Point-Spread Function Reconstruction for Integral-Field Spectrograph Data

Tuan Do[a], Anna Ciurlo[a], Gunther Witzel[a], Jessica Lu[b], Paolo Turri[b], Michael Fitzgerald[a], Randy Campbell[c], Jim Lyke[c], and Andrea Ghez[a]

[a]Physics and Astronomy Department, University of California, Los Angeles, CA, USA
[b]University of California, Berkeley, CA
[c]W. M. Keck Observatory, HI

ABSTRACT

Knowledge of the point spread function (PSF) is critical to many astronomical science cases. However, the PSF can be very difficult to estimate for cases where there are many crowded point sources or for observations of extended objects. Additionally, for adaptive optics observations, the PSF can be very complex with both spatial and temporal variability in the PSF. Integral-field spectroscopy behind adaptive optics is especially challenging because the fields of view are typically too small to sample the halo for even a single PSF. Here, we present a method for semi-empirical PSF reconstruction for integral field spectrographs using a combination of point source observations on a parallel imager, instrumental aberration measurements, and atmospheric turbulence profiles. This work builds upon the PSF reconstruction project AIROPA designed for imaging and extending it to IFU work (AIROPA-IFU). By using empirical calibrators from the parallel imager, which has a much larger field of view, and accounting for anisoplantic effects and instrumental aberrations, we can predict the PSF on the spectrograph. An important aspect is being able to predict the PSF at many different wavelengths based on observations from broad-band imaging. Here, we discuss how science cases such as observations of stars at the Galactic center can benefit from this method. We also establish metrics to quantitatively assess the performance of PSF reconstruction. We show that for bright stars, AIROPA-IFU can produce spectra with signal to noise ratio 50% higher than with simple aperture extraction of a data cube.

Keywords: Adaptive optics, point spread function

1. INTRODUCTION

Many astronomical observations require knowledge of the point spread function (PSF) in order to separate the intrinsic properties of an astronomical object from the effects of the instrument and atmosphere. For example, the inferred morphology of galaxies can vary significantly with assumptions about the PSF, since the PSF can distort intrinsic features and add artifacts 1. The PSF is very important for astrometric and photometric measurements of point sources as well. Knowledge of the PSF is often the major source of systematic uncertainty in astrometry and photometry 2. The need for PSF information for adaptive optics (AO) observations is even more acute because the atmosphere is constantly changing, which greatly increases the variations in the PSF and potentially, the scientific results.

PSF reconstruction for integral field spectroscopy behind AO is even more challenging. Often, integral field spectrographs (IFUs) have small fields of view because of the high spatial sampling required for AO observations. This often precludes having good PSF reference sources in the same field as the science target. Even for the cases where there are many point sources within the IFU field of view, such as observations of the Galactic center 3–5, source confusion and the small field of view limits our ability to estimate the PSF halos. For Galactic center observations, the spectra are usually extracted using a circular aperture centered on each star (Figure 1). This means that the halo of other stars often contribute flux in the aperture. This can dominate over other noise

Further author information: (Send correspondence to T. Do)
T. Do: E-mail: tdo@astro.ucla.edu

Adaptive Optics Systems VI, edited by Laird M. Close, Laura Schreiber, Dirk Schmidt, Proc. of SPIE Vol. 10703, 107030I · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2314216

sources depending on the distance to other sources. An accurate estimate of the PSF in conjunction with PSF fitting should be able to greatly improve the signal to noise ratio (SNR) of the extracted spectra.

In this work, we present a method for PSF reconstruction with AO IFU data. This method is an extension of the AIROPA (Anisoplanatic and Instrumental Reconstruction of Off-axis PSFs for AO) software package.[2] The extension, which we name AIROPA-IFU, uses a semi-empirical estimate of the PSF from a parallel imager (Figure 2), along with measurements of the atmospheric profile and instrument aberrations to predict the PSF on the spectrograph. In Section 2, we summarize the methodology. In Section 3, we discuss metrics for PSF reconstruction. In Section 4, we present results from simulations and applications to observations. We discuss the implications for this methodology in Section 5.

