Hybrid point spread function reconstruction with PRIME.

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ABSTRACT

We present PRIME (PSF Reconstruction and Identification for Multi-sources characterization Enhancement) as a novel hybrid concept to improve the PSF estimation based on Adaptive optics (AO) control loop data. PRIME uses both focal and pupil plane data to jointly estimate the model parameters, which are both the atmospheric ($C_n^2(h)$, seeing), system (e.g. optical gains, residual low-order errors). The parametric model in use is flexible enough to be scaled with field location and wavelength, making it a proper choice for optimized on-axis and off-axis data-reduction across the spectrum. We review the methodology and on-sky validations on NIRC2 at Keck II. We also present applications of PSF model parameters retrieval using PRIME: (i) calibrate the PSF model for observations void of stars on the acquired images, i.e. optimize the PSF reconstruction process (ii) update the AO error breakdown mutually constrained by the telemetry and the images in order to speculate on the origin of the missing error terms and evaluate their magnitude (iii) measure photometry and astrometry in stellar fields.

Keywords: Adaptive optics, PSF reconstruction, Keck, Error breakdown

1. INTRODUCTION

PSF reconstruction (PSF-R) is a well established technique[1–7] to estimate the PSF from Adaptive optics (AO) control loop data, but lacks regular operational use so far. One of the major drawbacks of PSF-R lies in the large amount of data and technical time it requires to reach a sufficient understanding of the overall system, such as obtaining static aberrations for instance. In other words, using the AO telemetry and the necessary matrices calibrated on laboratory (such as the interaction matrix, DM influence function for instance) is not sufficient. Experience at Keck[4,6,8] has shown that one must eventually adjust some parameters (like optical gains) to ensure a correct matching of the reconstructed PSF on sky data. Enabling a forward reconstruction that remains accurate is still feasible by sacrificing a large amount of telescope time, which is not necessarily desirable.

In this proceedings, we propose an alternative approach, so-called PRIME, to provide an accurate PSF model without requiring more telescope time than what required for the science observation. We start from the notice that PSF-R has already provided successfully results, signifying that the image formation model is correct. The real limitation is to be able to capture some parameters (seeing, $C_n^2(h)$, optical gains for instance) that may vary across time. One may try to understand how the AO system should behave with respect to observing conditions by using end-to-end simulations. Nevertheless, the deviation of the system behavior from what expected from the simulation may be the reason that explains that it still remains to make a PSF-R algorithm working accurately, reliably and sustainably.

With PRIME, we want to simplify this process. First, we need to identify key parameters that are either difficult to estimate and highly variable from an observation to another. Then, we build a model from the AO control loop data and end up defining a parametric function to describe the PSF for a given set of pupil-plane measurements. The final step will estimate the parameters by best-fitting available PSFs in the field. This

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Further author information: olivier.beltramo-martin@lam.fr technique will ensure that we obtain the most accurate PSF as possible using the PSF-R framework, but has the drawback of demanding the presence of stars in the field, which suits particularly to stellar fields observations. Moreover, PSF-R permits to extrapolate the PSF across field and spectrum. With PRIME, we aim at calibrating the PSF model and provide the observers with a grid of PSF at any desired position and wavelength. Thanks to this known diversity, PRIME can deal with cube of spectral data to perform a joint estimation of model parameters by using observations acquired at different wavelengths or field positions.

In this proceedings, we summarize the principle of PRIME and results obtained so far[9] and review the multiple possible applications.

2. CONCEPT

The first key step is to build the PSF model by using the AO control loop data. In the specific case of Keck II, the methodology is given in[4,6,9,10] and we end up with the following expression of the residual Optical Transfer Function (OTF)

$$\tilde{h}(\boldsymbol{\rho}/\lambda) = \tilde{h}_{\mathrm{stat}}(\boldsymbol{\rho}/\lambda, \boldsymbol{a}_{\mathrm{z}}) \exp\left(-0.5\left(g_{\mathrm{ho}}\mathcal{D}_{\mathrm{ho}}(\boldsymbol{\rho}) + g_{\mathrm{tt}}\mathcal{D}_{\mathrm{tt}}(\boldsymbol{\rho}) + r_0^{-5/3}(\mathcal{D}_{\mathrm{fit}}(\boldsymbol{\rho}) + \mathcal{D}_{\mathrm{al}}(\boldsymbol{\rho})) + \sum_{l=1}^{n_L} C_n^2(h_l)\mathcal{D}_{\mathrm{an}}(\boldsymbol{\rho}, h_l)\right)\right), \tag{1}$$

