamental limitations exist here. Also, with a MCAO system, the LGS WFS will have a fairly constant and relatively high SNR, which should facilitate the noise estimation. This is not the case for the NGS modes, but the work presented in reference [2] shows that the estimation of the contribution of the NGS modes should be possible nevertheless.

Another issue is that the LGS WFS are based on quad-cells, and that therefore their measurement is related to the actual wave-front by a gain factor (centroid gain). This gain depends on the size of the spot in each sub-aperture, and varies continuously, as the seeing, laser beam quality, and thickness of the sodium layer change. An error in the determination of this gain would reduce the performance of the AO system, but would still allow for some AO correction. However, an accurate knowledge of the gain is critical for PSF reconstruction. This emphasizes even more the need for a robust centroid gain tracking scheme.

Beside the two fundamental limitations emphasized in the previous section (inability to retrieve the field dependence and the speckle noise of the PSF), we should point out the risk posed by uncalibrated static aberrations. Indeed, everything that is not seen by the WFS's must be calibrated and entered into the PSF reconstruction method through OTF_{stat} . The stability / evolution of these "static" contribution has to be evaluated.

4. Automatic PSF reconstruction procedure

The general layout of the PSF reconstruction method is given in figure 1. During the science acquisition, the AO real-time computers gather some statistical information on the loop data. The exact nature of these data remains to be specified but an educated guess is given in reference [4]. It is important for the gathering of these statistical quantities to be synchronous with the actual science acquisition and there should be a mechanism that associates the statistical data with the science FITS image within the DHS.

The actual PSF reconstruction is performed off-line. The reason why the reconstruction cannot be performed on-line is that the image of a point source must be used to calibrate the static component of the PSF. This image may well be taken after the science exposure. It has also to be reduced (flat fielded, bias + sky subtracted, etc) before. The actual PSF reconstruction is made by combining 1) the calibration image 2) the statistics file associated to the calibration image and 3) the statistics file associated with the science exposure for which the PSF is required.

References:

[1] J.-P. Véran, F. Rigaut, H. Maître, and D. Rouan, *Estimation of the adaptive optics long exposure point spread function using control loop data*, J. Opt. Soc. Am. A, 14(11), 1997.

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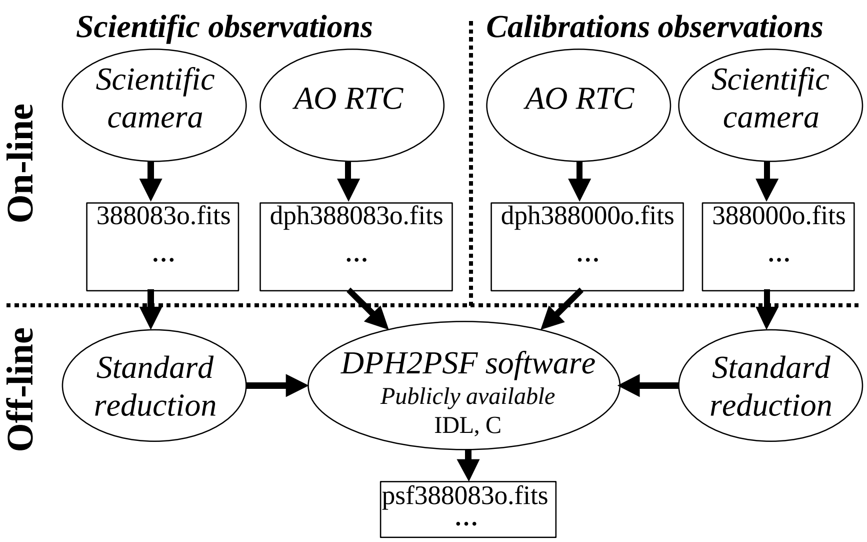

Figure 1: general block diagram for automatic PSF reconstruction