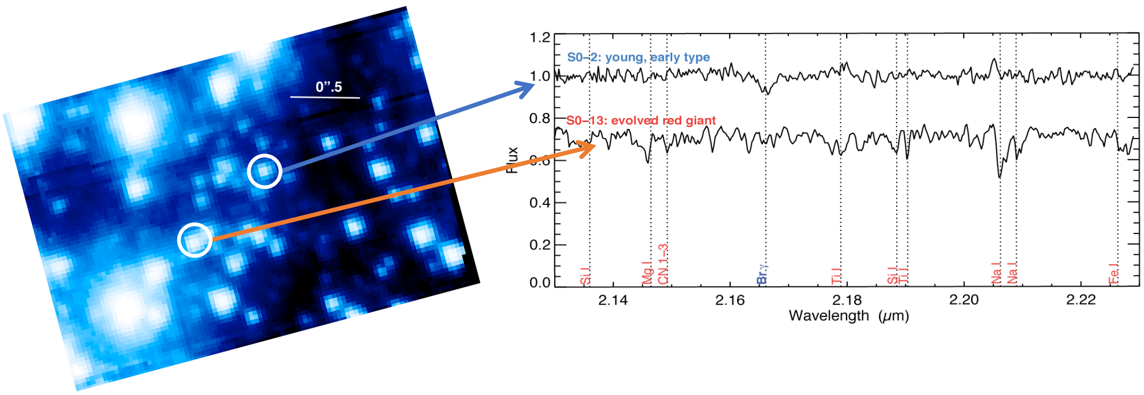

Figure 1. **Left:** Collapsed spectral cube from a typical observation of the Galactic center. **Right:** Example spectra of two stars in the field, extracted using a circular aperture for each spectral channel of the data cube. The spectra are from 4.

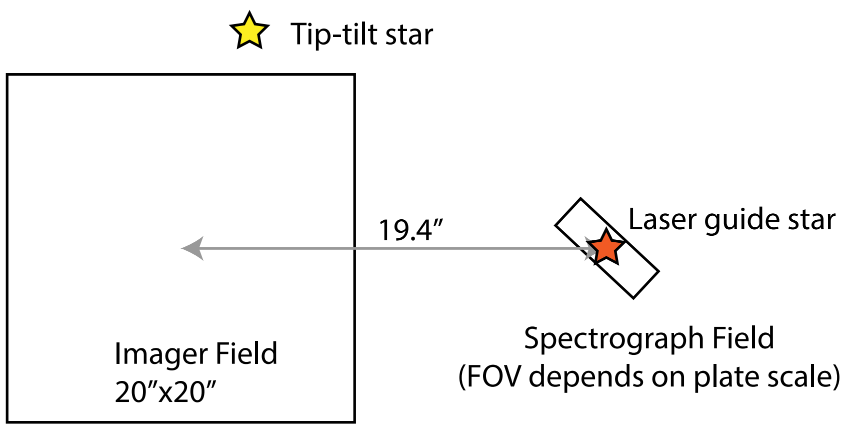

Figure 2. The instrument layout for the OSIRIS IFU. OSIRIS consists of two instruments, an imager and an IFU. The two instruments are about 20" apart in the focal plane. Typically, observations with the IFU will have the laser guide star centered on the spectrograph. A major advantage of OSIRIS is that both instruments can be used simultaneously, which enables observations of PSF references on the imager.

2. METHODOLOGY

2.1 AIROPA

The software package AIROPA assumes every PSF consists of the convolution of three components: (1) the on-axis PSF, (2) the instrumental aberration at that location, and (3) the atmospheric model to account for anisoplantism:

$$PSF_{off-axis} = PSF_{on-axis} * PSF_{Inst} * PSF_{atm} \tag{1}$$

By measuring these three components, the PSF observed at one location can be used to predict the PSF at any other field position. Details about the implementation of this code can be found in 2, 6. This semi-empirical approach requires three inputs: (1) an image (science data) that contains one or more point sources, (2) estimates of the instrumental phase errors at different locations on the detector, and (3) a turbulence profile from MASS/DIMM measurements taken at the same time as the science data. The advantage of this approach is that it can capture static errors in the PSF that are difficult to model *a priori*.