where

- $\tilde{h}_{\mathrm{stat}}(\boldsymbol{\rho}/\lambda, \boldsymbol{a}_{\mathrm{z}})$ is the telescope OTF including diffraction effect and calibrated static aberrations. We also incorporate $\boldsymbol{a}_{\mathrm{z}}$ as a list of Zernike coefficients to update the calibrated static aberration map with additional focus and astigmatism modes.
- $\mathcal{D}_{\mathrm{ho}}(\boldsymbol{\rho})$ is the tip-tilt (TT)-excluded AO residual phase Structure function (SF) derived from the Wavefront Sensor (WFS) measurements. Coefficient g_{ho} allows to mitigate variations of the optical gains during the observation.
- $\mathcal{D}_{\mathrm{tt}}(\boldsymbol{\rho})$ is the residual jitter SF that comes from the TT measurements and can be tuned thanks to g_{tt}.
- $\mathcal{D}_{\mathrm{fit}}(\boldsymbol{\rho})$ and $\mathcal{D}_{\mathrm{al}}(\boldsymbol{\rho})$ are respectively the fitting and aliasing SF resulting from the uncorrected high- spatial frequencies. Both of them are scaled to $r_0 = 1$.
- $\mathcal{D}_{\mathrm{an}}(\boldsymbol{\rho}, h_l)$ is the anisoplanatism SF given for a specific layer at height h_l and normalized to $C_n^2(h_l) = 1$. One may estimate the full $C_n^2(h)$ profile and use the integral of it to obtain r_0 for off-axis applications.

The herein PSF model is therefore parametrized over $n_z + n_L + 2$ variables, with n_z the number of Zernike modes to be retrieved (usually $n_z = 3$) and n_L the number of altitude bins used to discretized the atmospheric profile (usually $n_L = 7$), which lead to a 6 (on-axis) up to 12 (off-axis) parameters PSF model. We define $\boldsymbol{\mu} = [\boldsymbol{a}_{\mathrm{z}}, g_{\mathrm{ho}}, g_{\mathrm{tt}}, C_n^2(h)]$ as the unknowns vector. Then, assuming we are providing by an image d containing $n_\star$ stars, PRIME minimizes the following criterion

$$\epsilon(\boldsymbol{\mu}) = \left|\left|\sum_{i=1}^{n_\star} p_i \times \delta_{\boldsymbol{x}_i} * h(\boldsymbol{\mu}) + \eta - d\right|\right|_{L_2}^2, \tag{2}$$

where p_i and $\boldsymbol{x}_i$ are the photometry and astrometry (relatively to the image center) of the i^{th} source, h the $\boldsymbol{\mu}$-dependent PSF model and η a constant value to adjust the background level. Eventually, PRIME delivers the optimal reconstructed PSF as well as the by-products estimates, such as photometry, astrometry and PSF model parameters.

3. VALIDATION ON NIRC2 AT KECK II

In the following, we present PRIME results applied to the near infra-red imager NIRC2 at Keck II in narrow field mode with 9.94 mas/pixel sampling. We have processed 158 images collected simultaneously with the AO telemetry over three nights, in either NGS (August 1st 2013, March 14th 2017 and March 15th 2017, 80 images)[11] or LGS (March 14th 2017, 78 images)[12] mode. We have systematically retrieved the seeing, optical gains, focus and astigmatism terms by using PRIME. In LGS mode, the observations were taken with the NGS on-axis, which creates only focal anisoplanatism. This latter was not strong enough to identify a full C_n^2 profile but does impact the SR and has been used in parallel with the PSF halo to constrain the seeing value. The sky image was cropped to 168 pixels to limit the noise propagation through the fitting process, which corresponds to 4 times the AO correction band.

Over 238 NGS/LGS data, PRIME achieves an estimation of the Strehl-ratio and FWHM at respectively 0.7% and 2 mas-level error. The PSF shape is well retrieved as well with overall 2D residual ranging from 0.5% (NGS) to 2% (LGS), advocating that the parameters identification is the key process to make PSF-R working.

