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An optical distortion solution for the Keck I OSIRIS Imager

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ABSTRACT

We calculate an optical distortion solution for the OSIRIS Imager on the Keck I telescope, by matching observations of globular clusters to a Hubble reference catalogue. This solution can be applied to correct astrometric distortions in OSIRIS frames, improving the astrometric accuracy of observations. We model the distortion with a 5th order Legendre polynomial. The distortion we find matches the expected OSIRIS distortion, and has a fit error of 0.6 mas, but has large residuals of 7 mas. We are currently iterating on an improved reference frame to improve the residual. Additionally, we have installed the Precision Calibration Unit (PCU) on the Keck I optical bench, which will generate an artificial grid of stars for use in future distortion calculations.

Keywords: Distortion, Keck, OSIRIS

1. INTRODUCTION

OSIRIS is an adaptive optics fed instrument on the Keck I telescope, with a FoV of 20x20 arcseconds and a plate scale of 10 milliarcseconds per pixel. Like all instruments it is affected by distortion, which shifts the positions of stars on the detector away from their true sky positions, adding an error to astrometric measurements. Precise astrometry is essential for many types of astronomy, including the 2020 Nobel Prize winning discovery of the supermassive black hole at Sagittarius A*, and the detection of isolated stellar-mass black holes in the Milky Way.¹

In this work we characterize the static distortion in the OSIRIS Imager and calculate a solution for it, enabling much greater astrometric precision. We follow a similar procedure to that which was done for the NIRC2 instrument on Keck II.²

To derive the distortion we take images of globular clusters to get measurements of star positions across the OSIRIS detector, and compare them to an undistorted reference frame. For this work we are using a Hubble catalogue, which has already been distortion corrected.³

OSIRIS was opened for maintenance at the end of 2020, which may have affected the distortion. To account for this we split our data into two sets, 2020 and 2021, and calculate two distortion models, for use on data from before and after OSIRIS was opened.

2. METHOD

The method we used to generate the OSIRIS distortion solution is as follows (see Figure 1):

1. Take images of globular clusters with OSIRIS to get a densely sampled set of star position measurements. (Section 3)
2. Collect Hubble catalogues corresponding to the observed globular clusters.
3. Reduce and analyze the OSIRIS images to create starlists. (Section 4.1)

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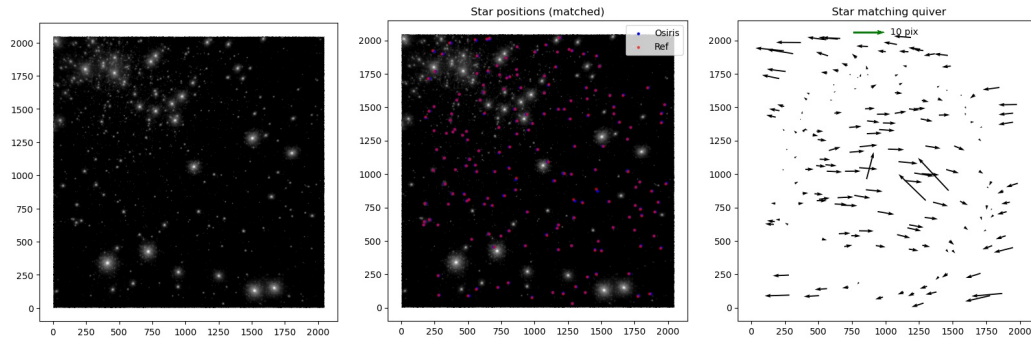


Figure 1. Left: An OSIRIS image of M15. Centre: The OSIRIS stars (blue) matched and aligned with the Hubble reference catalogue (red). Right: The remaining differences in position, ie, measurements of the distortion at those positions.

Table 1. OSIRIS observations

Date	Target	Frames	Filter	Trick	Dichroic
2020-08-04	M15	177	Kn3	open	
2020-07-31	M92	10	Kp	open	
2020-08-13	M92	10	Kp	open	
2020-08-14	M92	20	Kp	open	
2021-10-24	M15	186	Kn3	hband	

4. Project the Hubble catalogue positions forward in time to the OSIRIS epoch
5. Apply DAR to the Hubble catalogue. (Section 4.2)
6. Match and fit the OSIRIS starlists to the Hubble catalogue. (Section 4.3)
7. Using the matched star lists, calculate the best fitting Legendre polynomial transformation. (Section 5)
8. Calculate uncertainty using a full-sample bootstrap. (Section 8.1)

3. OBSERVATIONS

The OSIRIS observations are summarised in Table 1. Observations were taken of the globular clusters M15 and M92 on multiple nights in 2020, and of M15 on one night in 2021, using the Kn3 and Kp filters.

