A Comparison of Photometric Techniques for Astrometry of Close Double Stars

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Abstract: We study the accuracy of various photometry packages and AstroImageJ for measuring the separation and position angle of close double stars using a traditional imaging method. In particular, we focus on twelve systems with separations at and above the stars' full width at half maximum (FWHM) - separations ranging from two to seven arcseconds. Gaia DR2 serves as our reference to judge accuracy. Our images have a FWHM of 2.0", and AstroImageJ's residuals were roughly -0.1" down to just over twice the FWHM. The photometric algorithms presented mixed results. DOPPhot had the lowest residuals of the photometries, yet still presented a comparatively large random error of ±0.2". However, it outperformed AstroImageJ at closer separations, maintaining this ±0.2" error down to 1.5x the FWHM, 3.0". These results are surprisingly accurate given the modest imaging equipment used - a 100mm telescope operating at 714mm focal length.

Introduction

The desire to measure close double stars drives us to attempt increasingly difficult pairs. In a previous study of a close double star system, STF 619 (4.0" separation), measurements of position angle and separation made by AstroImageJ deviated slightly from the expected values (Wiese et al., 2020). Specifically, the star centroids were roughly 0.3" closer together than predicted based on previous measurements. This may be partially because the light from one star bled into its companion, 4.0" away. When the images were reduced with DAOPhot photometry, however, the measurements were more accurate, as shown in Figure 1.

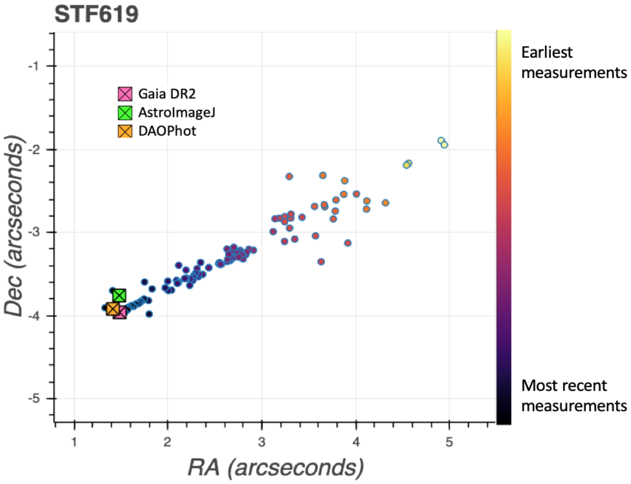

Figure 1. Plot of STF619's historical data, with the measurements of AstroImageJ, DAOPhot, and Gaia Data Release 2 overlaid. The historical measurements are plotted chronologically, with the earliest measurements lightest in color.

This prompted us to study when a given photometry is best suited to accurately measure the position angle and separation of close double stars. The algorithms we compare are AstroImageJ (AIJ), DAOPhot (DAO), DOPPhot (DOP), Source EXtractor (SEX), Source Extractor Kron (SEK), and PSFEx-Extractor (PSFEx). DAOPhot and DOPPhot are photometric reduction algorithms that were specifically developed to distinguish stars in crowded starfields, such as those of globular clusters (Stetson, 1987; Schechter, 1993). Similar imaging difficulties apply to close double stars because the light of one star bleeds into the other due to atmospheric scintillation. The SEX, SEK, and PSFEx algorithms

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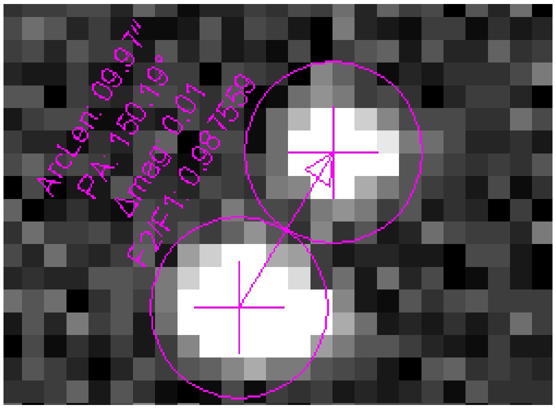

Figure 2. Double star data reduction in AstroImageJ software.

were developed by Bertin and Arnouts (Bertin and Arnouts, 2018). To assess their accuracy, we compared our measurements to the values reported in Gaia Data Release 2 (DR2) because it is the most accurate and recent astrometric data available (Lindegren, et al. 2018; Marakov, 2007).