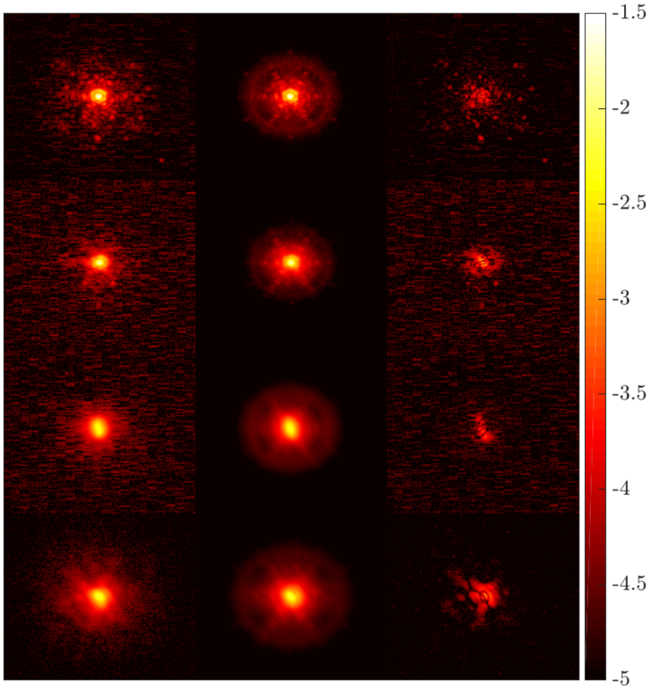

Figure 1: Illustration of NGS PSFs (row 1:3) and LGS PSF (row 4). Left: sky image middle: reconstruction right: residual

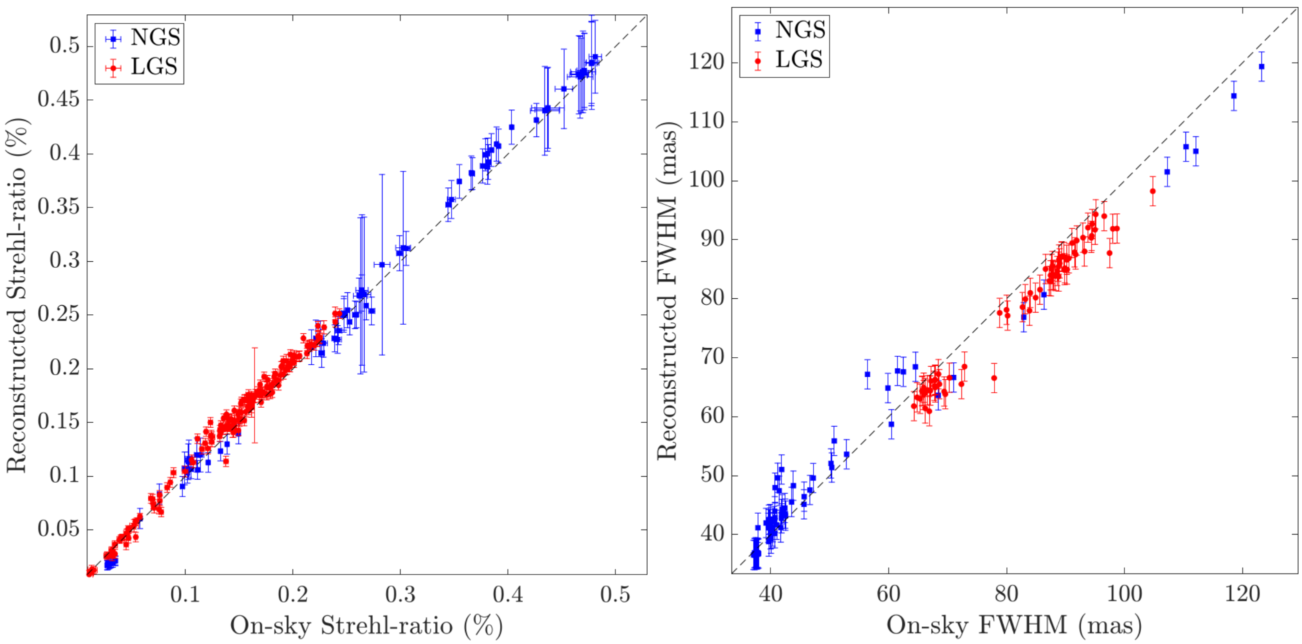

Figure 2: Reconstructed Strehl ratio and PSF FWHM versus image measurements obtained over 238 NIRC2 data sets.

This demonstrates that i) PSF-R is a good framework to obtain an accurate representation of the PSF from the AO telemetry ii) the main issue that has limited PSF-R efficiency so far lies in the determination of few parameters. Efforts should now focus on elaborating techniques to capture what should be these parameters from the AO contextual data to enable forward PSF-R.