Each set of observations dithered over a box-9 grid pattern with 5 arcsecond steps, to ensure that stars were detected on as many different pixels as possible. Observations were also taken at multiple position angles on each night to reduce errors. Any systematic errors in OSIRIS or Hubble star positions will rotate with the position angle, but the distortions will not.

TRICK, the Keck I infrared tip-tilt sensor, features a dichroic that can be inserted into the optical path to split off either H band or K band light. This dichroic may add small distortions, so observations were taken with the dichroic in the beam (hband) and out of the beam (open).

At each pointing, several frames were taken and the star positions averaged, to get a measure of the astrometric uncertainty in the OSIRIS observations.

4. REDUCTION AND MATCHING

4.1 Reduction

To generate list of stars from the OSIRIS images, we analyzed them with the KAI data reduction pipeline.⁴ KAI first reduces the data by applying a bad pixel mask, darks, flatfields, and skies to clean the images. KAI then runs the Starfinder algorithm to detect stars in the image, and returns a starlist. The positions of Hubble stars were projected to the OSIRIS observation epoch, using the Hubble proper motion data.

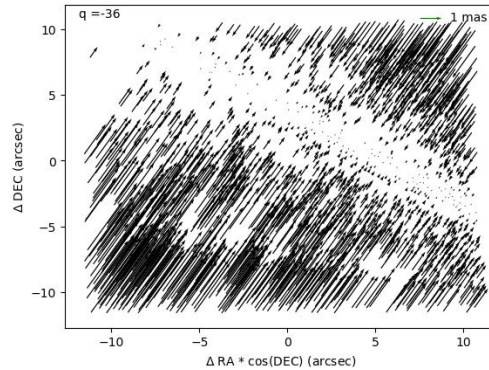


Figure 2. DAR applied to Hubble stars to match to an OSIRIS frame. DAR produces compression in the direction of the parallactic angle q .

4.2 Differential Atmospheric Refraction

Differential Atmospheric Refraction (DAR) compresses the apparent positions of stars in the zenith direction, due to differing atmospheric refraction at different angles through the atmosphere. This effect can be significant, deflecting stars by several milliarcseconds. Normally a correction is applied to the observations to remove DAR, but in this case we do not yet know the undistorted locations of the OSIRIS stars, which are required to calculate the DAR. Instead, we apply the inverse, adding DAR to the Hubble data, reproducing the positions that would be seen from Keck.

4.3 Matching and Fitting

To match the OSIRIS stars with the Hubble catalogue stars we use the Flystar package. Flystar identifies matching stars in each list using a triangle matching algorithm. It then calculates the four-parameter transformation that best matches the two lists. The four parameters in the transformation correspond to x,y translation, rotation, and scaling. By applying the transformation to the Hubble data we get the best pixel positions of the Hubble stars on the OSIRIS detector, accounting for telescope pointing, position angle, and pixel scale. Any remaining differences in the star positions are due to distortion (and uncertainty).

To assist the matching algorithm, the OSIRIS starlists were trimmed, removing stars fainter than magnitude 15.4, and removing any detected 'stars' within 5 pixels of the edge of the frame, as this region only contains noise. The Hubble catalogue was trimmed by removing stars that lay outside the OSIRIS frame.

5. FITTING DISTORTION WITH A LEGENDRE POLYNOMIAL

The Flystar algorithm produces matched lists of OSIRIS and Hubble stars with their positions in pixels, which gives us measurements of the distortion at many points on the frame. To construct a model of this distortion, we fit a Legendre polynomial to the OSIRIS-Hubble distortion vectors.

First, three-sigma outliers are removed. In this step the frame is broken up into 16 256x256 pixel boxes. Inside each box, we look at the distortion vectors for stars and calculate their Mahalanobis distances. (The Mahalanobis distance is the two dimensional distance from the mean in units of standard deviation). Any stars that are more than three sigma away from the mean (a Mahalanobis distance of 3) are discarded. This step is repeated until there are no more outliers detected. The resulting stack of vectors is plotted on the left in Figures 4 and 5. Flystar is then used to generate a Legendre polynomial transformation that best fits the stacked distortion vectors.

