PSF reconstruction at WMKO: Development, implementation and validation of PSF reconstruction techniques

Y9 CfAO project annual report

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1 Progress report

This document is a summary of the goals, current status and future schedule of the multi-year collaborative proposal [1] to the CfAO "Development, implementation and validation of PSF reconstruction techniques." The project started in November 2007 at the W. M. Keck Observatory (WMKO) under the direction of D. Le Mignant (PI), with postdoctoral researcher R. Flicker employed for the principal algorithm development and implementation.

1.1 Project milestones

The proposal outlined three major phases of the project, described in roughly chronological order as:

1. Initial development phase; on-axis NGS only (8 months)
   a. Review previous research on PSF reconstruction and select candidate algorithms
   b. Develop K2 AO simulation tools for the purpose of producing simulated AO telemetry data
   c. Develop TRS (telemetry recorder/server) query and analysis tools
   d. Develop prototype PSF reconstruction algorithm containing the fundamental components (fitting, aliasing, noise and bandwidth errors); test on simulated data and apply to real on-axis NGS K2 AO data
2. On-sky validation and component development phase; off-axis NGS, LGS, optical aberrations (12 months)
   a. Develop and validate angular and focal anisoplanatism components for NGS and LGS
   b. Develop static and dynamic telescope aberration components (segment figures, vibrations, instrument optical distortions); strategy for measuring them
   c. Integrated product development, preliminary deployment to routine observing
3. Final product and future development phase (4 months)
   a. Integrated product and user interface development
   b. Initial studies into PSF reconstruction techniques for future multi-beacon tomographic AO systems (i.e. MCAO, MOAO, LTAO) and extremely-high-order AO systems (applicable to, e.g., NGAO)

Each phase entails a number of sub-tasks most of which are omitted here for brevity. Much of the PSF algorithm development is modular, consisting of several estimation algorithms that are researched and developed largely independently (e.g., noise estimation, seeing estimation, aliasing and anisoplanatism modeling etc – all described in more detail in the documentation available on the PSF reconstruction project TWiki [2]).

1.2 Current status and schedule

This section summarizes in words the progress on various tasks, leaving more detailed technical discussions to be found in the documentation on the PSF reconstruction TWiki page [2].

Phase 1 (75% complete)

The milestones of Phase 1, covering the period 2007–11–01 to 2008–07–01, are either accomplished or well under way (100% to 50% complete), with the project on schedule.

1a. (100% complete) Reviewing the literature, we resolved to base our algorithm development on the previously most commonly applied method, introduced by J.-P. Véran in [3] (henceforth the "Véran method"). One recent improvement [5] to the Véran method was adopted early on as the baseline algorithm for PSF reconstruction at WMKO, as it reduces the computational complexity without sacrificing realism, potentially allowing the algorithm to be scaled up to high-order AO systems with future development.

1b. (100% complete) In order to prototype the PSF reconstruction algorithm, and for future debugging and sanity-checking, it was deemed important to have a capable simulation tool that emulates the current AO system on the Keck 2 telescope as closely as possible. Such a numerical simulation tool was developed within the first half of Phase 1, and has been employed to generate streams of fake AO telemetry data on the same format as the actual TRS, greatly facilitating development of the PSF reconstruction algorithms.

1c. (50% complete) The new wavefront controller (former NGWFC) recently implemented on the K2 AO system [4] is crucial to the success of PSF reconstruction, as it allows several nights of full-frame-rate AO telemetry to be recorded for later post-processing. This complete recording and generous storage capacity offered by the TRS obviates the need for real-time data reduction, and allows the PSF reconstruction to be carried out at any later time with complete access to the raw data. A set of general TRS database query tools were available at the start of this PSF reconstruction project, but for the PSF reconstruction task a number of extensions and modifications were identified as necessary. There is currently an ongoing effort, lead by proposal participant Erik Johanson (WMKO), to develop additional software tools and add such functionality to the TRS in order to facilitate PSF reconstruction, as well as other applications.

