PSF reconstruction for integral field spectrograph OSIRIS at Keck

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ABSTRACT

PSF information is central to extract science information with adaptive optics observations. However, spatial and temporal variations in the PSF have been a major obstacle in obtaining accurate PSFs. In particular, anisoplanatism is a dominant source of PSF variation for observations of the Galactic center with Keck, using laser-guide star adaptative optics. The Galactic Center Group at UCLA has developed algorithms to predict PSF variability for Keck AO images (Off-axis PSF reconstruction), creating a new software package (AIROPA). For OSIRIS integral field spectrograph the small field of view prevents from having a good estimate of the PSF. AIROPA allows to use a parallel imager to do so, correcting for the imager's anisoplanatism and for instrumental aberrations. Here, we present preliminary results of the application of this post-processing tool to OSIRIS datasets in the Galactic Center.

Keywords: Off-axis PSF Reconstruction, Field-dependent Aberrations, Integral Field Spectrograph, Keck Observatory, Keck I/OSIRIS, Near-infrared, Galactic center

1. INTRODUCTION

The Center of our Galaxy is a unique laboratory for the study of a supermassive black hole (SMBH) and its connection to galaxy evolution and formation. In particular, monitoring stars orbiting this SMBH gives a unique chance of testing General relativity in the strong gravity regime. In Summer 2018, the short-period star S0-2 will be at its closest approach to the SMBH. Measurements of this star will make it possible to explore the Einstein Equivalence Principle by detecting the gravitational redshift.[1,2] Such measurements are based on observations with the adaptive optics integral field spectrograph (IFS) at Keck, OSIRIS.[3]

The OSIRIS[4] field of view is of only 1-2 arcseconds for its smallest spatial scales (20 mas & 35 mas). Thus, there is often no good empirical point spread function (PSF) estimate for the OSIRIS spectrograph because the PSF halo is larger than the field of view. The empirical PSF estimation is also particularly difficult in the very crowded innermost region of the Galactic center (Fig. 1, right). OSIRIS is equipped with an imager that can take parallel observations to track changes in the PSF of a reference star (Fig. 1, left), but its distance of 20 arcseconds from the IFS makes it impossible to apply its PSF directly to spectroscopic data. This is due to atmospheric anisoplanatism and instrumental aberrations. For the imager, anisoplanatism is particularly severe because it is far form the laser guide star (LGS, centered on the IFS). The off-axis position of the tip-tilt stars, the LGS, and the off-axis science targets each probe different columns of atmosphere. The single-conjugate AO system, such as the one at the Keck Telescopes, cannot correct them all. Mitigating these effects requires multi-conjugate AO, but post-processing tools are a promising alternative.

The Galactic Center Group is developing a new software package to predict PSF variability for Keck AO images (Anisoplanatic and Instrumental Off-axis PSF Reconstruction, AIROPA[5]). The main goal of the project was to apply AIROPA to data taken with NIRC2 imager on Keck II.[5–7] The code requires two input models: a model describing the instrumental phase aberrations and an atmospheric model.

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In this work, we extend and adapt this post-processing tool for OSIRIS in order to use the observed imager PSF to predict the IFS PSF. The characterization of OSIRIS' aberrations is still under way but here we report preliminary results of the application of the AIROPA atmospheric model of anisoplanatism with LGS-AO to OSIRIS Galactic center data.

In Sect. 2 we briefly describe the method used by AIROPA to predict off-axis PSFs. In Sect. 3 we show how to apply AIROPA to an IFS. In Sect. 4 we show preliminary results on OSIRIS Galactic center data and in Sect. 5 we discuss the conclusions of this preliminary analysis.