We tested a range of polynomial orders for the Legendre transformation. For each polynomial order we generated a fit and calculated the residuals. We then did an F test on these residuals to see the improvement in fit gained by increasing the order. The results are shown in Figure 3. Reference 2 did the same calculation in their figure 4, and found F values around 20, whereas we find F values below 1. This indicates that the OSIRIS distortion is of low order, and that there is a small improvement gained by going to higher orders. The smallest

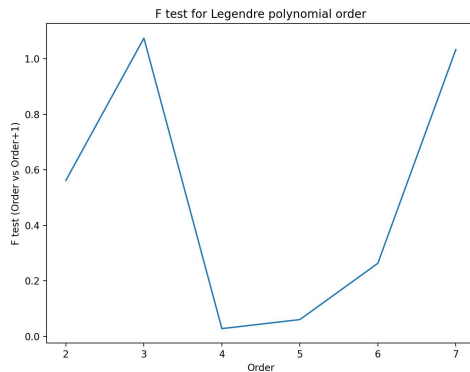


Figure 3. F test of Legendre polynomial orders. The value at order n indicates the result of the F test comparing order n and order $n+1$ Legendre polynomial fits to the distortion. A higher F test value indicates a greater improvement by going to the next order.

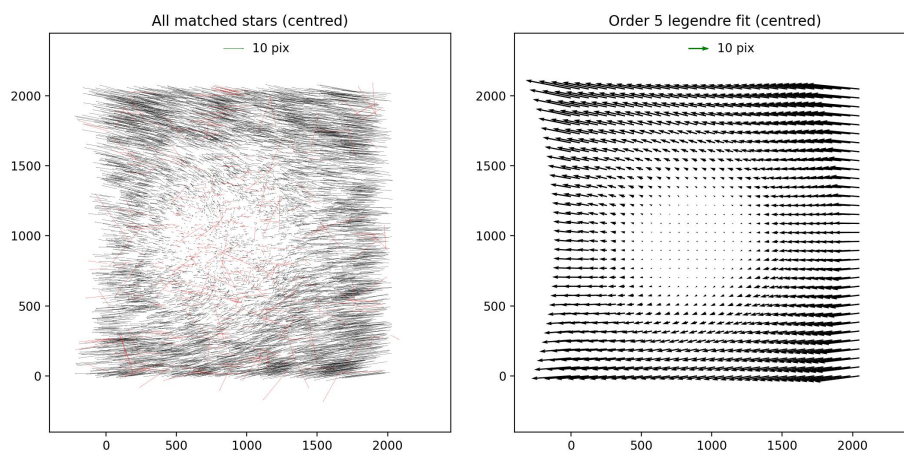


Figure 4. Left: Quiver plot of the positions of the matched OSIRIS and Hubble stars for 2020, stacked on one frame. 3-sigma outliers are marked in red and discarded from the fitting. Right: The 5th order Legendre polynomial fit to the distortion.

improvements in Figure 3 are when going from 4th order to 5th order, and from 5th order to 6th order. We settle on a 5th order polynomial as being sufficient to model the distortion.

6. RESULTS

The best fitting 5th order Legendre polynomial transform is shown on the right in Figures 4 and 5, for the 2020 and 2021 solutions.

The fitting algorithm produces a fit which minimises the average distortion across the frame, but it is more useful to have zero distortion at the centre of the frame. In this way a targeted star placed at the centre of the frame is defined to be on axis and is not distorted. We apply a translation to the fit to produce a model with zero distortion at the centre, which has been applied to Figures 4 and 5

7. POSITION ANGLE DISCREPANCY

As an aside, we re-ran the initial 4-parameter fit (Section 4.3) between Hubble and the distortion corrected OSIRIS data. The four parameters in this transformation correspond to the telescope RA and Dec, the plate scale, and the position angle (PA). We find the expected value for the plate scale, but there is a discrepancy between the PA in the image headers and the rotation we find in the four-parameter fit, which is found to change over the course of one night (Figure 6). We are investigating the cause of this variation in PA.

