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AIROPA:Off-Axis Adaptive Optics PSF Reconstruction in Simulation, On-Bench, and On-Sky

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Abstract

We present on-sky tests of AIROPA, a software package designed to model off-axis, adaptive optics (AO) point spread functions (PSF) and extract stellar astrometry and photometry. We test the effectiveness of AIROPA to reconstruct the PSF with Keck NIRC2 images in varying atmospheric conditions. We compare the astrometric precision and fitting residuals between a spatially uniform **single PSF** and a spatially **variable PSF** model that incorporates instrumental aberrations and atmospheric turbulence during exposures. We find photometric performance is improved by 10x as measured by the spread in a Keck+HST color-magnitude diagram at different distances from the field center or guide star. We find similar astrometric performance between both modes, with a 15% smaller astrometric uncertainty for variable-PSF over single-PSF mode in the best case. We attribute the limited astrometric improvements to telescope aberrations that are not characterized through afternoon adaptive optics (AO) bench calibrations.

What is AIROPA?

Imperfect knowledge of the spatially varying (i.e. off-axis) PSF in AO images limits astrometric and photometric science. The **Anisoplanatic and Instrumental Reconstruction of Off-axis PSFs for AO (AIROPA)** is a suite of software that generates a model of the field-dependent PSF for both natural guide star (NGS) and laser guide star (LGS) observations from the Keck AO-fed instruments, NIRC2 and OSIRIS.

AIROPA assumes that the field-dependent PSF is a convolution of:

- the on-axis PSF extracted from science images,
- a field-dependent, static instrumental aberration kernel, and
- a time-variable atmospheric anisoplanatism kernel.

Further descriptions of AIROPA and the sub-modules that it is built upon are given in (Witzel+ 2016, Turri+ submitted, Ciurlo+ submitted, Terry+ in prep).