The AIJ software is popular for double star data reduction because it has features designed for double star astrometry, as shown in Figure 2. In AIJ, a weighted average aperture photometry algorithm is used to calculate star centroids (Howell, 2006).

Target Selection

To choose double star systems to image, the Washington Double Star (WDS) catalog was searched using Stelle Doppie. The search was restricted to systems with a delta magnitude of less than 0.5, more than 50 historical observations, and systems in which the last observation was made in the last year. From the systems that met these criteria, we selected 12 doubles with separations ranging from two to seven arcseconds. Since we expected our measurements would begin to significantly deviate from Gaia DR2 at around four arcseconds, we centered the target systems at four arcseconds of separation. The targets with small separations of around three arcseconds were selected knowing that accurate measurements may not be possible. Our goal was to identify the separation at which our measurements began to substantially deviate from those reported in Gaia DR2.

Imaging Equipment

As described in Caputo, 2019, a four-inch refractor telescope was used to image each of the selected systems. The telescope has a focal length of 714 mm, and no Barlow or other image magnifier was used. The camera is a ZWO ASI-1600mm, with a pixel size of 3.8 µm, yielding a pixel scale of 1.12 arcseconds per pixel. Figure 3 shows two doubles with different separations imaged using this system.

By visual inspection of Figure 3, STF 2655 is well separated. However, STF 559 is not sufficiently resolved for confident astrometry, as will be shown below. Charles Bracken, in The Deep Sky Imaging Primer, explains the various limiting factors for resolving two point sources, including the atmosphere, optics, and sensor undersampling (Bracken, 2017). In this case, we believe that the atmosphere is the dominant limiting factor because the starlight is overlapping due to scintillation. In addition, our images appear to be slightly undersampled, further limiting our resolving power. To better quantify this, Steve Howell writes in his Handbook of CCD Astronomy that effective sampling can be modeled by the following equation:

$$r = \frac{FWHM}{p}$$

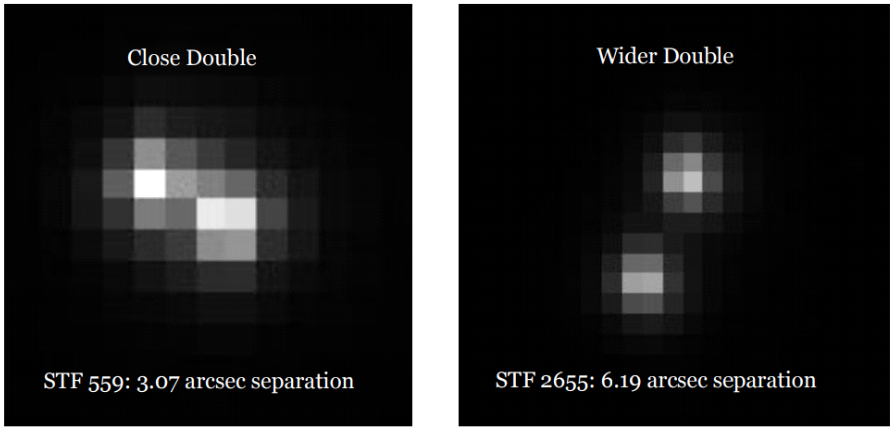

Figure 3: *A close double (STF 559) and a wide double (STF 2655) imaged for this study.*

In this equation, p is the pixel scale and the FWHM is the full width at half maximum of the stars in equivalent units. An r value less than 1.5 indicates undersampling (Howell, 2006). The software PixInsight was used to measure the FWHM of the images, and the average was 2.0". This gives an r value of 1.8, close to Howell's criterion of $r < 1.5$, which is similar to the Nyquist theorem stating that twice the spatial frequency of a given oscillation is required to perfectly reconstruct the original signal (Lévesque, 2014). Here, the "oscillation" is the FWHM, and the spatial frequency is the pixel scale of 1.12 arcseconds per pixel. By Howell's criterion, the images are close to being undersampled. This might affect the ability of the telescope to resolve down to the atmosphere-seeing limit, such as in the case of STF 559. A smaller sampling might allow more accurate measurements to be made in the same seeing conditions until the seeing limit is reached.