4. POTENTIAL APPLICATIONS

4.1 PSF-R calibration

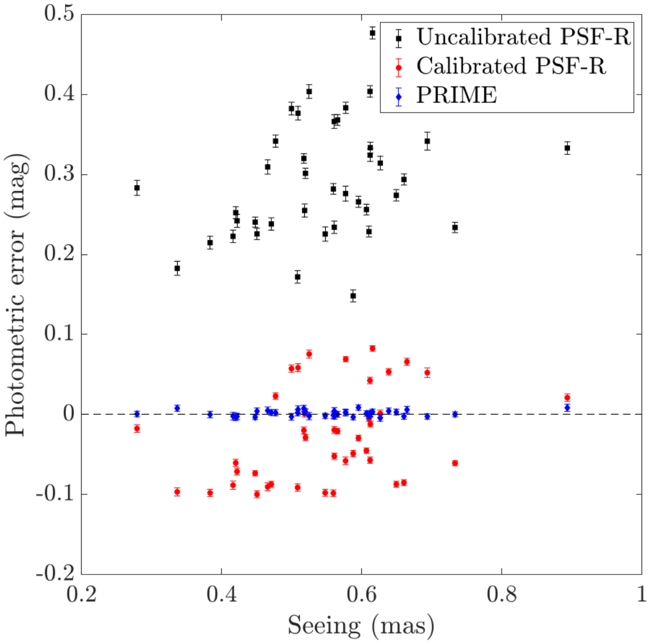

Figure 3: Photometric error as function of the seeing.

By applying PRIME over a substantial amount of archive data, one may infer the PSF model parameters from the AO telemetry directly. In other words, this aim at calibrating the forward PSF-R to make it accurate, without requesting additional engineering calibration time. To test this approach, we have split the 238 data sets into 198 learning sets + 40 test sets in order to extrapolate model parameters with respect to seeing estimation from the AO telemetry.

We report in Fig. 3 the photometric accuracy with respect to the seeing. Results highlight that the PSF-R calibration corrects for the bias on estimates and increases the precision by 50 % compared to the uncalibrated PSF-R. If point sources are available in the field to optimize the PSF-R using PRIME, we can expect a photometric accuracy at the level of 0.008 mag± 0.004 mag, that degrades to 0.06 mag ± 0.004 mag and 0.3 mag ± 0.008 mag by using respectively the calibrated and uncalibrated PSF-R.

Present results illustrates that PRIME can be deployed to calibrate the PSF-R computation in case the PSF best-fitting is compromised and ensures that PSF-R can deliver 6 % of photometry accuracy. Such results will be improved by increasing the size of the learning data set and choosing other descriptors than the AO telemetry seeing, such as the full residual wavefront and the telescope configuration.

4.2 Image-assisted error breakdown

PSF-R is a generalization of the AO wavefront error budget: we do calculate covariance matrices of errors instead of variance terms only. From the phase SFs that appear in the PSF model described in Eq. 1, one may derive the wavefront error budget. With PRIME, we basically scale these phase SFs regarding how they do impact the PSF morphology, in the sense that the absolute value of wavefront error terms are eventually updated through the best-fitting process. The use of the focal-plane image adds a constrain to force the Strehl-ratio (SR) to match the image SR. Preliminary tests on Keck II have shown meaningful results, that complies with theoretical formulas, and highlighted that low-order modes (focus, astigmatism) can be retrieved from the PSF in LGS operation.

Table 1: Examples of retrieved AO error breakdown on Keck II.

	LGS	NGS
K-band Strehl	19.8%	41.8%
Wavefront error	430	316
Low order modes	161	38
Atmospheric Fitting	141	150
Temporal error	149	141
Measurements error	161	85
WFS aliasing	58	66
Anisoplanatism	162	0
Tip-tilt bandwidth	237	118
Tip-tilt noise	42	46

4.3 Astrometry and photometry measurements

We illustrate in Fig. 4 the photometry and astrometry precision with respect to the artificial object magnitude. This plot shows two distinct regimes below and beyond magnitude 14 mag that respectively correspond to PSF-model and noise limitation regimes. For stars with $m_H > 14$ mag, the noise propagation through the fitting process dominates the estimation precision, while for stars with $m_H \leq 14$ mag for a given object magnitude, we improve the precision by a factor 2 and 1.5 on respectively the photometry and astrometry; or in other words, we get the same precision for objects one to two magnitudes fainter. Also, because PRIME does estimate PSF parameters in addition to photometry and astrometry, we were expecting more sensitivity to noise and see