1d. (50% complete) The first departure from the Véran method that we decided upon was to omit the pupil-averaging step, which approximates a non-stationary structure function by a stationary one in order to simplify computation. This approximation may lead to an underestimation of the optical transfer function (OTF), but we found that, in conjunction with the methodology in [5], the advance in affordable computing power has rendered the pupil-averaging approximation unnecessary. A second reason for avoiding pupil-averaging is that the structure function for focal anisoplanatism (cone-effect) with LGS is in itself non-stationary [6], and could not be used within the Véran method without some form of additional approximation. By evaluating the OTF directly from the non-stationary structure function, we avoid applying any additional approximation to the focal anisoplanatism term.

The fitting and aliasing components have been modeled and implemented into the algorithm, as described in the documentation on the TWiki [2]. In brief, both are based on Fourier-domain modeling. The fitting component consists of a numerically generated Fourier domain mask that is applied to a model turbulence power spectral density function (PSD). The PSD mask takes into account the shape of the DM influence functions, producing a smoother and more realistic roll-off at the AO cut-off frequency than simple analytical models (e.g. [7]). The aliasing component is modeled by an analytical PSD model based on the formalism in [8], generalized here to closed-loop conditions (see Appendix 1 in [2]).

The noise/servo-lag component is the central object that is computed from real-time AO telemetry. The Véran method applies two approximations to this component that we too have used initially. In order to achieve a PSF reconstruction algorithm that is reliable also in high-noise conditions (faint guide star regime), however, we also consider more realistic representations of this component that include the temporal filtering (omitted in [3]). Considerable effort is devoted during the second half of Phase 1 to model this component and verify it against AO lab data. The details are outlined in [2]. One set of AO lab data was collected for initial model testing. Unfortunately the test needs to be repeated and new lab data collected, due to a failure to record all the necessary telemetry the first time.

On-sky data was also collected on bright NGS for testing the fitting and aliasing components, as well as providing data for validation of the seeing estimator (see Sect. 1.3). A reliable and accurate r_0 estimation is essential to PSF reconstruction, so testing and potentially making improvements to the algorithm currently in operation is a high-priority task that is being carried out presently.

Phase 2 (10% complete)

2a. (33% complete) As implied above, anisoplanatism modeling became pursued and largely accomplished within the time frame for Phase 1. The research was recently submitted to a peer-reviewed journal, and an upcoming engineering run with K2AO aims to collect NGS anisoplanatism data for on-sky validation, well ahead of schedule. The results produced include analytical formulas for angular and focal anisoplanatism structure functions, which take into account the finite outer scale of atmospheric turbulence. Although the outer scale is a poorly known quantity, it was found that, for a 10-meter telescope, outer scales on the order of ∼30 meters or less would have a significant impact on Strehl ratio and PSF shape.

1.3 Technical challenges

The more challenging technical aspects of the project which are currently being worked on as part of Phase 1 include seeing estimation, noise modeling, and residual error covariance matrix modeling.

- Seeing estimation. The atmospheric seeing (or r_0) is one of the most important parameters to have a good estimate of. Even though we are employing the approximation that the long-exposure PSF can be represented by an average r_0 value (while we know that r_0 can vary strongly even on short time scales), the PSF is still very sensitive to this value. As part of the PSF reconstruction project we therefore deemed it necessary to validate the seeing estimation algorithms currently used with K2 AO (based on Schoeck et al. [10]). Data that was collected during two half-nights of observing (in January and April 2008) are being analyzed currently.

- Noise model. This is one of the critical components of the PSF reconstruction algorithm, and the realism of this component decides whether the algorithm can be applied in the high-noise regime of faint AO guide stars. Depending on how the calculation is pursued, we either estimate a noise covariance matrix in the WFS domain and a temporal noise transfer function, or we can try to estimate the temporally filtered noise covariance matrix in the DM domain in one step. Most previous PSF reconstruction projects have followed the first approach, which requires good knowledge of the noise in the WFS and other hard-to-measure quantities such as the centroid gain. No successful implementation of the latter approach has yet been demonstrated, but it is the goal of the current project to investigate this method and attempt to implement it. For the purpose of testing the noise modeling in an idealized setting, noisy AO telemetry data was collected from the AO bench operating on the internal (fiber) light source, with no atmospheric turbulence (hence no fitting or aliasing error) present. This data and the noise models are currently being tested.