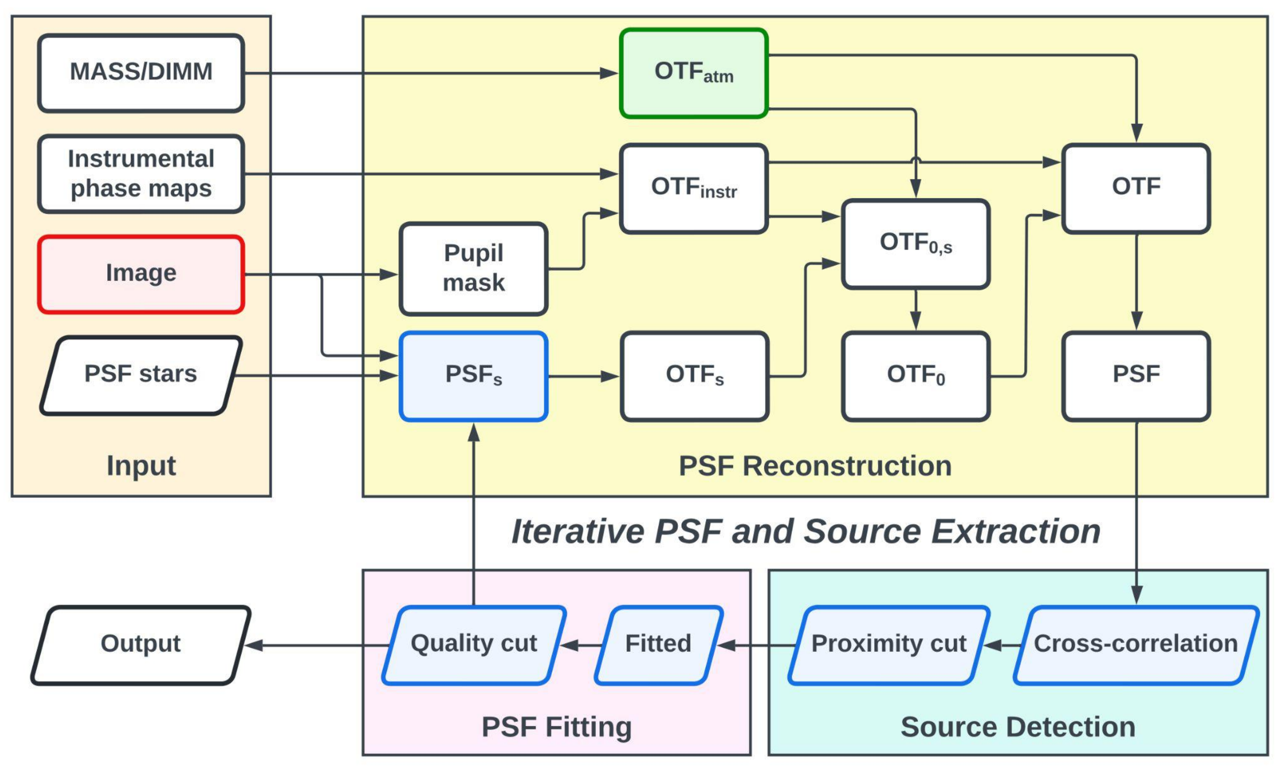


Figure: AIROPA's input ingredients, including MASS/DIMM atmospheric profile data, instrumental phase maps constructed from phase diversity data from an AO bench calibration source, science images, and a list of locations