2.2 Extensions for integral field spectroscopy: AIROPA-IFU

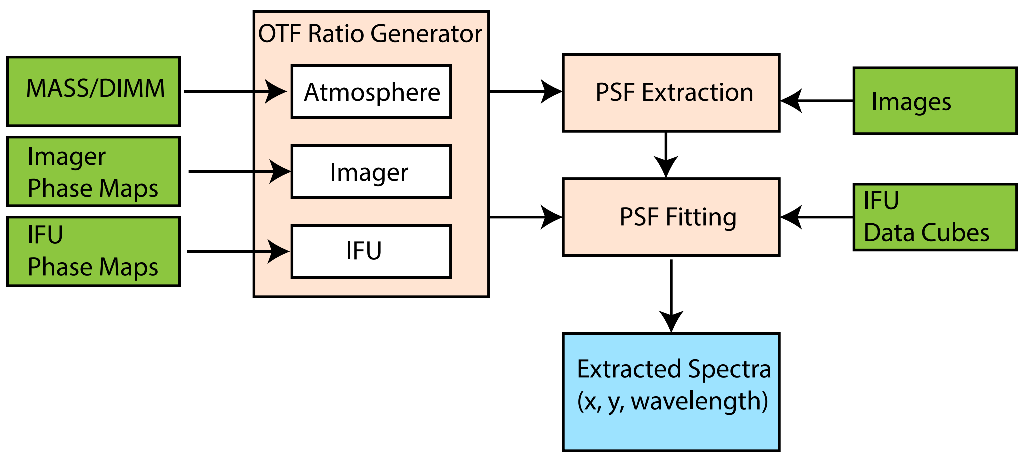

Figure 3. Diagram of the major components of AIROPA-IFU. Green are input data, orange are the AIROPA-IFU software components, and blue indicates the output.

We adapted the AIROPA software for spectroscopy by including three additional components:

- Initial empirical PSF estimation using a parallel imager (can be substantially off-axis from the spectrograph).
- Phase maps from imager and spectrographs in PSF estimation and prediction
- Account for PSF estimation at one wavelength (from the imager), but predictions at many other wavelengths (spectrograph). We also account for potential changes in plate scale between the imager and spectrograph.

We describe these modifications in more details below. We will use the example of the application to the OSIRIS instrument at W. M. Keck Observatory.

2.2.1 Initial PSF Estimation

The initial empirical PSF estimate is obtained by using a parallel imager. For OSIRIS, this is about 20” off-axis from the IFU. This imager has a field of view of 20”x20”, which is substantially larger than is possible with the IFU. Any bright point source with sufficiently well sampled halo can be used on the imager. Multiple stars on the imager can also be used to better sample the PSF. The chosen PSF is deconvolved by using both the instrumental and atmospheric phase maps to obtain the PSF that would be observed if both the tip-tilt star and laser guide star are on axis. We term this the on-axis PSF. This process is repeated for the case of multiple stars before combining them. The resulting PSF is a semi-empirical estimate that will be used for all subsequent off-axis PSF reconstruction.

2.2.2 Instrumental aberrations

Since AIROPA-IFU uses an imager and IFU, it must use estimates of the instrumental aberrations for both instruments. The instrumental aberration map for the imager are used in the initial PSF estimate as outline above, while the IFU phase map is used to generate PSF predictions. For OSIRIS, we map the spatial variations in the aberration using phase diversity across the imager in a 9×9 grid. We measure the phase aberrations of the central position of the IFU because of its much smaller field of view. See Ciurlo et al. (these Proceedings) for more details.

2.2.3 Predictions at different wavelengths and plate scales

We have also adapted AIROPA to easily produce predicted PSFs at wavelengths different than the one used for the initial semi-empirical PSF estimate. This is important as as the OSIRIS imager can use a wide range of filters, independent of the filter for the IFU. In addition, the IFU wavelength coverage can be fairly broad. We account for three components that have a wavelength dependence: (1) diffraction, (2) transformation of instrumental phase maps measured in radians to wavefront error, and (3) the atmospheric model.

For OSIRIS, the imager is at a fixed plate scale, while the IFU have multiple plate scales. To account for the changes to the plate scale, we resample the imager PSF to that of the spectrograph PSF after the initial PSF estimation stage. See Ciurlo et al. (these Proceedings) for more details.

3. METRICS

To test the performance of our PSF reconstruction, we utilize several metrics to characterize the precision and accuracy of the reconstruction. The metrics are:

- Fraction of variance unexplained (FVU) - the FVU is defined as the mean square error of the PSF estimate divided by the variance of the observed PSF:

$$FVU = \frac{\sum_i (PSF_{i,obs} - PSF_{i,model})^2}{Var(PSF_{obs})} \tag{2}$$

  where i is the ith pixel of the PSF. The FVU is a measure of how well the model can describe the data. It has several useful properties. If the FVU > 1, then using the mean of the PSF is a better description of the PSF than the model. When the model fits the data perfectly, then FVU $= 0$. The FVU is related to other common measures of model deviance, such as the coefficient of determination R^2, which describes the is the proportion of the variance in the dependent variable that is predictable from the independent variable ($FVU = 1 - R^2$).