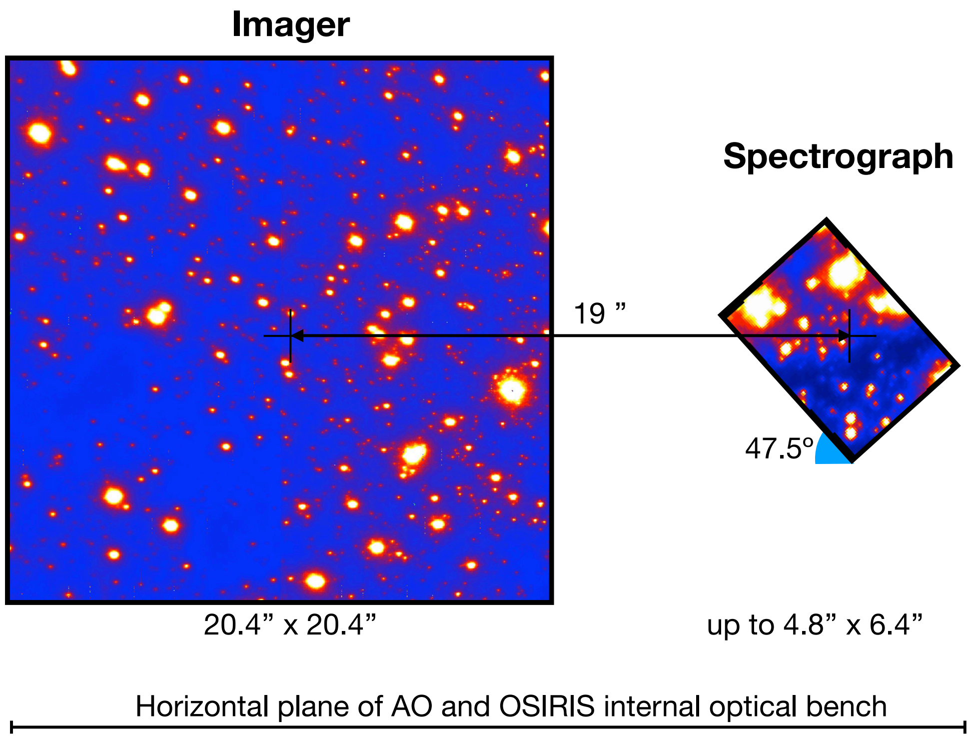

Figure 1. Representation of OSIRIS imager and spectrograph relative inclinations with an example of Galactic center dataset.

2. METHOD: OFF-AXIS PSF RECONSTRUCTION

AIROPA models the field-dependent PSF using two separable components that contribute to phase aberrations:

- Instrumental phase aberrations – these represent the phase aberrations coming from the telescope and instruments. We derive the phase aberrations as a function of field location using phase diversity data. These are obtained taking a sequence of out-of focus images on the detector with a fiber light source. This measurement is repeated at several positions covering roughly the whole detector field to obtain a grid of the static instrumental aberrations[6] (phase maps grid).
- Atmospheric effects – these represent the aberrations coming from atmospheric phase errors and the cone effect due to single-conjugate LGS AO. We use MASS/DIMM turbulence profiles independently recorded at the Telescope site to estimate the long-exposure phase aberrations at different field positions.[7,8]

Once these two components are characterized, starting from an empirical on-axis PSF, the corrected PSF_{final} can be written as:[8,9]

$$PSF_{final}(r) = PSF_0(r=0) \otimes PSF_{instr}(r) \otimes PSF_{atm}(r). \quad (1)$$

Where $PSF_0(r=0)$ is the empirical central PSF; $PSF_{instr}(r)$ is estimated with AIROPA instrumental code using the phase map grid in relation to the position on the detector; $PSF_{atm}(r)$ is estimated with AIROPA atmospheric code. For more details on the atmospheric and instrumental models and the AIROPA concept see.[5–7]

This factorization allows to use the on-axis PSF_0 (with no anisoplanatism and no instrumental aberrations) as a reference for PSFs throughout the field of view (off-axis). AIROPA has been applied to Keck/NIRC2 and is being tested with simulations and on-sky data (Witzel *et al.*, in prep.).

This approach is very well suited to solve the OSIRIS PSF estimation problem: adapting AIROPA to OSIRIS allows to correctly make use of the imager that functions in parallel to the IFS.

3. APPLICATION OF AIROPA TO AN INTEGRAL FIELD SPECTROGRAPH

With AIROPA the PSF observed on the imager can be used to correctly predict the PSF on the spectrograph, taking into account all the atmospheric and instrumental effects: correction of the anisoplanatism for the imager, and correction of the instrumental aberrations for both.

In doing so one has to take into account the fact that on the spectrograph we need to predict a PSF for each spectral channel. Also, the imager and the spectrograph have different pixel scales, thus the PSF needs to be rescaled accordingly. The procedure to obtain the corrected IFS PSF using the imager is as follows:

- Several off-axis stars on the imager are used to construct an on-axis imager PSF (Fig. 2).
- The on-axis imager PSF is then converted to the first wavelength on the spectrograph spectral band.
- The wavelength-corrected on-axis imager PSF, together with a turbulence profile (obtained through MASS/DIMM data obtained the same night as the observations) is fed into AIROPA to estimate the PSF on the spectrograph.
- This PSF is then rescaled to the IFS pixel scale.

The same process is repeated for all wavelength channels in the spectrograph filter. In this procedure we also take into account the fact that imager and IFS are rotated one in respect to the other of 47.5 degrees (Fig. 1). Fig 2 shows the imager empirical PSF and the predicted spectrograph PSF at two different wavelengths, obtained for Galactic Center data in 2017.