for PSF stars. AIROPA's outputs are a list of extracted stellar positions and fluxes.

Instrumental Calibration from Phase Diversity Data:

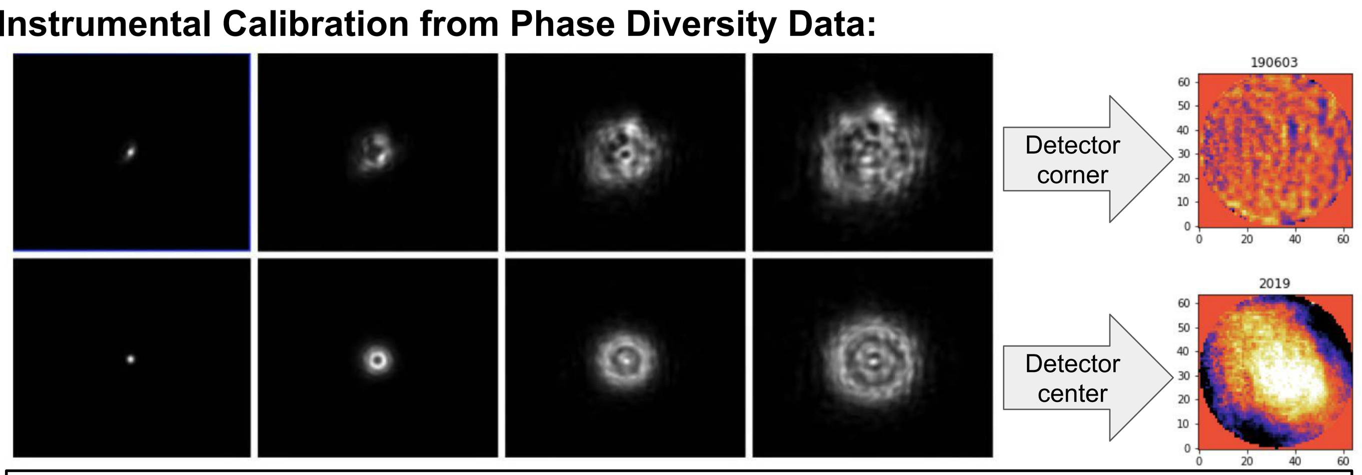
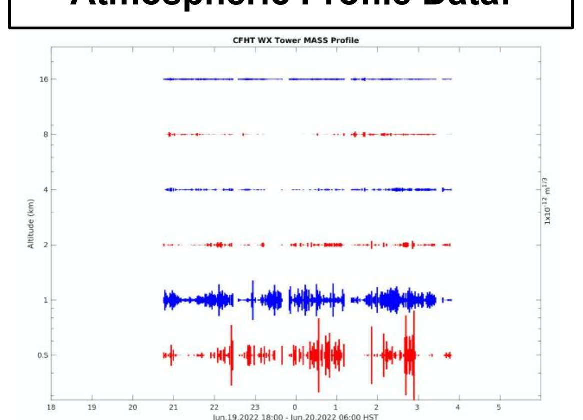
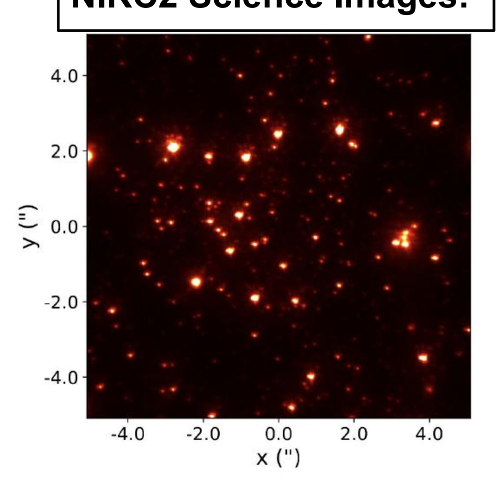