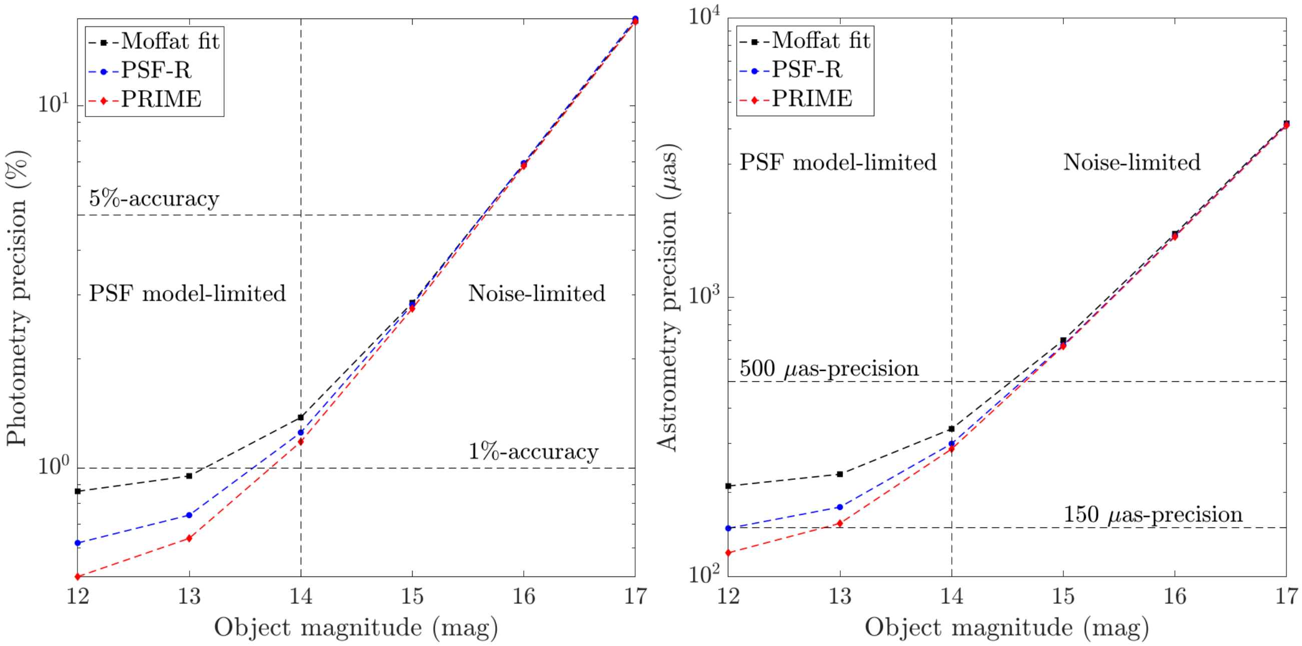

Figure 4: Precision on the 2MASS00535794+2535445 binary stellar parameters wrt the magnitude for various PSF models.

the metrics precision getting worse faster than the uncalibrated PSF-R model, which does not occur. Finally, we understand that the present implementation of PRIME is efficient when feeding it with image of stars of magnitude $\mathrm{m_H} \leq 14\,\mathrm{mag}$ stars with 50 s of exposure time, which is accessible in the Galactic center[13] and makes it feasible to deploy PRIME on such a science case.

5. CONCLUSION

We have introduced PRIME as an extension to the PSF-R framework that couples AO telemetry and focal plane images to provide i) estimations of atmospheric and system parameters such as the $C_n^2(h)$ profile, system optical gains or even non-sensed low-order modes, ii) an accurate error breakdown and thereupon PSF model across field locations and wavelengths and iii) photometry and astrometry estimates on fields with multiple sources where a non-linear least-squares PSF fitting routine is employed. In addition, statistical analysis with PRIME provides useful information and trends of parameters variations with respect to observing conditions thus being valuable to optimize runtime AO performance and to calibrate a-priori parameters for later PSF reconstruction.