- Astrometric and photometric precision - using a stack of images (either simulated or taken throughout one night), we can measure the standard deviation of the position and brightness of stars in the field. We use this as a measure of the precision of the measurements by assuming that the intrinsic position and brightness of these stars do not change during the night.

- Astrometric and photometric bias - using simulations where the input position and brightnesses of stars are known, we can measure the offset between the input position and the inferred one from PSF modeling and fitting. This is a measure of the accuracy of the PSF predictions.

- Signal to noise ratio (SNR) - for IFU observations, the measure of performance is the final signal to noise ratio of the spectrum as measured by the noise properties in regions of the spectrum that are free of stellar features. We define the SNR as the SNR per spectral channel.

4. RESULTS

Using metrics from Section 3, we estimated the performance of PSF reconstruction for two test cases. The first is an simulation of imaging observations of stars at the Galactic center to test the performance of the PSF reconstruction algorithm with perfect knowledge of the atmosphere and instrumental phase errors (Section 4.1). The second test is the spectral extraction of a bright star at the Galactic center observed with the OSIRIS spectrograph on the Keck I telescope (Section 4.2). In addition, parallel imaging observations and MASS/DIMM measurements were taken simultaneously. We also use instrumental phase maps for the imager and IFU. For details on this test case see Ciurlo et al. (in these Proceedings).

4.1 AIROPA Performance

In order to test if AIROPA is algorithmically sound and to determine the photometric and astrometric improvements that can be expected, we created a suite of test and simulation code. These simulations test how AIROPA performs assuming that the instrument model is accurate. We simulate the stars at the Galactic center to examine a realistic science case. To start, we use a long integration time empirical on-axis PSF from observations of a binary star system where the two components are separated by about the same amount as the distance from the supermassive black hole, Sgr A*, is from the tip-tilt star. We then generated a PSF grid based on the instrumental phase maps, and simulated a typical GC observations based on an empirical star list and a simulated underlying population of unresolved sources. These simulations used a pixel wise interpolation of the PSFs for position between grid points, and properly account for photon noise and readout noise contributions.

We then execute AIROPA's PSF extraction and PSF fitting algorithm on this dataset. Every step of the analysis is done exactly as for science data. The difference is that we use the same model for the differential PSF variations as the one used to create the simulations. This guarantees a test of all other components of AIROPA, from empirical on-axis PSF extraction, over PSF grid generation, to final PSF fitting. The resulting output positions and flux densities are then compared to the input lists.

To compare the performance of AIROPA, we performed PSF fitting on the simulated Galactic center data using a single average PSF as well as variable PSF predictions from AIROPA. The residuals from the fit are much lower when accounting for variations in the PSF using AIROPA (Figure 4 & 5). More quantitatively, we also measure the FVU and astrometric and photometric biases for the two cases (Figures 6 & 7). By these measures, AIROPA significantly improves upon using a single PSF. The FVU is up to a factor of 10 smaller for bright stars with AIROPA. Astrometric and photometric biases are also reduced by several factors when using AIROPA.

4.2 AIROPA-IFU Performance

To evaluate the performance of AIROPA-IFU, we compare the result of spectra extraction using a circular aperture to that of PSF reconstruction with AIROPA-IFU. Starting with an initial PSF estimate with the imager, along with instrument aberration maps and atmospheric profile, we reconstructed the PSF for the spectrograph (Figure 8). We then used this PSF for PSF fitting on the IFU data cube. In order to reduce the effect of noise on PSF fitting, we combine every 5 spectral channels together using a median. For the OSIRIS observations with the Kbb filter, this reduces the number of spectral channels from 1665 to 333 channels. We find that for bright sources such as IRS 16C, PSF fitting can significantly increases the SNR of the extracted spectra by up to 50 % (Figure 9. This is likely because PSF fitting is better able to separate the intrinsic flux from the star from the background. With aperture extraction, the background is estimated using an annulus around the extraction aperture. This can include the halo from the source itself, which would increase the noise of the extracted spectrum.

While the AIROPA-IFU appears to be promising for extracting spectra for bright sources, it can produce large artifacts for fainter sources. More work and verification will be necessary to implement AIROPA-IFU for general use. See Ciurlo et al. (these Proceedings) for more details.