Figure: From left to right: in-focus and out-of-focus (-2,-4,-6 mm) fiber images (*left panel*) used to reconstruct phase aberration maps (*right panel*). The top-right corner (*top row*) and the center (*bottom row*) of NIRC2 show large variations.

MASS/DIMM Atmospheric Profile Data:



NIRC2 Science Images:



Simulation Results

[*Turri et al., submitted*]

A NIRC2 Galactic Center image was simulated using realistic conditions (i.e. zenith angle, MASS/DIMM profile) and AIROPA was run in single- and variable-PSF modes (Turri et al., submitted).
Metric = Output - input positions (Δr) and brightness (Δm).

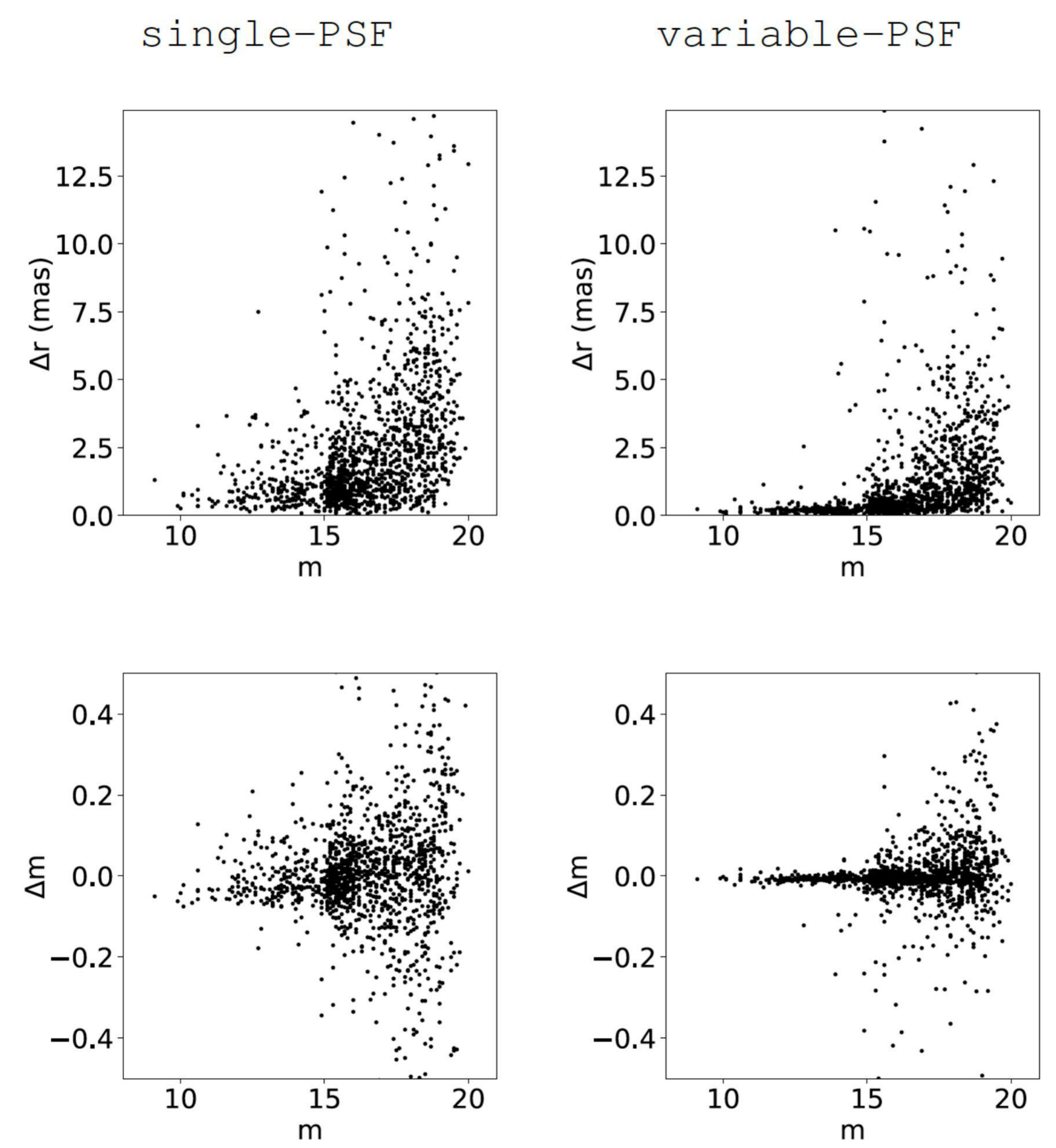


Figure: Astrometric (*top row*) and photometric (*bottom row*) residuals with AIROPA on a simulated Galactic Center image, as a function of magnitude.

A clear reduction in the astrometric and photometric residuals can be seen in Variable mode, as well as an **order of magnitude smaller FVU values**. This shows that AIROPA Variable mode is successfully modeling the spatially varying off-axis PSF in simulated data. The next steps are to perform these tests on real science images from NIRC2 (see right panel of this poster).

On-Bench Results

[*Ciurlo et al., submitted*]

Images were taken of a calibration fiber at numerous field positions and AIROPA was run in single- and variable-PSF modes. The fractional residuals after subtracting the model PSF improved from 4.1×10^{-3} to 1.7×10^{-3} in variable mode.
Metric = Observed - model PSF and the fraction of variance unexplained (FVU)