Note that the error on the centroid position introduced by undersampling is independent of the separation of the stars. However, when the separation is low, the error on centroid position causes a larger percent error on separation. Averaging many measurements increases the accuracy because the centroid position error is random, not systematic. However, highly accurate results cannot be obtained from poor measurements.

Centroiding in AstroImageJ

AstroImageJ uses the Howell centroid algorithm to compute the centroid of a star (Howell, 2006). It is a weighted average, otherwise known as an intensity centroid algorithm. It produces an astrometric, not photometric, measurement. The algorithm gives highly repeatable results such that it is relatively independent of the starting location, as long as the user clicks somewhat near the centroid (Collins, 2017). From our rough testing, deviations of a pixel (which are visually clearly off center) yielded the same centroid results for most stars. To better measure the centroid, AstroImageJ employs a sigma-clipping algorithm to reject background pixels with a flux greater than two standard deviations from the mean flux of the background region. Figure 4 shows the rejected pixels, labeled with white dots. Pink circles have been placed around the white dots for clarity. Many of these "background" pixels actually contain the secondary star, and the algorithm correctly rejects them to get a better measure of the true background. However, because the rejection algorithm does not operate within the innermost aperture, if the innermost measuring aperture contains starlight from the other star, the centroid will be computed incorrectly. Setting the size of the innermost aperture is therefore very important because too large a size will erroneously draw the centroids closer, while too small a size will not sample the entire point spread function of the star. Some of the inner apertures used in this study needed to have a radius between one and two pixels because the two stars were so close. While this might degrade the accuracy of our measurements, a larger size would have included the secondary star. As Buchheim notes, when the secondary star is so close to the primary that there is not a well-defined "valley" between them, making aperture photometry inaccurate (Buchheim, 2008). For this reason, our smaller separation measurements are excluded from the measurements we will report below.

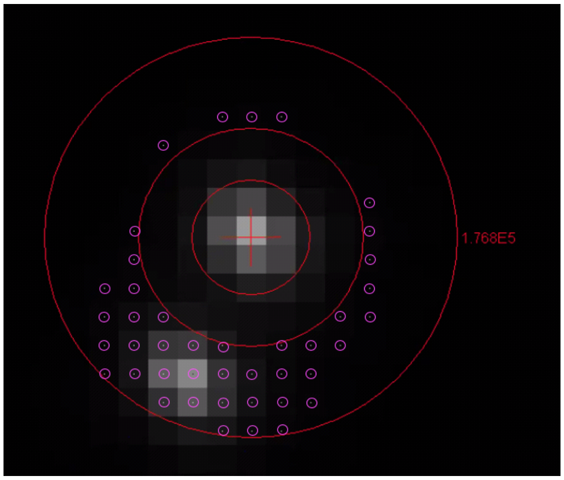

Figure 4: Sigma-clipping rejection for STF 2655.

Historical Observations and Our Measurements

The plots in Figure 5 (below) are color-mapped; darker points are most recent. All of the historical data points have been corrected to account for Earth's axial precession since the time of their measurement, and outliers more than three standard deviations from the mean have been removed. For each plot, our measurement using AstroImageJ is green, Gaia DR2 is pink, and DOPPhot is orange. Note that there is no green measurement for STT 437AB since we were not able to resolve it sufficiently to measure it in AstroImageJ. Also, DOPPhot was not able to measure STF 2947AB, so there is no orange measurement for that system. The other photometric algorithms each only measured the larger half of the separations, and including their points would make these plots more difficult to read. Therefore, their output is not shown on the historical data plots, though their residuals are studied in Figure 6.