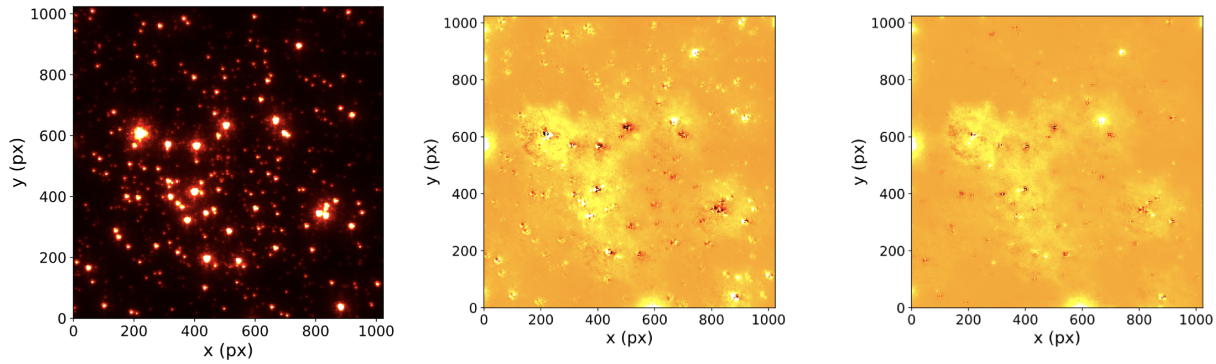

Figure 4. **Left:** Simulated Galactic center image using known sources. These simulations use variable PSFs generated by AIROPA along with instrumental aberration maps for the imager and atmospheric profile. **Center:** residual map from subtracting point sources detected using a single PSF for PSF fitting across the field of view. **Right:** residual map from subtracting point sources using variable PSFs from running AIROPA on the simulated data. The residuals are reduced when using variable PSFs.

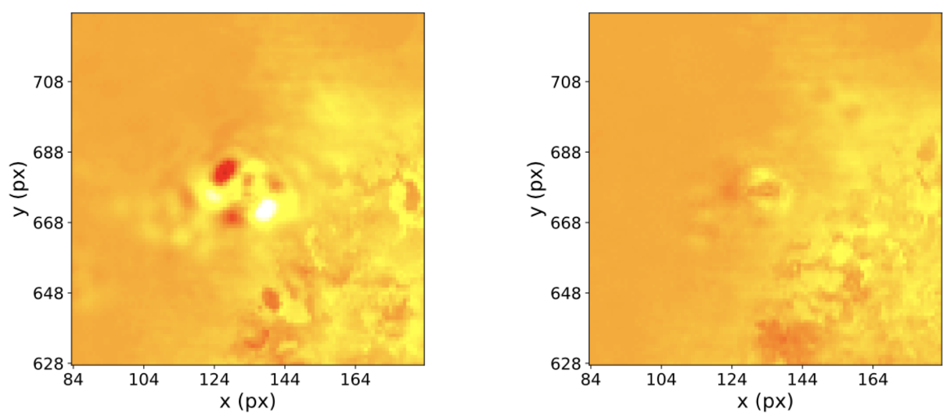

Figure 5. Examples of PSF residuals zoomed in from Figure 4. **Left:** residuals using a single PSF for PSF fitting (left) are larger than when accounting for variable PSFs with AIROPA (right).

5. CONCLUSIONS

In this work, we have demonstrated that AIROPA and its extension AIROPA-IFU can perform well for simulations and for spectroscopic extraction of bright stars. This semi-empirical approach is promising for the difficult problem of PSF reconstruction for IFU data in order to enable better spectral extraction. This work is also complementary to PSF reconstruction efforts using AO telemetry data to predict the on-axis PSF (e.g 7, 8). AIROPA can use this PSF instead of the initial empirically estimated PSF. The power of AIROPA is to be able to predict the PSF at any off-axis point in the field. The issues of PSF reconstruction will become more important as the next generation of AO instruments and telescopes seek to maximize their scientific output.

ACKNOWLEDGMENTS

This work was funded by the Moore Foundation and the W. M. Keck Foundation.

REFERENCES

[1] Wright, S. A., Larkin, J. E., Law, D. R., Steidel, C. C., Shapley, A. E., and Erb, D. K., "Dynamics of Galactic Disks and Mergers at z ˜ 1.6: Spatially Resolved Spectroscopy with Keck Laser Guide Star Adaptive Optics," ApJ **699**, 421–440 (July 2009).