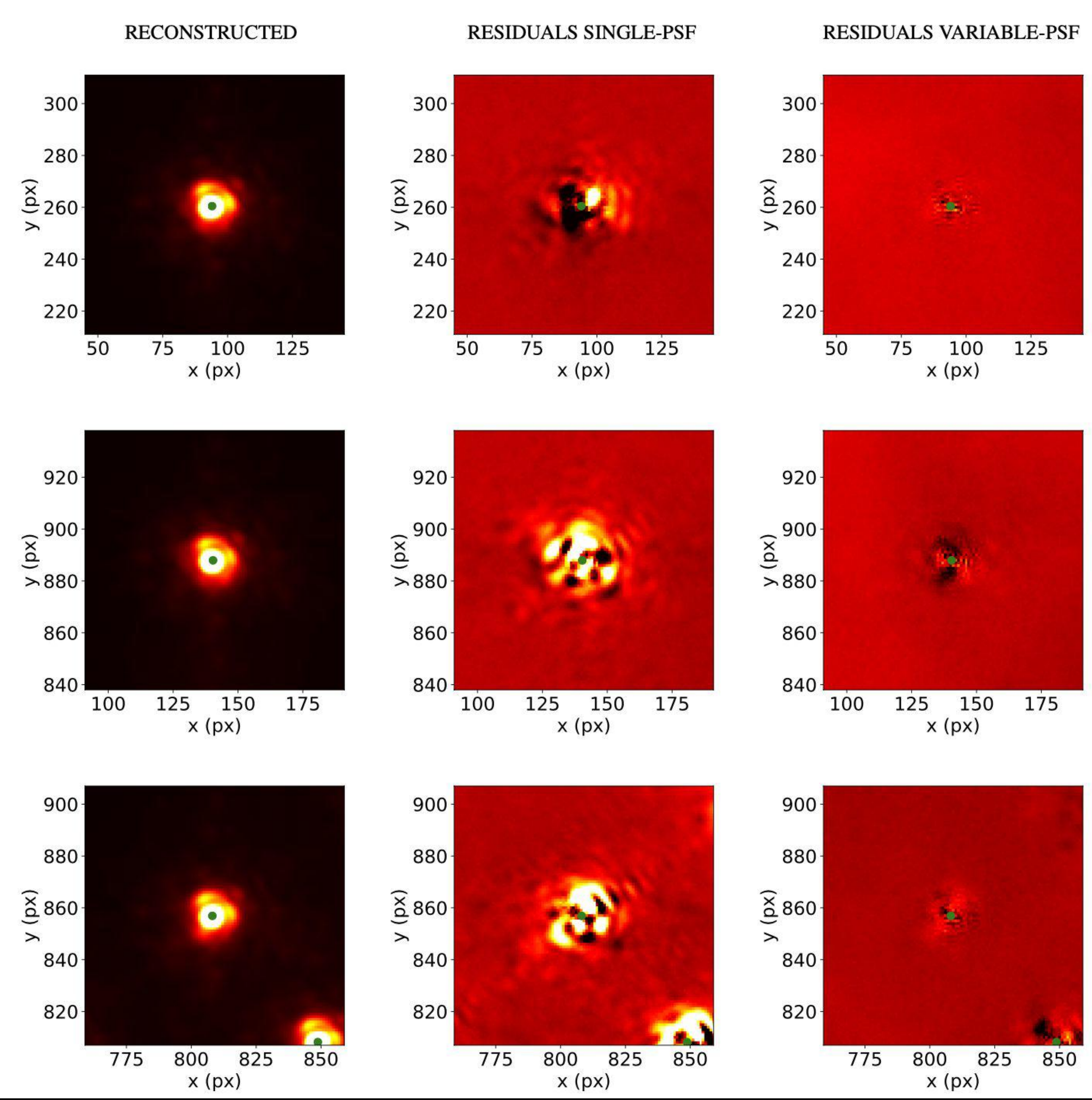


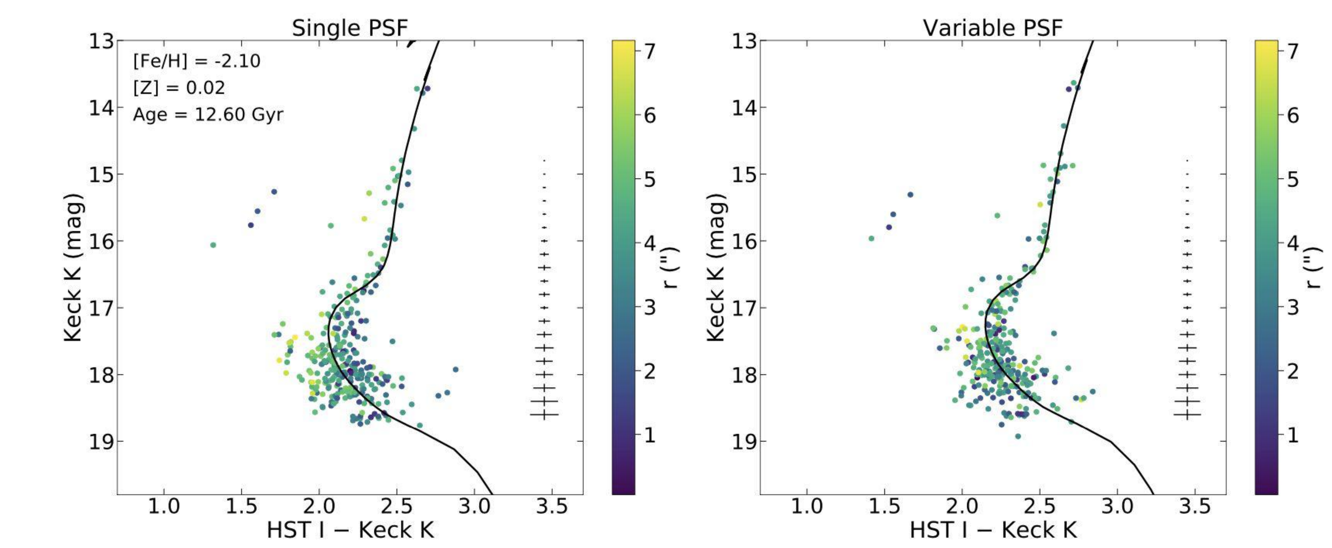
Figure: Reconstructed (*left*) and residual (*center* and *right*) images of fiber images. Single and Variable images have identical color scales. The Variable mode residuals are significantly smaller than the Single mode residuals.