There are several cases for which the data shows a clear trend. These include STT 437AB and STF

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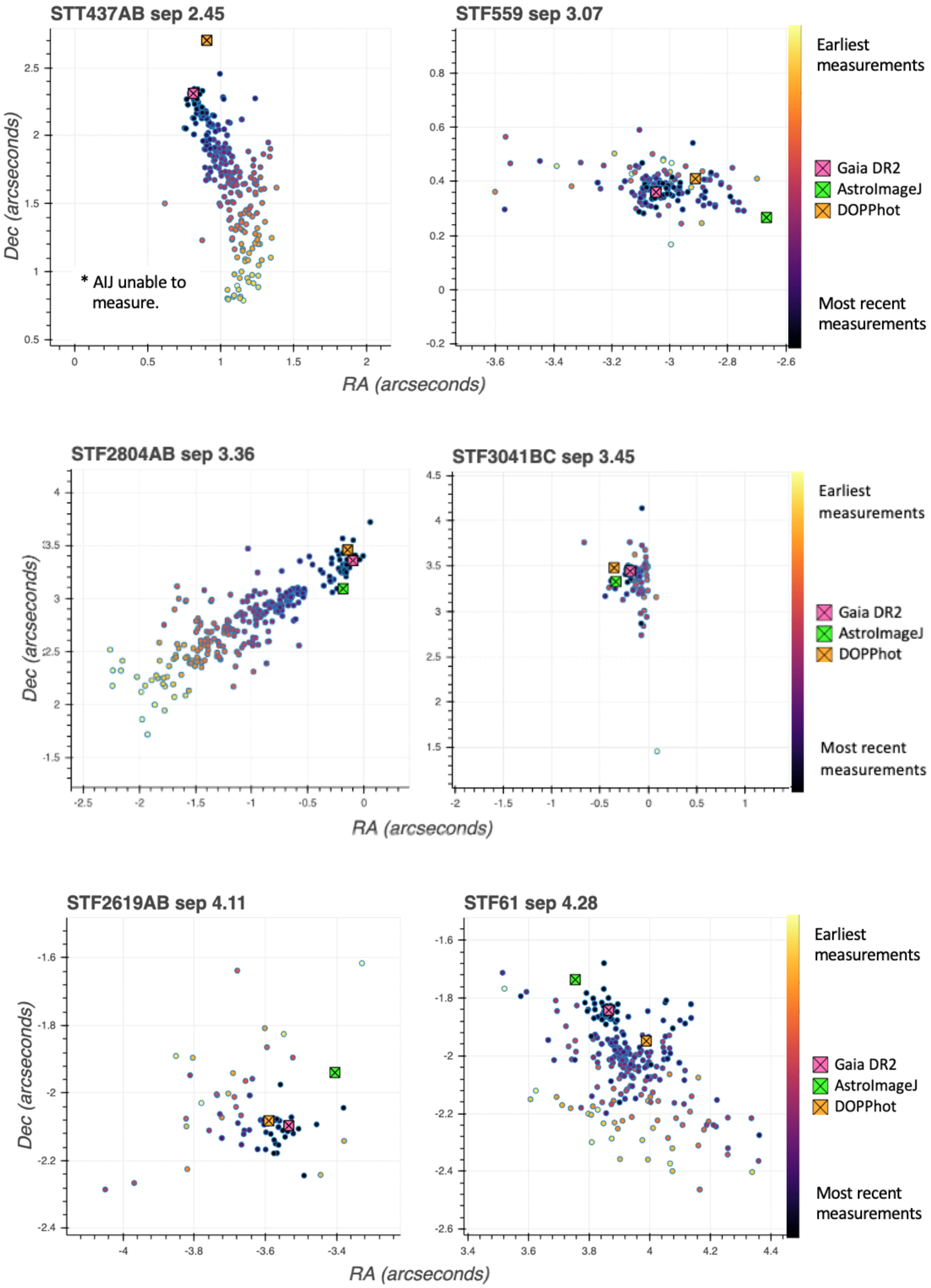
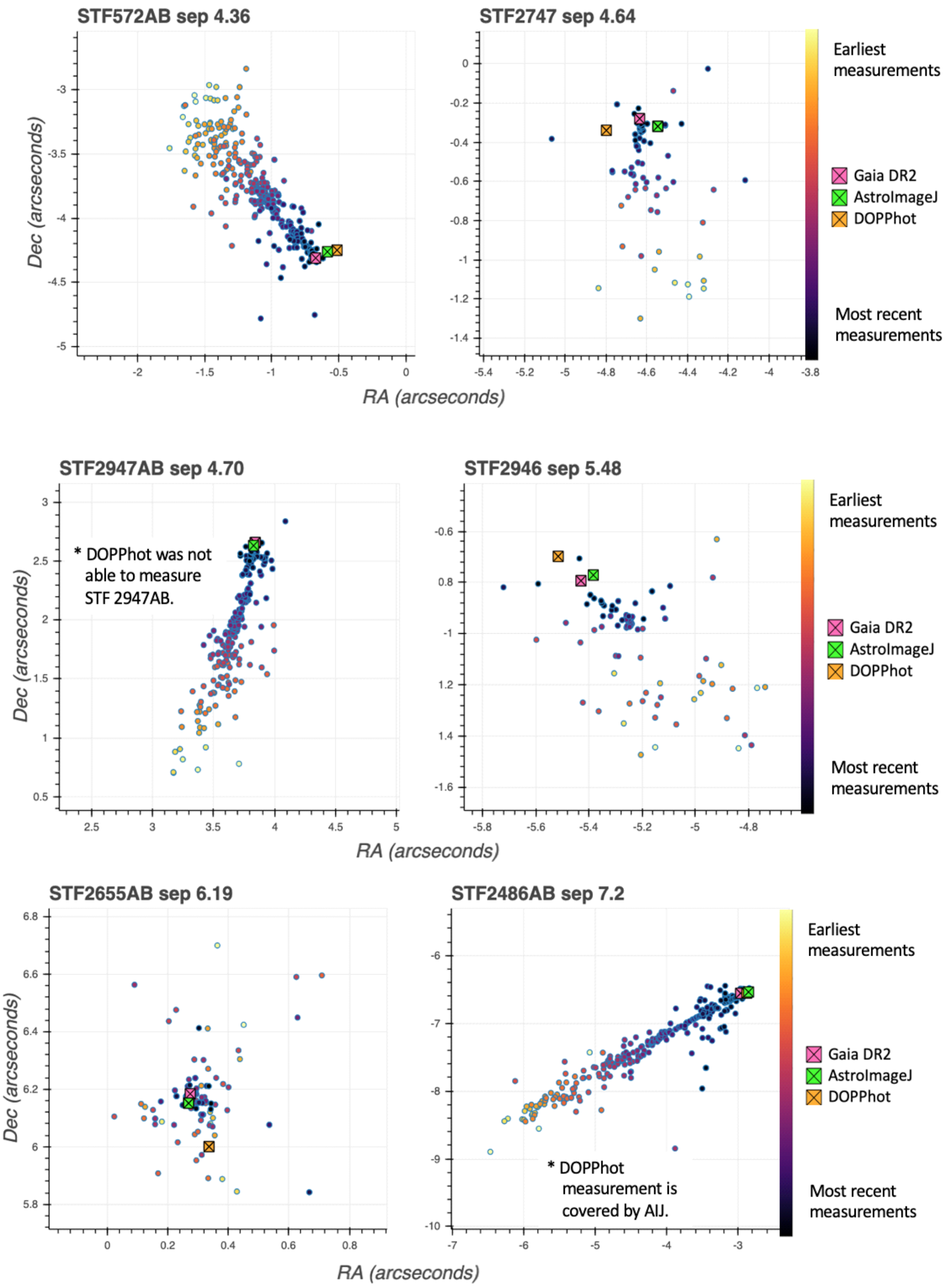