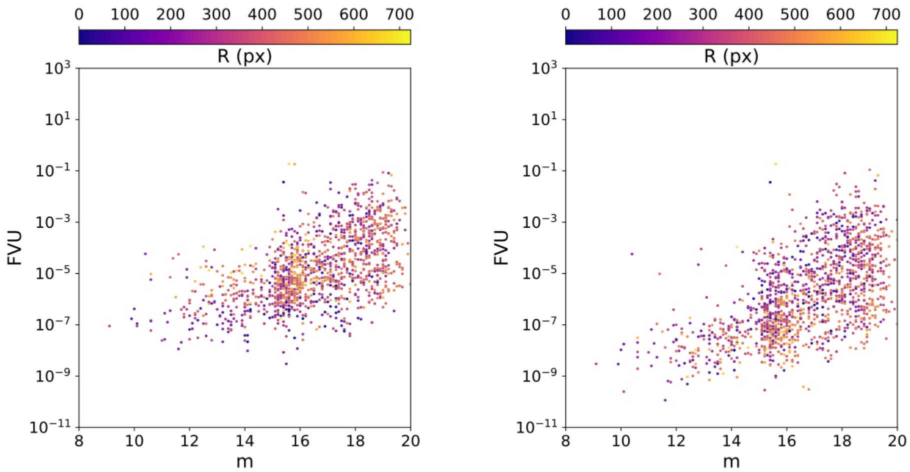

Figure 6. The relationship between the magnitude of a star and the resulting FVU from using a single PSF (left) compared to variable PSFs from AIROPA (right). The color of the points represent the distance from the center of the image in pixels. The FVU can be lower by a factor of 10 for bright stars using AIROPA.

[2] 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).

[3] Eisenhauer, F., Genzel, R., Alexander, T., Abuter, R., Paumard, T., Ott, T., Gilbert, A., Gillessen, S., Horrobin, M., Trippe, S., Bonnet, H., Dumas, C., Hubin, N., Kaufer, A., Kissler-Patig, M., Monnet, G., Ströbele, S., Szeifert, T., Eckart, A., Schödel, R., and Zucker, S., "SINFONI in the Galactic Center: Young Stars and Infrared Flares in the Central Light-Month," ApJ **628**, 246–259 (July 2005).

[4] Do, T., Ghez, A. M., Morris, M. R., Lu, J. R., Matthews, K., Yelda, S., and Larkin, J., "High Angular Resolution Integral-Field Spectroscopy of the Galaxy's Nuclear Cluster: A Missing Stellar Cusp?," ApJ **703**, 1323–1337 (Oct. 2009).

[5] Støstad, M., Do, T., Murray, N., Lu, J. R., Yelda, S., and Ghez, A., "Mapping the Outer Edge of the Young Stellar Cluster in the Galactic Center," ApJ **808**, 106 (Aug. 2015).

[6] 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).

[7] Martin, O. A., Correia, C. M., Gendron, E., Rousset, G., Gratadour, D., Vidal, F., Morris, T. J., Basden, A. G., Myers, R. M., Neichel, B., and Fusco, T., "Point spread function reconstruction validated using on-sky CANARY data in multiobject adaptive optics mode," *Journal of Astronomical Telescopes, Instruments, and Systems* **2**, 048001 (Oct. 2016).

[8] Ragland, S., Jolissaint, L., Wizinowich, P., van Dam, M. A., Mugnier, L., Bouxin, A., Chock, J., Kwok, S., Mader, J., Witzel, G., Do, T., Fitzgerald, M., Ghez, A., Lu, J., Martinez, G., Morris, M. R., and Sitarski, B., "Point spread function determination for Keck adaptive optics," in [*Adaptive Optics Systems V*], Proc. SPIE **9909**, 99091P (July 2016).