On-Sky Results

[*Terry et al., in prep*]

On-sky science images were obtained of the globular cluster, M53, and the Galactic center in good (GQ), average (AQ), and poor quality (PQ) conditions.

Metric = CMD: Photometric uniformity over the image was **improved by 10x** in variable mode as seen from an analysis of the spread in a color-magnitude diagram. There is a clear trend in the color difference (*data - isochrone model*) as a function of radius from the image center for the Single mode (Terry et al., in prep).



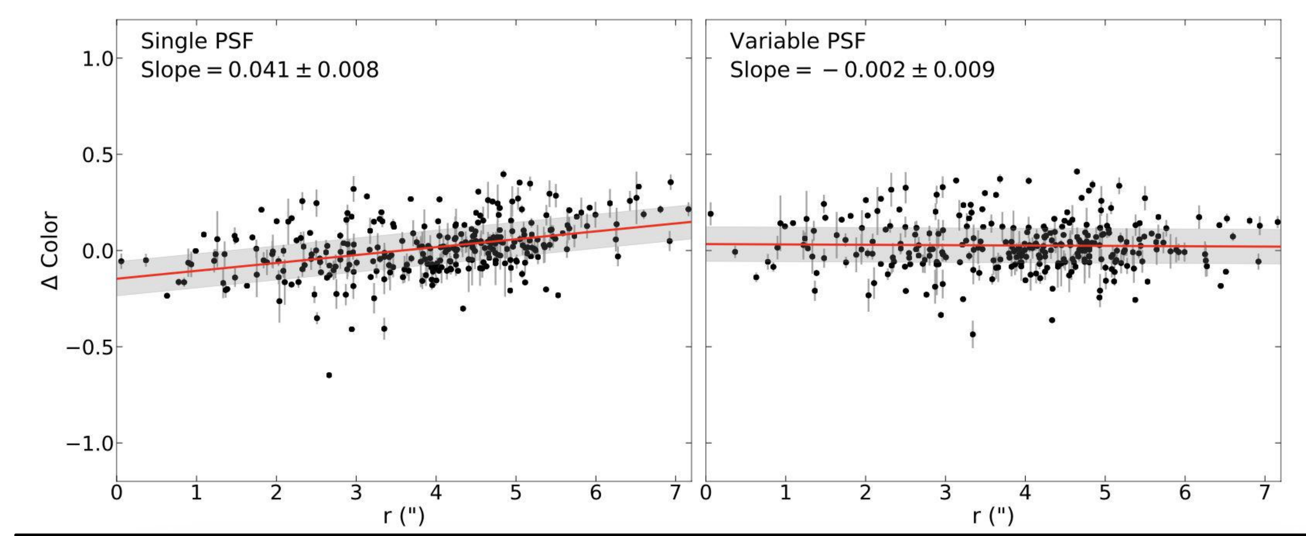


Figure: *Top*: HST I - Keck K vs. Keck K CMD for M53 stars, colored by off-axis radial distance (*r*) in the Keck image. A best-fit isochrone is shown (black). *Bottom*: Color difference between the data and isochrone as a function of *r*. Single mode has a clear trend in radius whereas Variable mode is flat.

