CCD MEASUREMENTS OF VISUAL DOUBLE STARS

Robert K. Buchheim
Altimira Observatory, Coto de Caza, CA
rbuchheim@earthlink.net)

Abstract

The CCD-imaging equipment that many amateur astronomers use for astrophotography and photometry can also be used to measure the separation, position angle, and magnitude difference of visual double stars. There are a few imaging and data analysis procedures that are unique to this project. I describe a simple PSF-model that provides good accuracy and repeatability in measurements of pairs which – due to their close spacing and/or large magnitude difference – would be beyond the reach of standard astrometric software. This project has some conceptual similarities to asteroid lightcurve determination: in both cases, we are presented with a huge number of potential targets that need observation; repeated observation at different epochs adds value to the initial observations; there are very few professional astronomers pursuing these studies; and there exists a Journal devoted to publication of these observations so that they will be available to the professional community. Hence, double star measurement may be a fruitful area for amateur contributions.

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1. Introduction

Binary stars are important astrophysical laboratories: knowledge of the spectra, photometry, and orbital properties provides the basis for determination of the masses and sizes of the stars. “Visual binaries” are pairs in which both stars can be separately observed (e.g. Sirius and its “Pup”, or the beautiful colored pair Alberio). This distinguishes them from most eclipsing (photometric) binaries and spectroscopic binaries, whose angular separation is so tiny that the individual stars cannot be resolved, and hence appear in the telescope as single stars. A visual binary may be a chance alignment of two stars, or it may be a gravitationally bound pair. The distinction between the two can sometimes be inferred by their relative brightness and spectra. Determining the relative motion of the two stars – and their orbit in the case of a gravitationally bound pair – requires observation of the pair at multiple epochs (to map out their motions). Because the orbital periods of most visual binaries are quite long, these observations must be carried out over decades or centuries in order to provide a good estimate of the orbit.

The fundamental parameters of interest are the separation and position angle of the secondary star relative to the primary, as shown in Figure 1.

Since the measurement of ρ and θ is fundamentally a project of astrometry, the same skills, equipment, and software that are used for astrometry of asteroids can be applied to double-star measurements. There are, however, a few special challenges that are unique to double-star measurements: accurately measuring two closely-spaced stars, dealing with large delta-mags, and the quite different cadence, compared to asteroid astrometry. I will discuss these, with examples from recent projects, in the following sections.

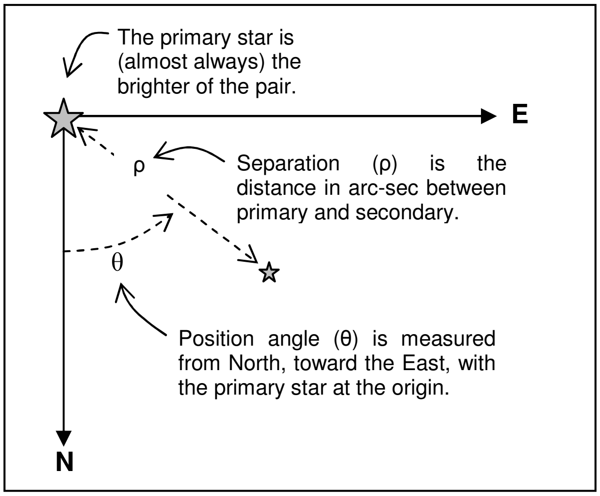


Figure 1: Separation and Position angle of a double star

2. Fundamental Equations:

If we know the RA, Dec coordinates of two stars, their separation and position angle are given by:

$$\left.\begin{aligned}\rho &= \sqrt{(\Delta\alpha\cdot\cos\delta_1)^2+(\delta_2-\delta_1)^2}\\[2ex] \theta &= \tan^{-1}\left[\frac{\Delta\alpha\cdot\cos\delta_1}{(\delta_2-\delta_1)}\right]\end{aligned}\right\}\text{Eqs (1)}$$

where both ρ and θ are given in radians,

δ_1, δ_2 are the declination of the primary and secondary stars, respectively,

α_1, α_2 are the right ascension of the primary and secondary stars, respectively,

$\Delta\alpha = \alpha_2 - \alpha_1$ is the difference of RA,

and all angles are in radians (Smolinski et al, 2006). These equations are derived using the small-angle approximation, where

$$|\Delta\alpha| << 1 \text{ and } |\delta_2 - \delta_1| << 1$$

This approximation is well-satisfied for visual binary star pairs.

Alternatively, we may know the x,y pixel coordinates of the two stars, and the plate constants that relate pixel coordinates to RA, Dec. In that case, a straightforward application of algebra can convert (x,y) into (RA,Dec), and then Eqs (1) can be used to determine (ρ,θ).

3. Commercial Software: MPO Canopus, Astrometrica, CCDSoft

The popular CCD image-processing programs (e.g. CCDSoft, MaximDL, and AstroArt) have the ability to link images to an astrometric star database, determine plate constants, extract stellar objects, and assign accurate RA, Dec coordinates to these objects. For example, the "Research/Insert WCS AutoAstrometry" menu in CCDSoft will do this. Once astrometric information has been calculated, you can click on any star in the image and get a report of its RA, Dec coordinates, with precision usually 0.01 sec of RA and 0.1 sec of Dec. The accuracy depends on the star catalog used and degree of plate constant modeling. These results can then be used in conjunction with Eqs. 1, to determine the (ρ, θ) of the pair.