- Covariance matrix model. This aspect of modeling covers how the components of noise, aliasing and residual turbulence error are combined into a single covariance matrix that is used in the final OTF calculation. Approximations can creep in at different stages here, as the quantities are either poorly known or their exact representations become too complicated to deal with numerically. Firstly, there are cross-terms between the AO telemetry and the noise and aliasing terms, and secondly there is the temporal filtering mentioned in relation to the noise model above. In following the approach suggested by Véran [3] both of these effects are approximated to a degree, but the goal of the project is to investigate the feasibility and performance of more realistic representations.

2 Publications and documentation

The project has been extensively documented. We have created a TWiki page at the CfAO that allows anyone to check our progress. The TWiki page presents the various phases for the project and provides details for the current active phases [2]. A research paper on the effects of a turbulence outer scale on the PSF and methods for modeling those in the PSF was submitted to a peer-reviewed journal in early April [6].

3 Participants and collaborations

Ralf Flicker has been dedicated full-time to this project. Erik Johansson and David Le Mignant have provided support for the project at about 5-10% level. Other participants have been consulted for technical issues for modeling, analysis or data management. This includes Marcos van Dam (AO scientist at WMKO-left 12/07), Matthew Britton (AO scientist at COO), Jeff Mader (software engineer at WMKO) and Michael Fitzgerald (post-doctoral researcher at LLNL). All these individuals are already participants of the CfAO.

4 Center activities

Ralf Flicker attended the CfAO 2007 fall retreat and gave a presentation on the proposed work. This was only two days after the starting date of the project.

David Le Mignant is the lead instructor for the fourth edition of the Akamai Observatory Short Course (AOSC) taking place on June 2-6 in Hawaii. The AOSC is part of the Akamai Internship Program that provides an internship within the Mauna Kea observatories for 15 students.

References

[1] "Development, implementation and validation of PSF reconstruction techniques," Y9 CfAO proposal (2007) URL: `http://lao.ucolick.org/twiki/pub/CfAO/PsfReconstruction/CfAOY9LeMignant_v3nobudget.pdf`

[2] PSF reconstruction project TWiki web page and document collection, URL: `http://lao.ucolick.org/twiki/bin/view/CfAO/PsfReconstruction`

[3] 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** (1997).

[4] M. van Dam, E. Johansson, P. Stomski, J. Chin, R. Sumner and P. Wizinowich, "Keck Adaptive Optics Note 489: Performance of the Keck II Next-Generation Wave Front Controller", URL: `http://www2.keck.hawaii.edu/optics/aodocs/KAON489.pdf`

[5] E. Gendron, Y. Clénet, T. Fusco, and G. Rousset, "New algorithms for adaptive optics point-spread function reconstruction," Astron. Astrophys. **457**, 359–363 (2006).

[6] R. Flicker, "Outer scale effects on anisoplanatism in adaptive optics," submitted to OSA, April 2008.

[7] L. Jolissaint, J.-P. Veran and J. Marino, "OPERA, an automatic PSF reconstruction software for Shack-Hartmann AO systems: application to Altair," Proc. SPIE **5490**, 151–163 (2004).

[8] F. J. Rigaut, J. Veran, and O. Lai, "Analytical model for Shack-Hartmann-based adaptive optics systems," Proc. SPIE **3353**, 1038–1048 (1998).

[9] R. Flicker et al., "NGAO High-Contrast & Companion Sensitivity Performance Budget," KAON 497 (2007) URL: `http://www.oir.caltech.edu/twiki_oir/pub/Keck/NGAO/HighContrastBudget/contrast.pdf`

[10] M. Schöck, D. Le Mignant, G. A.Chanan, P. L.Wizinowich, and M. A.van Dam, "Atmospheric turbulence characterization with the Keck adaptive optics systems. I. Open-loop data," Appl. Opt. **42**, 3705–3720 (2003).