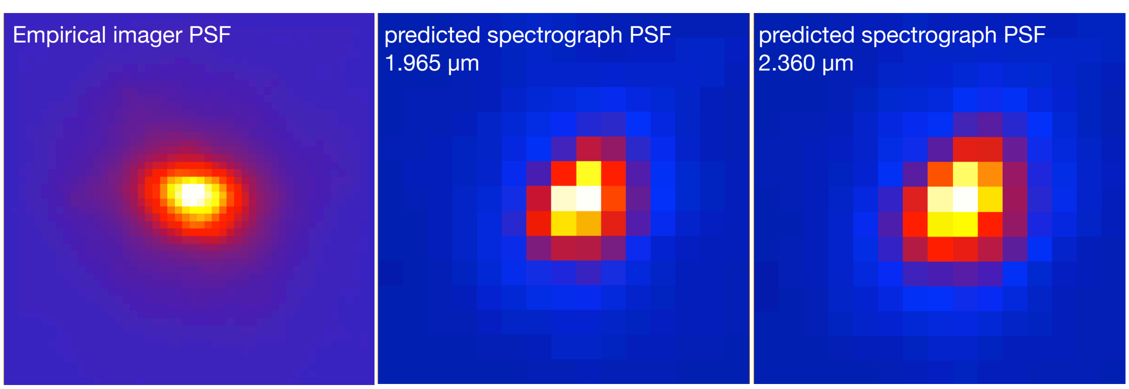

Figure 2. Example of prediction of IFS PSF from imager PSF using AIROPA atmospheric code. *Left:* empirical imager PSF. *Center and right:* derived IFS PSF at two wavelengths.

4. PRELIMINARY RESULTS

We applied the method outlined above to model 2017 data of a star in the central few arcseconds of the Galactic center (S2-36[10]), located very close to a bright star (GCIRS16 CC). Due to the proximity to the bright star, S2-36 spectrum is very hard to extrapolate without a good knowledge of the PSF halo.

The predicted PSF (Fig 2, center and right) is used to fit the data (Fig 3, left) and produce a model of the observations (Fig 3, center). For comparison, we also fit the same data with multiple 2D-Gaussians without any knowledge of the PSF shape (Fig 3, right). The model obtained with the AIROPA-predicted PSF well reproduces the observations: both stars are recovered, the PSF shapes are very consistent and have a well-reproduced core. The 2D-Gaussians are incapable of recovering the fainter star, which shows this model is inadequate to describe AO data.

This example of AIROPA application is still missing the instrumental model but these preliminary results show that this procedure is very promising for the prediction of PSFs: with AIROPA the PSF core is well reproduced and the halo is better constrained even in crowded fields, such as the Galactic Center.

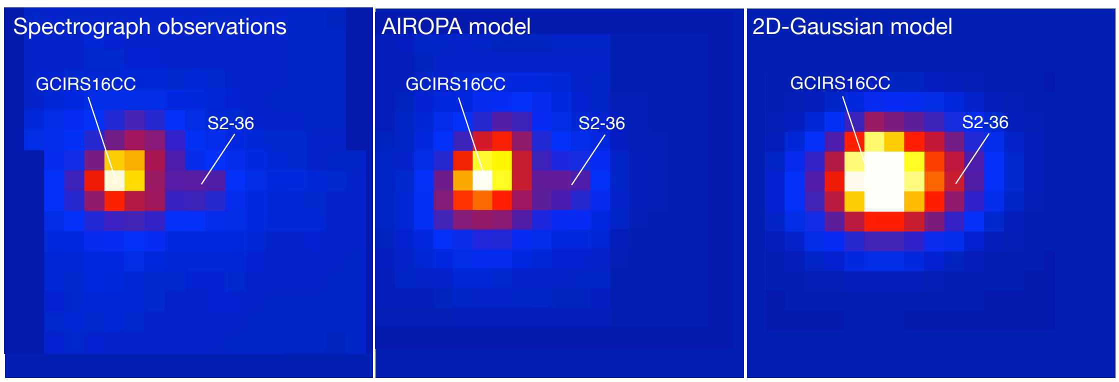

Figure 3. Application of predicted PSF to spectro-imaging data of two close stars at the Galactic center: spectroscopic observations (*left*) can be modeled through the AIROPA-predicted PSF (*center*) and compared to multiple 2D-Gaussians profile fit (*right*).