Astrometrica is a special-purpose program for CCD astrometry. It has the sometimes-useful features of (a) high-order plate constant models, (b) display of the Gaussian-fit to the stellar point-spread function, and (c) internet-based link to the USNO B-1 astrometric catalog for outstanding accuracy in the astrometric database.

MPO Canopus provides the full array of astrometric fitting, including support of the UCAC-2 astrometric catalog. It provides a convenient method for adjusting the size of the measuring aperture, and a unique tool that directly computes the separation and position angle of any selected pair of stars (including the required precession calculation, as described below).

I found that both MPO Canopus and Astrometrica were easy and effective tools for measuring well-separated double-stars. MPO Canopus has the edge in terms of convenience, since its double-star measuring utility does all of the calculation of Eqs (1) for you – just click on the primary star and select it as the reference, then click on the secondary star, and out comes the (ρ,θ). Pretty neat!

4. My equipment:

For double-star astrometry, I've been using the same CCD imaging equipment that I use for photometry projects: 11-inch SCT with a focal reducer to yield F/6.3, an SBIG ST-8XE (NABG) CCD imager with 9 μm square pixels, and filter wheel with photometric B, V, R and "clear" filters. The resolution of this system is 1.2 arc-sec per pixel, which provides well-sampled images considering the so-so seeing at my low-altitude location (typical star images have FWHM ≈ 3.5 pixels).

5. The simplest case: widely-spaced pairs

Figure 2 is the image of a field containing the double star CHE 49 (WDS 02070+2923). This is a relatively widely-spaced pair of stars, with almost equal magnitudes. This sort of system can be reliably measured by any suitably accurate astrometric software – determine the RA, Dec coordinates of each star, and apply Eqs 1.

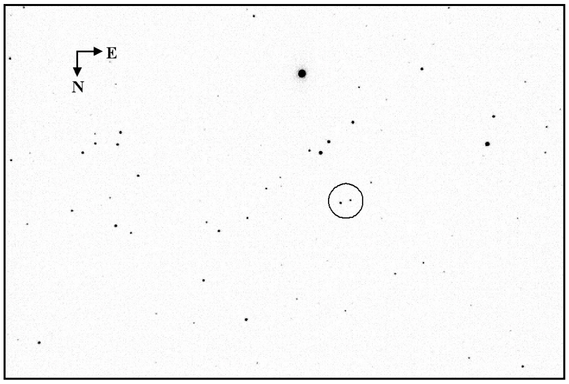


Figure 2: CCD image of the pair CHE 49. The field of view is 27 X 18 arc-min. The separation of the pair is ρ ≈ 32 arc-sec, in position angle θ ≈ 111 degrees.

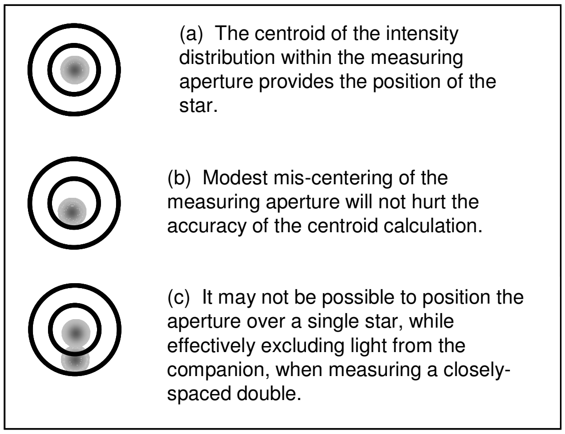
This sort of pair is "easy" because of the following features:

- The stars are separated by more than a dozen pixels. This makes it easy to place a measuring aperture over each individual star, and establish the centroid of the star's image without capturing any interfering light from the companion star.
- The stars are bright enough that they present a good SNR_{peak}, leading to excellent astrometric accuracy.
- There are no other nearby stars to interfere with placement of the measuring aperture, or calculation of the centroid of the star images.

Because of the wonderful convenience of MPO Canopus' double-star measuring utility, it is the method that I use for these cleanly-separated pairs. The procedure is: select an appropriate measuring aperture (of diameter about 3X FWHM of the stellar images), click on the primary star and set it as the reference, then click on the secondary star. Bingo! The program tells you the separation and position angle without you needing to do any calculations.

6. How close can you go?

MPO Canopus' double star utility performs an "aperture astrometry" calculation. You position the measuring aperture over the desired star, and the program calculates the intensity centroid of the signal contained within the measuring aperture. The principle is illustrated in Figure 3. If the measuring aperture is precisely centered on the target star, then the calculated centroid is indeed the centroid of the star's intensity – i.e. the position of the star. If the measuring aperture is modestly misplaced, then a portion of the light in the "halo" of the point spread function may be excluded from the calculation of the centroid. If the measuring aperture is chosen to be large enough to include the entire star PSF (with a little sky background for safety), then this isn't a problem: the resulting centroid calculation is still an excellent estimator of the star's position.



