The PSF reconstruction effort for NICI, the high-contrast coronagraphic imager of GEMINI observatory: a snapshot

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Abstract. PSF reconstruction is a "holy grail" of (astronomical) adaptive optics (AO) instrumentation. Since the (one?) successful implementation for a curvature system of Veran et al. [5] (from now on JPV) many tried to implement PSF retrieval on AO supported instrumentation. From the astronomical community these efforts likely are perceived as an unsatisfying success so far particularly since no observatory to our knowledge has reached a comparable level of AO telemetry data handling as is standard for the direct scientific data. Since AO is key for ELTs this should change in a not too far future. Even though more than one and a half decades ago, the PSF retrieval implementation of JPV for PUEO/CFHT is still the encouraging example and light tower. Technical reasons for the "viscosity" encountered by many others might be that curvature systems are indeed much more favorable for PSF retrieval, but it might be as well simply the lack of having dedicated and knowledgeable manpower on PSF retrieval and AO telemetry data handling working full time at observatories with AO facility instrumentation. Gemini has two PSF reconstruction efforts ongoing: one for Altair [3,4] and one on the dual channel coronagraphic imager NICI presented in this poster. Since recently Gemini is collaborating with Pontificia Universidad Catolica (PUC) in Chile to assist the observatory exploiting its AO telemetry data. Topics addressed by this collaboration are the Gemini internal vibration mitigation effort [1,6], turbulence profile reconstruction [2] and PSF retrieval and system monitoring.

1 Status

In August 2009, Paris, Damien Gratadour coded from scratch the framework of APETY (A PSF Estimation Tool for Yorick, `http://github.com/dgratadour/apety`) following JPV which we have been verifying and optimizing since then in comparison with direct simulation output. In January 2010 (Big Island and La Serena) we implemented the real time (RT) calculation of the covariance matrices (M. Chun) on NICI RT machine. We successfully demonstrated that these RT covariance matrices match our Circular Buffers (recorded in parallel). In May 2011, during a vibration mitigation related ENT (Gemini Engineering Night Time Task), we obtained AO telemetry and imaging data to compare APETY retrieved PSFs with directly observed PSFs; the data are under study. Most of the work that could be done so far focused on optimizing and comparing simulated PSFs (for a NICI alike curvature system) with the APETY output. For our end-to-end simulations we use YAO, a full-fledged Monte Carlo Simulator for single and multi-conjugated Adaptive Optics written by F. Rigaut (`http://frigaut.github.com/yao/`).

2 Comparing YAO simulated with reconstructed PSFs

An accurate estimation of the parallel part of the wavefront (roughly spoken the part that can be controlled by the AO system) based on the WFS telemetry is key to the basic performance of APETY. Fig. 1 shows the parallel phase structure function as reconstructed by APETY (top row) in comparison with the one extracted from YAO (bottom row). Index 1 labels DM based phase splitting (left column) and index 2 WFS based phase splitting (middle column). The shown parallel phase structure functions correspond to the PSFs rec1 and rec2 depicted in Fig. 3.