5. CONCLUSIONS

We have adapted the AIROPA tool for off-axis PSF prediction for use with the Keck OSIRIS integral field spectrograph. We can predict the spectrograph PSF using simultaneous off-axis images of stars in a crowded field, together with a turbulence profile and AIROPA atmospheric modeling. The adaptation of AIROPA is still on-going, but preliminary results show that the predicted PSF is well matched to observations.

Knowledge of the halo of the IFS PSF will significantly improve the extraction of stellar spectra in crowded fields such as the Galactic center, or for high-contrast applications. The parallel imager corrected images can also open a new window to the use of imager and IFS in parallel, which was previously difficult to exploit without PSF reconstruction.

The generalization of AIROPA is a milestone on the way of implementing the semi-empirical off-axis PSF reconstruction approach to future instruments at extremely large telescopes such as the Thirty Meter Telescope (TMT).

REFERENCES

[1] Zucker, S., Alexander, T., Gillessen, S., Eisenhauer, F., and Genzel, R., “Probing post-newtonian gravity near the galactic black hole with stellar doppler measurements,”

[2] Hees, A., Do, T., Ghez, A. M., Martinez, G. D., Naoz, S., Becklin, E. E., Boehle, A., Chappell, S., Chu, D., Dehghanfar, A., Kosmo, K., Lu, J. R., Matthews, K., Morris, M. R., Sakai, S., Schödel, R., and Witzel, G., "Testing general relativity with stellar orbits around the supermassive black hole in our galactic center," (05 2017).

[3] Boehle, A., Ghez, A. M., Schödel, R., Meyer, L., Yelda, S., Albers, S., Martinez, G. D., Becklin, E. E., Do, T., Lu, J. R., Matthews, K., Morris, M. R., Sitarski, B., and Witzel, G., "An improved distance and mass estimate for sgr a* from a multistar orbit analysis," (07 2016).

[4] Larkin, J., Barczys, M., Krabbe, A., Adkins, S., Aliado, T., Amico, P., Brims, G., Campbell, R., Canfield, J., Gasaway, T., Honey, A., Iserlohe, C., Johnson, C., Kress, E., LaFreniere, D., Lyke, J., Magnone, K., Magnone, N., McElwain, M., Moon, J., Quirrenbach, A., Skulason, G., Song, I., Spencer, M., Weiss, J., and Wright, S., "OSIRIS: a diffraction limited integral field spectrograph for Keck," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Proc. SPIE **6269**, 62691A (June 2006).

[5] Witzel, G., Lu, J. R., Ghez, A. M., Martinez, G. D., Fitzgerald, M. P., Britton, M., Sitarski, B. N., Do, T., Campbell, R. D., Service, M., Matthews, K., Morris, M. R., Becklin, E. E., Wizinowich, P. L., Ragland, S., Doppmann, G., Neyman, C., Lyke, J., Kassis, M., Rizzi, L., Lilley, S., and Rampy, R., "The AIROPA software package: milestones for testing general relativity in the strong gravity regime with AO," in [*Adaptive Optics Systems V*], Proc. SPIE **9909**, 99091O (July 2016).

[6] Sitarski, B. N., Witzel, G., Fitzgerald, M. P., Meyer, L., Ghez, A. M., Campbell, R. D., Lu, J. R., Matthews, K., Wizinowich, P., and Lyke, J., "Modeling instrumental field-dependent aberrations in the NIRC2 instrument on the Keck II telescope," in [*Adaptive Optics Systems IV*], Proc. SPIE **9148**, 91486T (Aug. 2014).

[7] Fitzgerald, M. P., Witzel, G., Britton, M. C., Ghez, A. M., Meyer, L., Sitarski, B. N., Cheng, C., Becklin, E. E., Campbell, R. D., Do, T., Lu, J. R., Matthews, K., Morris, M. R., Neyman, C. R., Tyler, G. A., Wizinowich, P. L., and Yelda, S., "Modeling anisoplanatism in the Keck II laser guide star AO system," in [*Adaptive Optics Systems III*], Proc. SPIE **8447**, 844724 (July 2012).

[8] Britton, M., "The anisoplanatic point spread function in adaptive optics,"

[9] Fusco, T., Conan, J.-M., Mugnier, L. M., Michau, V., and Rousset, G., "Characterization of adaptive optics point spread function for anisoplanatic imaging. Application to stellar field deconvolution," A&AS **142**, 149–156 (Feb. 2000).

[10] Do, T., Lu, J. R., Ghez, A. M., Morris, M. R., Yelda, S., Martinez, G. D., Wright, S. A., and Matthews, K., "Stellar Populations in the Central 0.5 pc of the Galaxy. I. A New Method for Constructing Luminosity Functions and Surface-density Profiles," ApJ **764**, 154 (Feb. 2013).