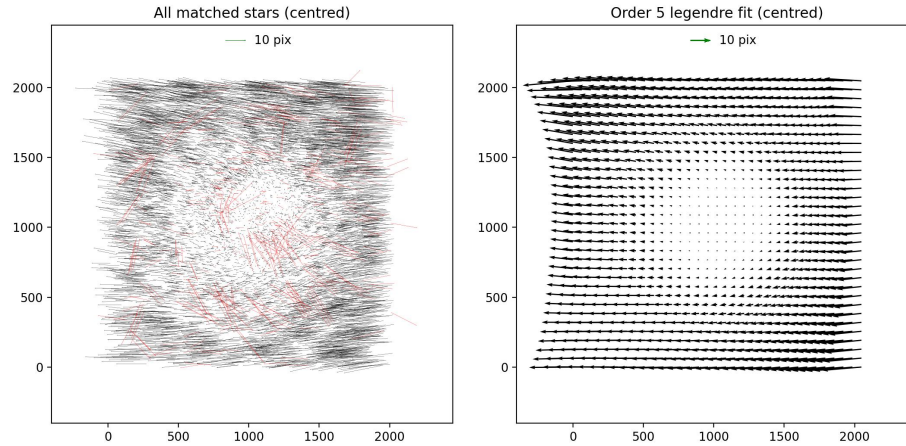


Figure 5. Same as Figure 4 but with the 2021 data

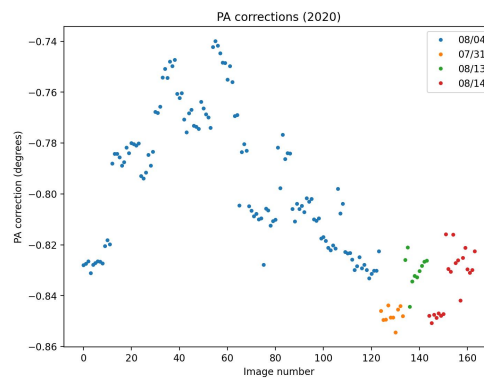


Figure 6. Correction to the Position Angle for the frames from all 4 nights in 2020.

8. UNCERTAINTY

8.1 Bootstrapping

To get a measure of the uncertainty in the Legendre fit, we perform a full-sample bootstrap. We take a random sample of the distortion measurements (with replacement) equal in size to the original list of measurements (i.e. a full sample). This random sampling is repeated 100 times to generate 100 samples. For each sample a 5th order Legendre fit is found. The standard deviation in these 100 Legendre fits gives us a measure of the uncertainty in the fit at each pixel. The bootstrap x and y standard deviations are shown in Figure 7. We see the smallest uncertainty in the centre, and greater uncertainty near the corners of the frame where there are fewer points. The mean uncertainty is 0.065 pixels, or 0.65 milliarcseconds, indicating high precision fit. A similar value was found for the NIRC2 distortion in Reference 2.

8.2 Residuals

Unfortunately there are large residuals between the Legendre corrected OSIRIS stars and the Hubble stars, with a mean of 0.7 pixels, or 7 milliarcseconds (Figure 8). This is likely due to uncorrected Hubble distortion, and uncertainties in the proper motions and positions. To correct for this, we can generate an improved reference catalogue to use instead of the Hubble catalogue. We apply our initial distortion correction to the OSIRIS stars, remove DAR from them, and combine them together into one catalogue, taking the average position of stars that appear in multiple images (the Hubble catalogue is used as an initial guess for this matching, to get the catalogue into RA and Dec). We can then match the distorted OSIRIS stars to this improved catalogue, calculating the distortion in the same manner as before. This step can be repeated, applying the new distortion each time to generate an improved reference frame, and reducing the residuals. This work is ongoing.

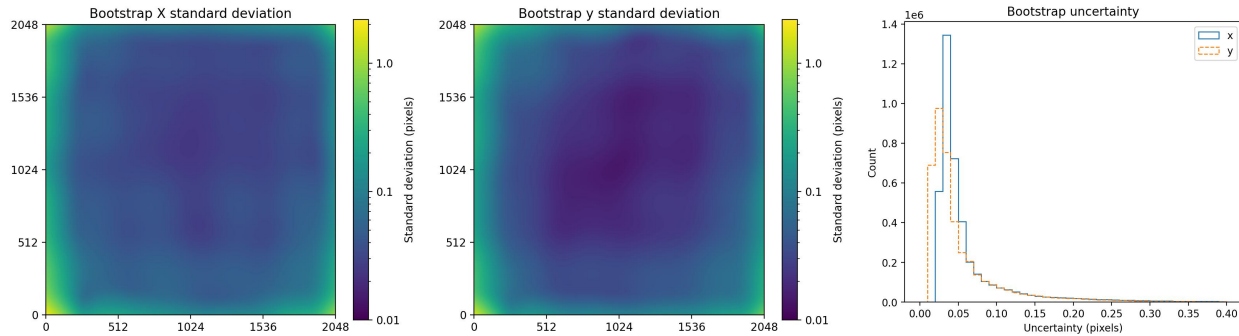


Figure 7. The standard deviation in the 5th order Legendre polynomial fit, calculated using a full-sample bootstrap with 100 iterations. Left: Standard deviation in x at each pixel. Centre: Standard deviation in y at each pixel. Right: Histogram of standard deviation in x and y.