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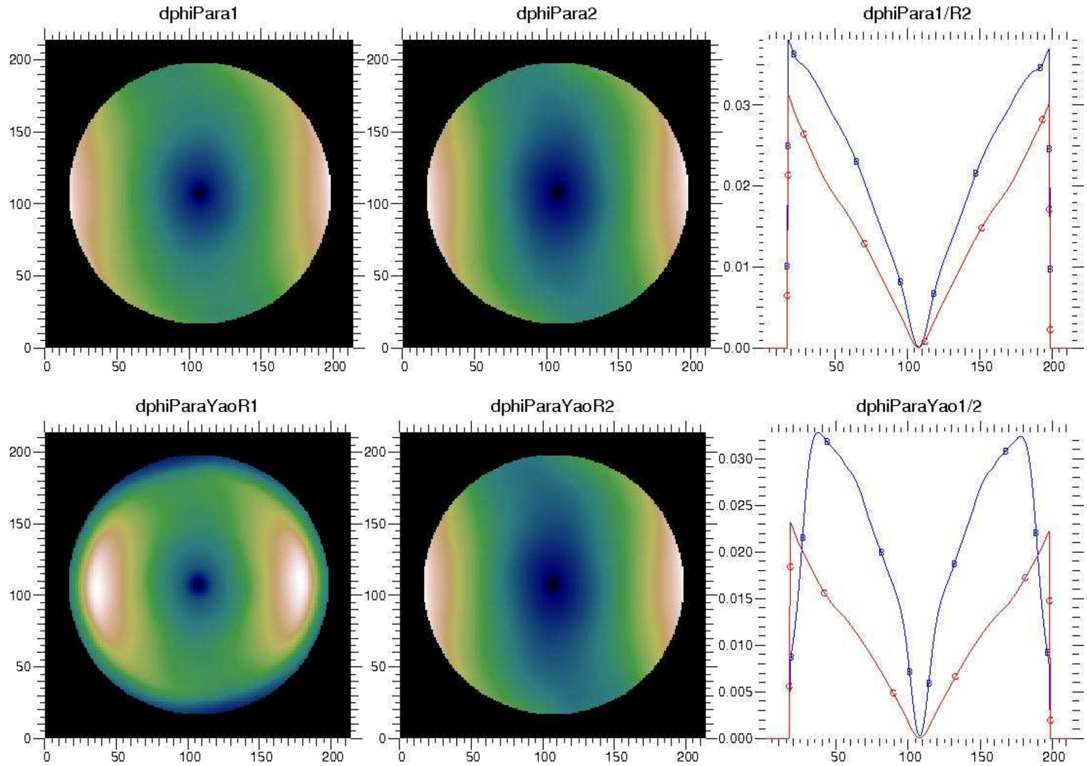

Fig. 1. The top row displays parallel APETY phase structure functions, the bottom row the expected phase structure functions according to YAO. The first column (index 1) correspond to a DM based split, the second column to WFS based split (which is clearly a better match). The last column shows corresponding horizontal cuts (upper curve DM based/index 1, lower curve WFS based/index 2).

Notably, the parallel phase structure functions compare better when the phase split is based on the WFS geometry (index 2). This is a subtlety: Instead of projecting the simulated phase directly on the DM modes, the phase is sampled by the WFS first, and then projected on the DM modes (and/or influence functions). JPV's theoretical description does the phase splitting directly on the DM (zonal modes and/or influence functions), even though in practice (also in his implementation) one naturally passes through the WFS. For a numerical implementation and comparison using Monte Carlo simulators, this subtlety matters. For a correct comparison, the parallel phase needs to be constructed passing by the WFS (WFS based split). Obviously, this point is also relevant to compute a representative orthogonal phase (to be scaled by a measured r_0) that APETY or other retrieval codes would use to assemble an appropriate long exposure PSF.

In Fig. 2 we depict 50 iterations of DM commands and WFS measurements and a corresponding WFS covariance matrix. Following JPV the parallel phase structure function is calculated based on the WFS covariance matrix (using the Uij functions) after applying some correction terms (e.g aliasing). In closed loop we expect "smooth" looking DM commands (compensating the atmosphere) but it might appear surprising that the WFS error signal does not look noisy (assuming small residual errors) on a bright star. This illustrates how high order aliasing error from the orthogonal part of the phase folds in ("tracing" the phase screen).