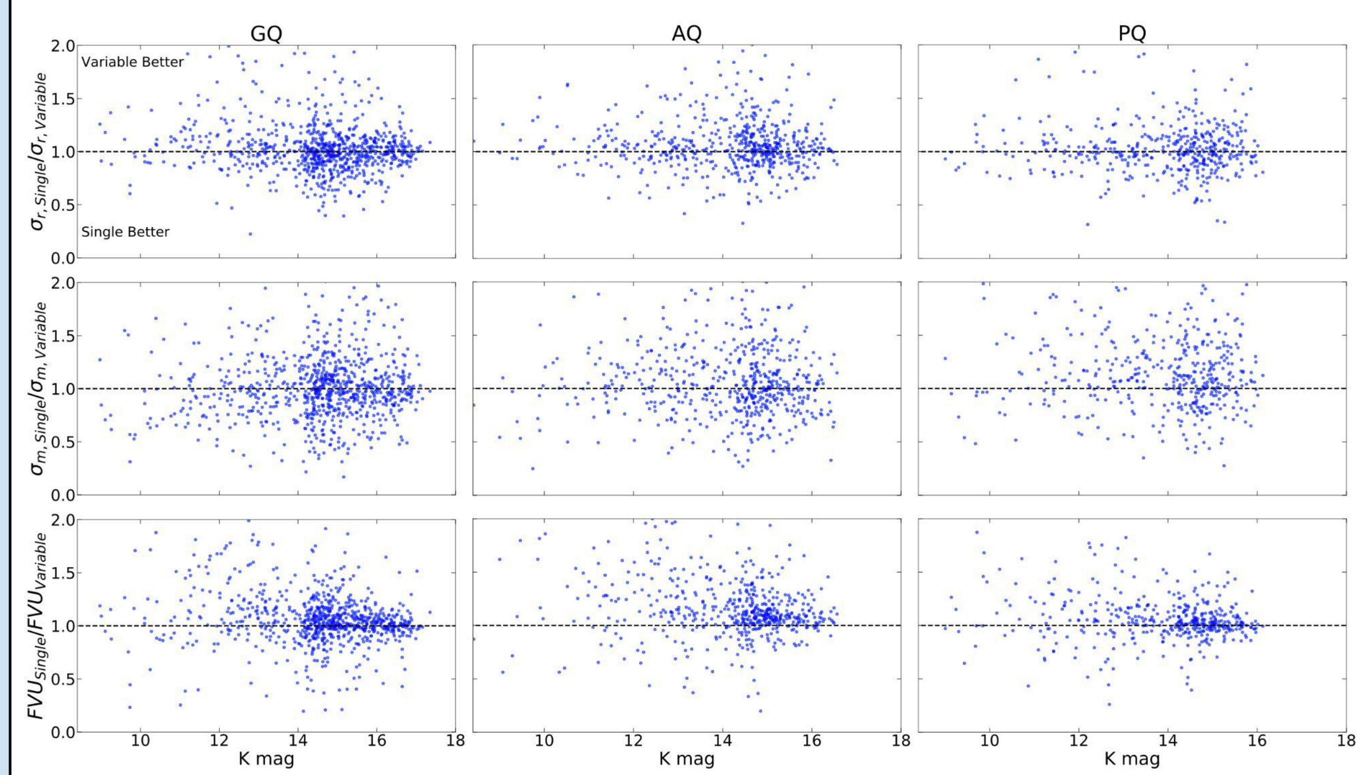


Figure: Ratio of astrometric errors, photometric errors, and FVU values for three GC datasets. Values larger than one indicate Variable mode resulted in smaller errors and FVU values, respectively.

Metric = Photometric/Astrometric Precision: On GC images, the photometric and astrometric precision as measured over a stack of images in a night does not show improvement in Variable mode. For the brightest stars, there is a <10% improvement in the FVU values reported by Variable mode. The best improvement seen in astrometric precision is for a microlensing target (not pictured), that gives a ~15% smaller astrometric error in Variable versus Single mode.

Conclusions

AIROPA's variable-PSF mode shows significant improvements in photometric accuracy and uniformity over the field. However, the astrometric accuracy and the on-sky image residuals still show marginal improvement. The limitations likely come from inaccurate calibration of field-dependent instrumental aberrations using calibration fibers that do not send light through the telescope, only the AO system.

We plan to conduct on-sky phase diversity measurements to evaluate the on-sky vs. bench calibrations. We are also extending AIROPA to work with OSIRIS images and spectra. Ultimately, AIROPA will be combined with on-axis PSF reconstruction as part of KAPA to deliver spatially variable PSF models for all OSIRIS science images.

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