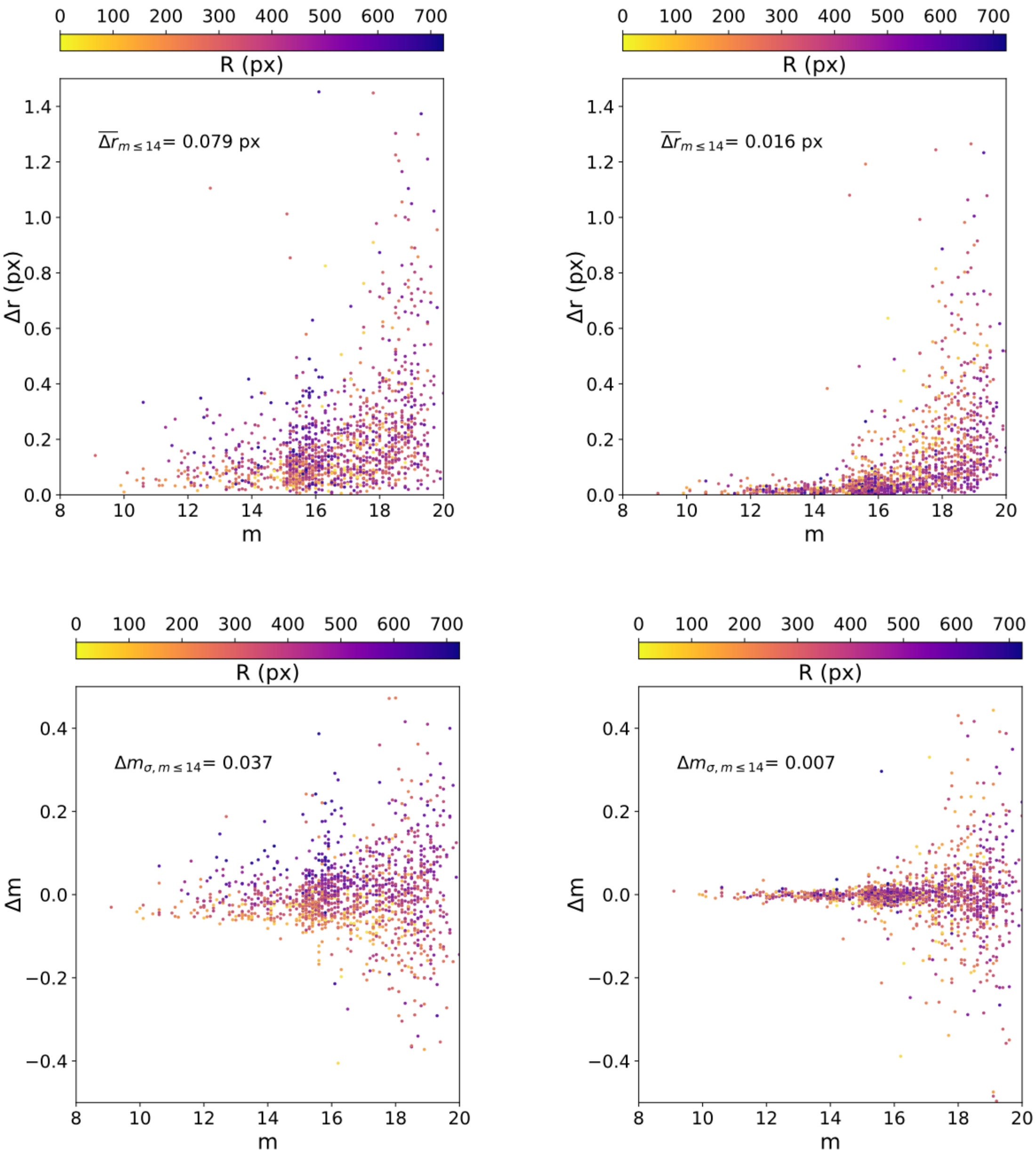

Figure 7. **Top:** The difference between input and inferred astrometric positions of stars in the simulation using a single PSF (left) and variable PSFs with AIROPA (right). **Bottom:** The difference between input and inferred brightness (magnitude) of stars in the simulation using a single PSF (left) and variable PSFs with AIROPA (right). The color of the points represent the distance from the center of the image in pixels. By accounting for PSF variations, AIROPA can significantly reduce both astrometric and photometric biases.