In Fig. 3 we compare PSFs as retrieved using APETY with a YAO simulated PSF. We used D/r0=40, a 5 mag star, and 5000 iterations corresponding to 3.8 seconds observing time (NICI AO runs with 1300 Hz). This is a trade-off of calculation time and getting good enough statistics for first comparisons. For the APETY PSF to the left, the parallel and orthogonal wavefront bases are split based on the DM, for the middle PSF the split is based on the WFS. It can be seen that PSF rec1 is slightly overestimated, i.e. there is too much "clearing" between the Airing rings. Evidently, PSF rec2

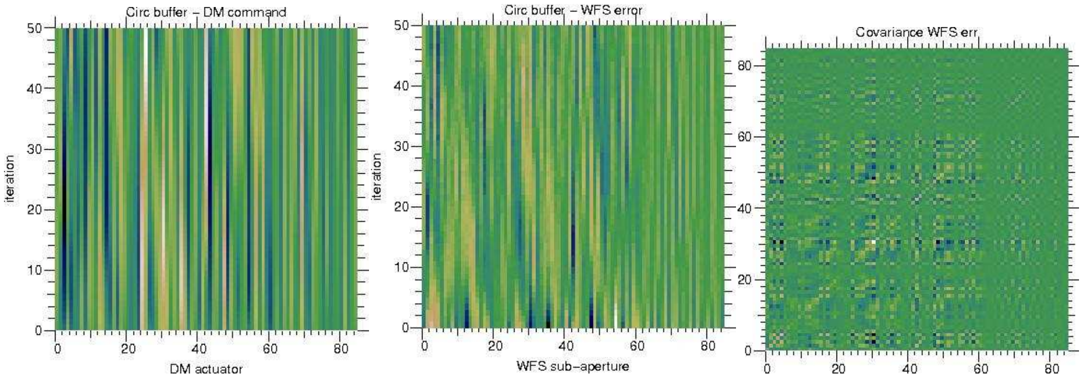

Fig. 2. *To the left and in the middle:* 50 iterations of DM commands and WFS measurements, respectively. *Right:* A WFS covariance matrix used to calculate a parallel phase structure function via the Uij functions.

compares better with the expected PSF (to the right) and the basis separation along the WFS gives more accurate results. Note that this a case study for the NICI AO system design and the impact of this effect should differ for other AO systems (depending on DM influence functions and WFS geometry).

Since these simulations were done with a relative low number of iterations (5000 iterations, i.e. 3.8 seconds in real life) there are still speckles visible that have not yet averaged out. Note that the particularly accurate matching of speckles of the YAO simulated PSF with the reconstructed PSFs occurs because we use the same orthogonal phase as simulated in a YAO run to build the reconstructed PSF. This does not reflect reality (for an instrumental implementation) where the orthogonal phase information is lost (the WFS sees only the parallel part) but it is a convenient way to study the performance of APETY with a low number of iterations.

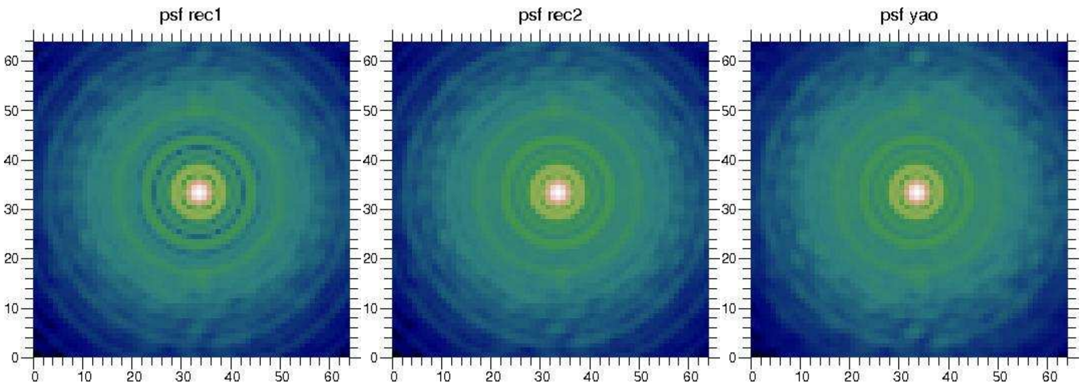

Fig. 3. *To the left and in the middle:* Reconstructed PSFs with APETY using DM based (*left*) and WFS based wavefront split (*middle*). *Right:* The expected PSF from the Monte-Carlo simulator YAO.