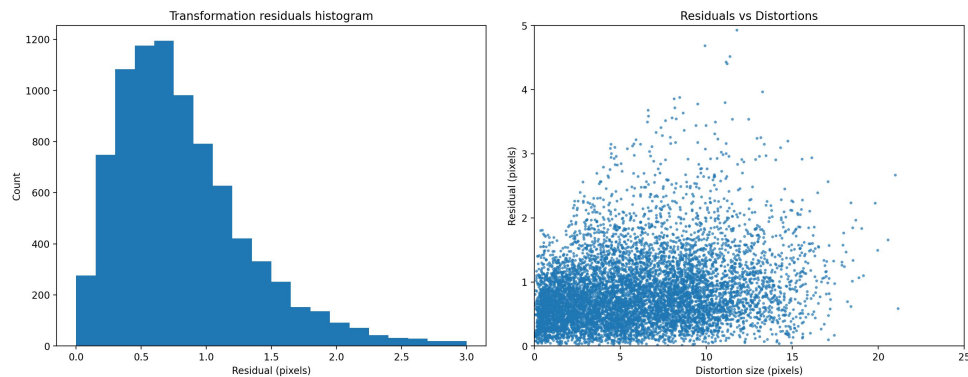


Figure 8. Left: Histogram of the residual distortion for 2021. Right: Residual distortion plotted against the size of the distortion for all 2021 stars.

9. PINHOLE CALIBRATION UNIT (PCU)

There are two major limitations to the current distortion solution: limited access to on-sky observations, and uncertainty in the reference frame. Both will be greatly improved by the Precision Calibration Unit (PCU), which has been installed on the Keck I optical bench (Figure 9). It features a pinhole mask mounted on linear stages, which can drive it to a focal point in the optical path. By back-illuminating the pinhole mask, OSIRIS can image a grid of artificial ‘stars’ with precisely known positions. The distortion can then be calculated as we have done here, using the grid positions as the reference. Reference 2 reports a residual distortion of 2-3 mas when using a pinhole mask.

The PCU offers many advantages over using on-sky images:

- The grid of ‘stars’ fully covers the OSIRIS detector.
- The positions of the pinholes are precisely known.
- Observations can be taken during the day, saving valuable night time hours.
- The process can be automated, and run repeatedly throughout the year to keep track of any non-static distortions.

The PCU is currently undergoing testing, and is expected to be operational later this year. The distortion solution in this work will be a useful sanity check, to make sure that the PCU-derived distortion matches the on-sky distortion.

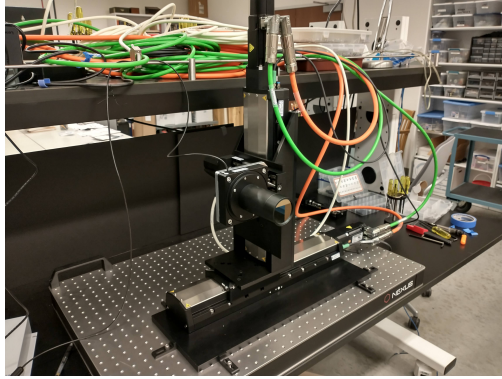


Figure 9. The PCU being assembled in the lab prior to shipping. The pinhole mask is visible at the centre.

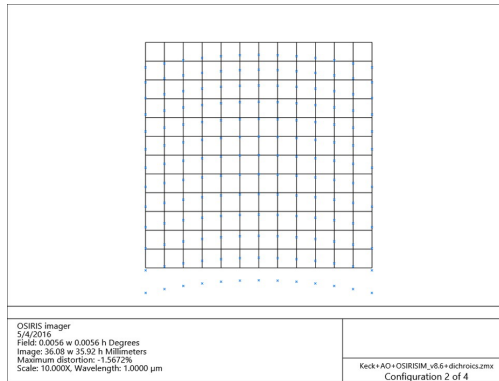


Figure 10. The distortion model from the OSIRIS Imager development. Blue points show the distortion away from the grid corners.