Figure 5. Plots of historical measurements and our results (continued on next page).


STF572AB sep 4.36

STF2747 sep 4.64

STF2947AB sep 4.70

* DOPPhot was not able to measure STF 2947AB.

STF2946 sep 5.48

STF2655AB sep 6.19

STF2486AB sep 7.2

* DOPPhot measurement is covered by AIJ.

Figure 5. Plots of historical measurements and our results .

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2486AB, which are short-arc binaries with orbital solutions. STF 2804, STF 572AB, and STF 2947AB have linear solutions. In these cases, the Gaia DR2 point follows the trend more closely than the measurements from AstroImageJ or DOPPhot, solidifying our selection of it as our standard.

Some of these stars have more scatter than others, such as STF 3041BC. This is most likely because the stars are moving in the sky slowly relative to each other, so past and current measurements do not show much trend.

Analysis

Photometry may substantially affect the accuracy of astrometric measurements of close double stars, especially those with separations approaching the FWHM. Figure 6 below shows the residuals for all the photometric methods and AIJ. AIJ's intensity centroid algorithm contains a systematic error that pulls close centroids closer together. DOPPhot, which uses a Gaussian model, does not have this systematic error. For the images studied here, measurements in AIJ above 4.5" separation contain a systematic error of -0.1". Below 4.5", the magnitude of AIJ's systematic error increases rapidly and is no longer accurate enough for confident measurements. We are not confident enough to suggest adding 0.1" to measurements in AIJ because this study is only confined to a single telescope operating during a single night.

We expect all the algorithms to converge to an accurate measurement with increasing separation, as a larger separation is intuitively easier to measure. However, to our surprise, not all the algorithms converged, though our limited data set makes any generalization tentative. We initially looked at those that did converge, and they are AIJ, SEX, and possibly PSFEx. AIJ shows the most clear convergence trend, underestimating the separation and converging to a systematic error of -0.1" at separations above 4.5". SEX converges slightly more slowly, but from above rather than from below. Of these two, AIJ has a narrow lead on accuracy. PSFEx behaves strangely near 4" - the residuals are very large and erratic. Looking past these few outliers, there are only a few data points on which to base our judgement. There appears to be convergence from below, but the four data points present are not enough to form solid conclusions. Of the algorithms which converge, AIJ appears to be the most accurate. We do not know why these algorithms have a systematic error even at larger separations of 7", for these stars were clearly resolved in the images, but the trend appears regardless.

DOPPhot is the only algorithm which has residuals scattered around zero, with a range of approximately ±0.2". As a comparison, DAOPhot's residuals range from 0" to +0.4" - giving it the same scatter as DOPPhot but around a systematically overestimated separation. This means that DOPPhot appears to be more accurate than DAOPhot. Furthermore, DOPPhot is the only photometry of the six studied here to have a low error of ±0.2" for separations between 3" and 4". However, it is important to note that only DOPPhot and AIJ were able to measure separations in this range.

Our images have an average FWHM of 2.0", measured with the software PixInsight. A 2.0" FWHM should allow separations of approximately twice the FWHM (4") to be accurately measured with standard weighted-average astrometry; for the photometric algorithms, separations equal to the FWHM should be measurable (Buchheim, 2008). We established AIJ as performing accurately within ±0.1" above 4.5" separation - consistent with Buchheim's criterion. However, for DOPPhot, we do not see this expected accuracy in the 2" - 3" range, and we believe this to be limited by pixel scale, as shown in Figure 3 above. The stars are not undersampled as defined by the seeing limit. However, because DOPPhot is able to resolve within the seeing limit (1.5x the FWHM instead of 2x), the pixel sampling needs to be correspondingly finer to maintain proper resolution. This could perhaps improve the accuracy of DOPPhot, pushing its capabilities to 1x the FWHM or reducing the error below ±0.2", whereas AIJ will likely see little improvement.

Despite the sampling issues identified above, it is important to note that DOPPhot did still measure most of the closest-separation stars within ±0.2", which is impressive. Increasing sampling can be done by simply adding a Barlow or other image magnifier. Thus, DOPPhot holds the potential to be very accurate down to separations equal to the FWHM.

Measurements to Report

Five double stars - above 4.5" - have low enough systematic errors that we are confident in our measurements. They are reported below in Table 2.