For a more quantitative comparison of APETY's performance we show in Fig. 4 intensity cuts in linear and logarithmic presentations for different atmospheric conditions and compare with the YAO PSF. The first column corresponds to a (500 nm) seeing of 0.5" (D/r0=40) and the second to 0.8" (D/r0=60). We used a 5 mag star (hence focus on the bright star case) and 10k iterations to achieve reliable statistics. There is less agreement for the worse seeing condition despite a bright guide star and therefore high feedback gain (0.3). Note that the inner part of the PSF appears to be consistently overestimated while the outer part (a few λ/D) is underestimated.

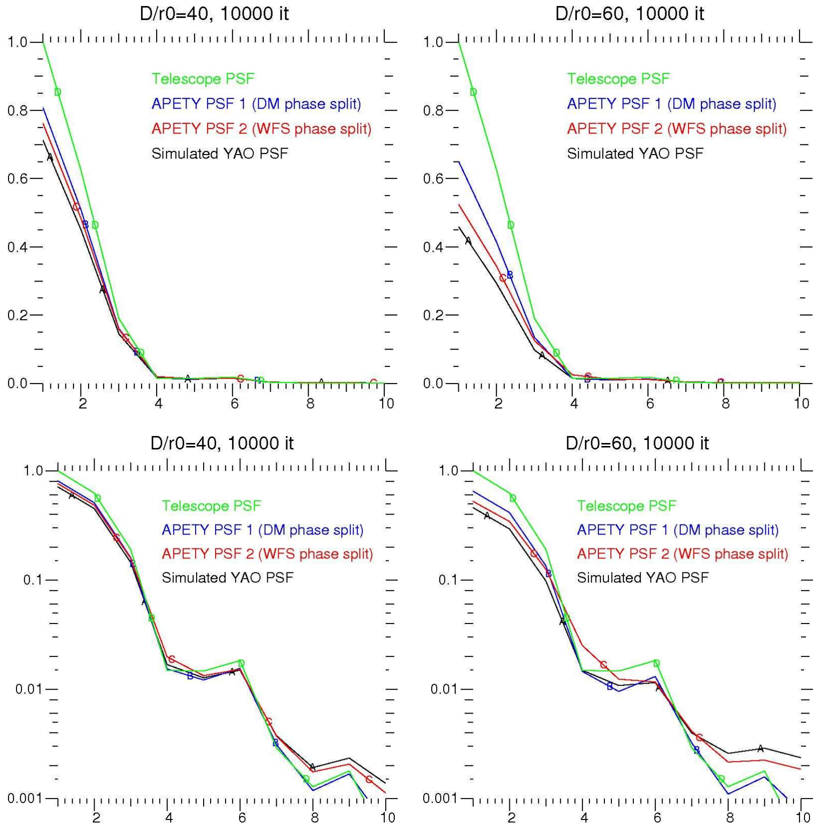

Fig. 4. Comparison of APETY reconstructed PSFs with YAO simulated PSFs for a seeing of 0.5” (*left* and 0.8” (*right*). *Top row:* linear representation. *Bottom row:* logarithmic representation.

3 Final Words

Whoever wishes to understand (and master) the full error budget of his AO system should pursue the effort to derive his PSF from AO telemetry. Even though when the ultimate goal (reconstructed PSF, simultaneously with the science data obtained and archived including regularly bootstrapped on-sky NCPA calibrations) might recall us of the Greek Sisyphus myth, the value for a profound understanding of the system, monitoring, and performance optimization is tremendously. For a successful end-to-end implementation, PSF reconstruction should be foreseen in planning and design, and the allocation of the necessary resources may not be underestimated.

References

1. Christou et al., this conference
2. Cortes et al., this conference
3. Jolissaint et al., SPIE **7736**, (2010) 77361F-77361F-12
4. Jolissaint et al., this conference
5. Veran et al., JOSAA **14**, (1997) 3057-3069
6. Rodriguez et al., this conference