We have deployed PRIME on Keck II on-sky PSF in engineering mode when guiding either on a NGS or a LGS on-axis. We have demonstrated that only few parameters must be estimated carefully (seeing, optical gains plus additional focus and astigmatism terms) to reach 0.8 % ± 0.5 % of accuracy on SR, 2.8 mas ± 0.9 mas on FWHM and 0.008 mag ± 0.004 mag on photometry. Over a sub-sample of data, we have calibrated the PSF-R model accordingly to the AO telemetry-based seeing that have been used to calculate the PSF from the direct model. We have shown that this calibration permits to decrease the photometry error from 0.3 mag ± 0.008 mag down to 0.06 mag ± 0.004 mag. We have also illustrated on NIRC2 binary images that PRIME is sufficiently robust to noise to retain photometry and astrometry precision below 0.005 mag and 100μas on a $\mathrm{m_H} = 14\,\mathrm{mag}$ object, whereas a loss is to expect when using Moffat models or pre-calibrated PSF parameters. This is indicative of the usefulness of estimating PSFs based on the actual observations (images and telemetry) to avoid errors to creep in and degrade seek-after observable.

Future step will lay in pushing the verification further by collecting more data and applied PRIME to others AO instruments, such as tomography-based systems.

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REFERENCES

[1] Veran, J.-P., Rigaut, F., Maitre, H., and Rouan, D., "Estimation of the adaptive optics long-exposure point-spread function using control loop data.," *Journal of the Optical Society of America A* **14**, 3057–3069 (Nov. 1997).

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

[3] Gilles, L., Correia, C., Véran, J.-P., Wang, L., and Ellerbroek, B., "Simulation model based approach for long exposure atmospheric point spread function reconstruction for laser guide star multiconjugate adaptive optics," *Appl. Opt.* **51**, 7443–7458 (Nov 2012).

[4] Jolissaint, L., Ragland, S., and Wizinowich, P., "Adaptive Optics Point Spread Function Reconstruction at W. M. Keck Observatory in Laser Natural Guide Star Modes : Final Developments," in [*Adaptive Optics for Extremely Large Telescopes IV (AO4ELT4)*], E93 (Oct. 2015).

[5] 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).

[6] Ragland, S., Dupuy, T. J., Jolissaint, L., Wizinowich, P. L., Lu, J. R., van Dam, M. A., Berriman, G. B., Best, W., Gelino, C. R., Ghez, A. M., Liu, M. C., Mader, J. A., Vayner, A., Witzel, G., and Wright, S. A., "Status of point spread function determination for Keck adaptive optics," in [*Adaptive Optics Systems VI*], *Proc. SPIE* **10703**, 107031J (July 2018).

[7] Wagner, R., Hofer, C., and Ramlau, R., "Point spread function reconstruction for single-conjugate adaptive optics on extremely large telescopes," *J. of Astronomical Telescopes, Instruments, ans Systems* **4**(4), 049003 (2018).

[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).

[9] Beltramo-Martin, O., Correia, C. M., Ragland, S., Jolissaint, L., Neichel, B., Fusco, T., and Wizinowich, P., "PRIME: Psf Reconstruction and Identification for Multiple sources characterization Enhancement. Application to Keck NIRC2 imager," *M.N.R.A.S* (2019).

[10] Flicker, R., "PSF reconstruction for Keck AO," tech. rep., W.M. Keck Observatory, 65-1120 Mamalahoa Hwy, Waimea, HI 96743, United-States (2008).

[11] Wizinowich, P. L., Acton, D. S., Lai, O., Gathright, J., Lupton, W., and Stomski, P. J., "Performance of the W.M. Keck Observatory Natural Guide Star Adaptive Optic Facility: the first year at the telescope," in [*Adaptive Optical Systems Technology*], Wizinowich, P. L., ed., *Proc. SPIE* **4007**, 2–13 (July 2000).

[12] Wizinowich, P. L., Le Mignant, D., Bouchez, A. H., Campbell, R. D., Chin, J. C. Y., Contos, A. R., van Dam, M. A., Hartman, S. K., Johansson, E. M., Lafon, R. E., Lewis, H., Stomski, P. J., Summers, D. M., Brown, C. G., Danforth, P. M., Max, C. E., and Pennington, D. M., "The W. M. Keck Observatory Laser Guide Star Adaptive Optics System: Overview," *Publications of the Astronomical Society of the Pacific* **118**, 297–309 (Feb. 2006).

[13] Yelda, S., Lu, J. R., Ghez, A. M., Clarkson, W., Anderson, J., Do, T., and Matthews, K., "Improving Galactic Center Astrometry by Reducing the Effects of Geometric Distortion," *The Astrophysical journal* **725**, 331–352 (Dec. 2010).