10. DISCUSSION

The distortion model we find in Figure 5 is similar to the distortion in OSIRIS' design specification in Figure 10 (given a 90 degree rotation). This indicates that the majority of the distortion is inherent to the OSIRIS Imager, with less contributed by the other telescope optics. While the distortion is of low order and matches OSIRIS' expected distortion, it is unfortunately large, reaching 15 pixels at the corners. OSIRIS observations that require precise astrometry should attempt to place targets close to the centre of the frame.

In this project we initially used GAIA as a reference catalogue, but found it to have few stars and large errors in our observed regions. The residuals to the Legendre fit were approximately 20 milliarcseconds, and many of our GAIA stars had high astrometric noise parameters, with $\sim 80\%$ of them having `astrometric_excess_noise` > 1 milliarcsecond. Other papers using GAIA data such as Ref 5 and 6 find the majority of astrometric errors to be below 1 milliarcsecond. Ref 6 used GAIA EDR3 and cut stars with `astrometric_excess_noise` > 0.68 to achieve 90.3% completeness. We conclude that GAIA has poorer astrometry towards these globular clusters.

We find a residual distortion of 7 milliarcseconds in our fit, which is too large to declare a high confidence in the distortion model. We are currently generating an improved reference frame (see section 8.2) to reduce this residual distortion. Once it is complete we will make the fit available to the public, as FITS files in the KAI package, and as Legendre polynomial coefficients for independent use.

ACKNOWLEDGMENTS

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REFERENCES

- [1] Lam, C. Y., Lu, J. R., Udalski, A., Bond, I., Bennett, D. P., Skowron, J., Mroz, P., Poleski, R., Sumi, T., Szymanski, M. K., Kozłowski, S., Pietrukowicz, P., Soszynski, I., Ulaczyk, K., Wyrzykowski, L., Miyazaki, S., Suzuki, D., Koshimoto, N., Rattenbury, N. J., Hasek, Matthew W., J., Abe, F., Barry, R., Bhattacharya, A., Fukui, A., Fujii, H., Hirao, Y., Itow, Y., Kirikawa, R., Kondo, I., Matsubara, Y., Matsumoto, S., Muraki, Y., Olmschenk, G., Ranc, C., Okamura, A., Satoh, Y., Ishitani Silva, S., Toda, T., Tristram, P. J., Vandorou, A., Yama, H., Abrams, N. S., Agarwal, S., Rose, S., and Terry, S. K., “An isolated mass gap black hole or neutron star detected with astrometric microlensing,” *arXiv e-prints*, arXiv:2202.01903 (Feb. 2022).
- [2] Service, M., Lu, J. R., Campbell, R., Sitarski, B. N., Ghez, A. M., and Anderson, J., “A New Distortion Solution for NIRC2 on the Keck II Telescope,” *PASP* **128**, 095004 (Sept. 2016).
- [3] Bellini, A., Anderson, J., van der Marel, R. P., Watkins, L. L., King, I. R., Bianchini, P., Chanamé, J., Chandar, R., Cool, A. M., Ferraro, F. R., Ford, H., and Massari, D., “Hubble Space Telescope Proper Motion (HSTPROMO) Catalogs of Galactic Globular Clusters. I. Sample Selection, Data Reduction, and NGC 7078 Results,” *ApJ* **797**, 115 (Dec. 2014).
- [4] Lu, J., “Keck-DataReductionPipelines/KAI: v1.0.0 Release of KAI,” (May 2022).
- [5] Gandhi, P., Buckley, D. A. H., Charles, P. A., Hodgkin, S., Scaringi, S., Knigge, C., Rao, A., Paice, J. A., and Zhao, Y., “Astrometric excess noise in gaia edr3 and the search for x-ray binaries,” *Monthly Notices of the Royal Astronomical Society* **510**, 3885–3895 (dec 2021).
- [6] Rybizki, J., Green, G. M., Rix, H.-W., El-Badry, K., Demleitner, M., Zari, E., Udalski, A., Smart, R. L., and Gould, A., “A classifier for spurious astrometric solutions in gaia edr3,” *Monthly Notices of the Royal Astronomical Society* **510**, 2597–2616 (dec 2021).