Conclusion

We measured 12 systems from the Washington Double Star catalog and studied the effect of photometry on astrometry. We report measurements for five systems above 4.5" in separation. For these images, whose stars have FWHM of 2.0", measurements of separations above 4.5" have the lowest residuals with AIJ's aperture photometry. In general, for separations more than twice the FWHM, AIJ is a good choice, even if the

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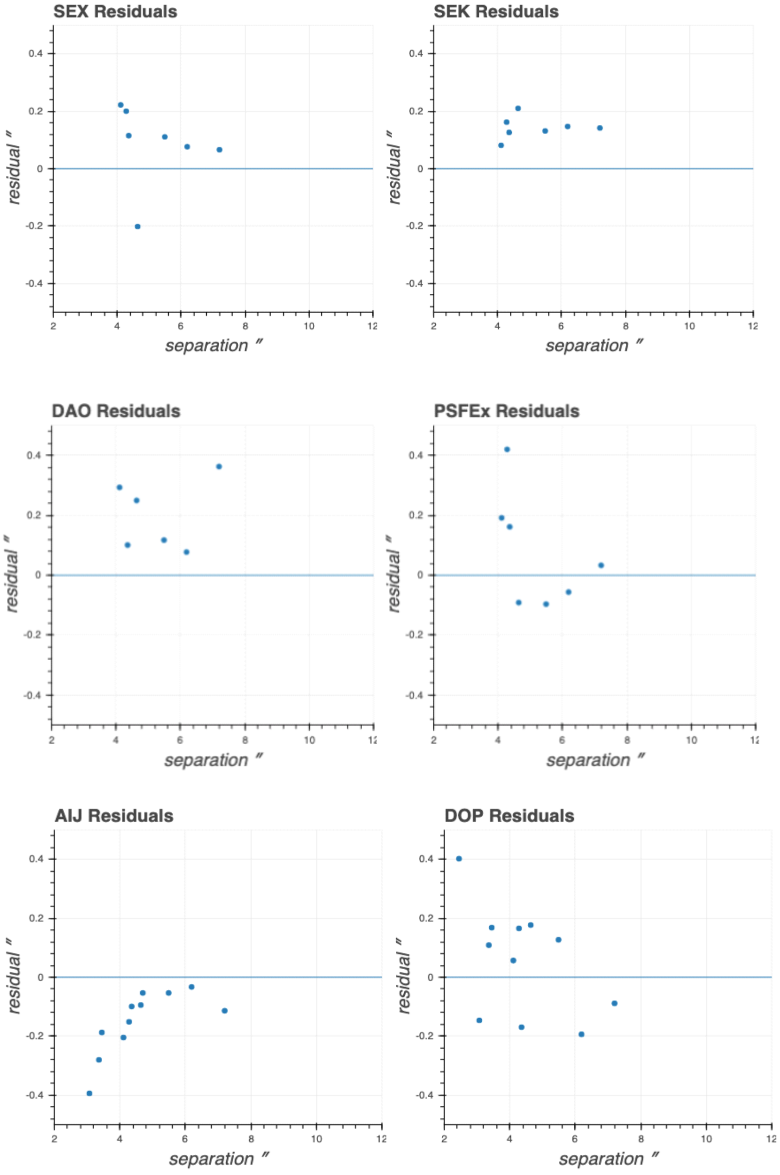
System	Date	Number of Images	Position Angle (°)	Std. error on Position Angle (°)	Separation (″)	Std. Error on Separation (″)
STF2747	2019.85	32	266.0	0.15	4.56	0.008
STF2947AB	2019.85	40	55.5	0.08	4.65	0.011
STF2946	2019.85	31	261.9	0.08	5.44	0.015
STF2655AB	2019.85	30	2.5	0.08	6.16	0.014
STF2486	2019.85	40	203.6	0.09	7.14	0.012

Table 2. Five double stars measured in October, 2019.



SEX Residuals

SEK Residuals

DAO Residuals

PSFEx Residuals

AIJ Residuals

DOP Residuals

Figure 6: Residuals for the various photometries as a function of separation..

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pixel scale large such that the stars are separated by only a few pixels. For stars separated by less than twice their FWHM, a point-spread method such as DOPPhot might give more accurate measurements. We believe a smaller pixel scale is more important to properly sample stars for DOPPhot because it is able to measure within the seeing limit, albeit to a limited extent. The specific telescope, camera, and seeing conditions are huge variables which affect the closest measurable separation. The results here might not directly translate to different observers. However, our analysis suggests that measurements of close double stars are possible at a relatively large pixel scale using a small 100mm telescope, assuming the seeing conditions are good.

Acknowledgments

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