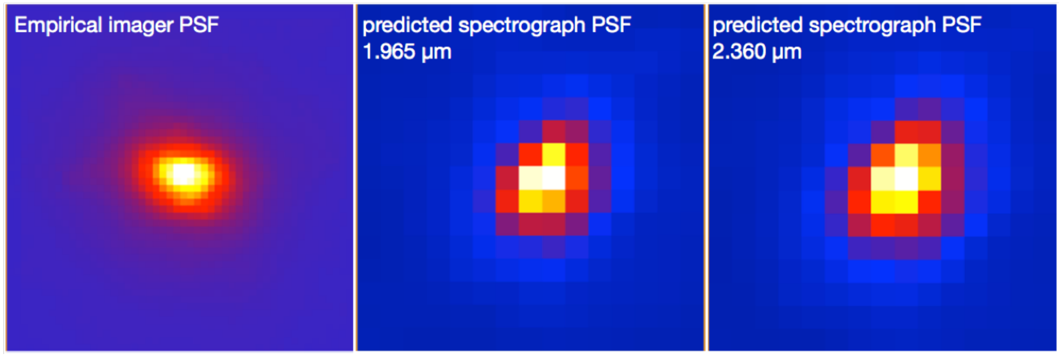

Figure 8. Example of AIROPA-IFU PSF reconstruction for OSIRIS. **Left:** PSF estimate from the OSIRIS imager (20 mas plate scale). **Center:** PSF predicted for the IFU at 1.965 μm (35 mas plate scale). **Right:** PSF predicted for the IFU at 2.360 μm. The rotation in the predicted PSF arises from the relative rotation angle between the OSIRIS imager and IFU.

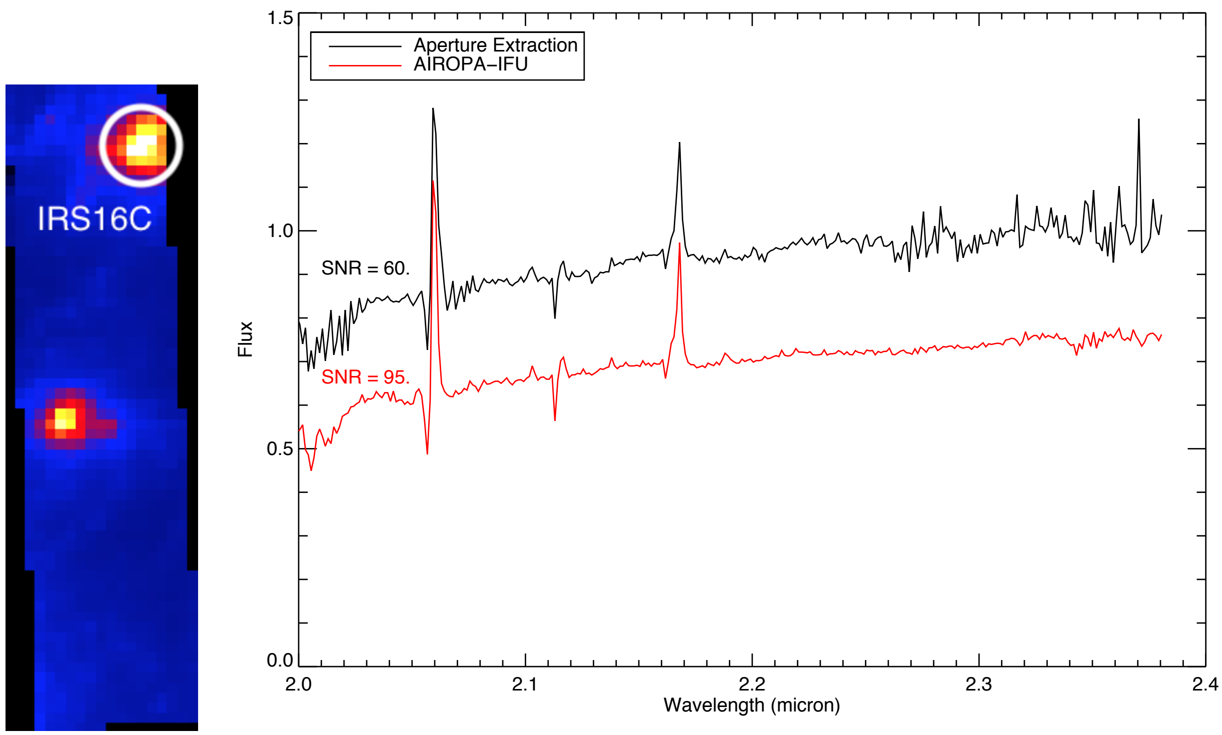

Figure 9. **Left:** An image from a median collapse of an OSIRIS IFU data cube. We test our IFU PSF reconstruction on the star IRS 16C (white circle). These observations are at a plate scale of 35 mas per spaxel and using the Kbb filter. The field of view is $0.56'' \times 2.24''$. **Right:** the spectrum of IRS16C as extracted using a circular aperture (black) compared to using PSF reconstruction and PSF fitting with AIROPA-IFU (red). For bright point source such as IRS16C, AIROPA can improve the SNR of the extracted spectra by up to 50% compared to using aperture extraction.