(a) The centroid of the intensity distribution within the measuring aperture provides the position of the star.

(b) Modest mis-centering of the measuring aperture will not hurt the accuracy of the centroid calculation.

(c) It may not be possible to position the aperture over a single star, while effectively excluding light from the companion, when measuring a closely-spaced double.

Figure 3: Principle of aperture astrometry, as exemplified by MPO Canopus' double-star utility.

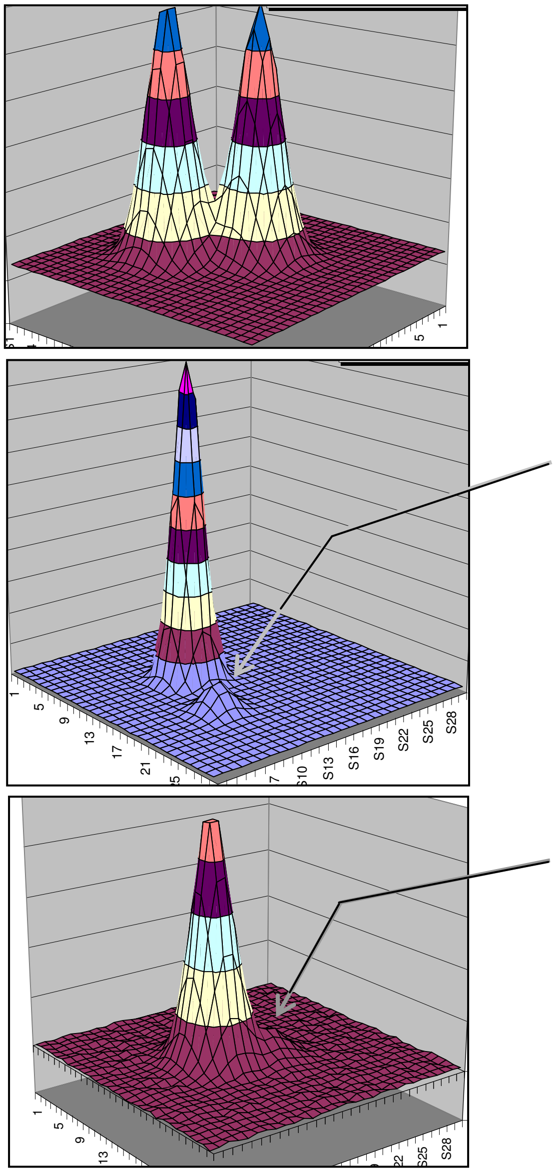
However, in order to measure a double star, we need to be able to place the aperture over first one, and then the other star. If they are widely-spaced, that is not a problem. For pairs that are too close together, the aperture photometry method becomes problematic. You have to make the measuring aperture smaller in order to exclude light from the other star; and a smaller measuring aperture is more sensitive to misplacement relative to the star's centroid. At some point, it is almost impossible to effectively avoid light from the companion star spilling into the measuring aperture [see Figure 3(c)]. In my experience, the first sign that this is occurring is that if the same image is measured several times, the reported (ρ,θ) will fluctuate noticeably. This is symptomatic of the result being sensitive to the size and placement of the measuring aperture. It is a sign that the pair is too closely spaced to be measured with the aperture astrometry method. I haven't done an exhaustive study, but it seems that the center-to-center separation of the stars must be greater than about 2 times the FWHM of the PSF for the aperture astrometry method to work reliably with equal-brightness pairs. If Δm is greater than 1 magnitude then a separation of ~3X FWHM may be needed to cleanly separate the stars. Closer than that, and the results are not repeatable (at the ±0.2 pixel level).

Some programs (including Astrometrica) attempt to automatically center the measuring aperture over the star's image. This is a good thing for photometry of single stars – it means that the user doesn't have to be meticulous in placement of the aperture. However, in the case of a close pair, the software may be pulled to the centroid of the pair, and place the aperture nicely centered over the intensity-weighted mid-point of the two stars. This obviously doesn't help us measure the separation of the two stars! [A long time series of such centroid measurements could show a pattern of astrometric wander of the centroid. Some binary stars, including Sirius and Procyon, were recognized from such wander before the companions were actually resolved (Mason, 2008)].

Astrometrica uses a slightly different approach to astrometry. It establishes a measuring aperture, does a Gaussian fit to the star's PSF within the measuring aperture, centers the aperture over the peak of the PSF, and reports out the RA, Dec coordinates of the resulting peak of the PSF. From my (limited) comparison tests, it appears that this method enables the measurement of pairs that are a bit closer than can be done with MPO Canopus. However, with close pairs the Astrometrica approach will still tend to "grab" the weighted centroid of the pair. Because the position of the measuring aperture is under the control of the software (not the operator, as in the case of MPO Canopus), repeated measurements of the same image will give very consistent results; but when the star images overlap, this consistency may be masking systematic errors between the "reported" versus the "true" separation of the stars. With stars that are closer than about 2-3 times the FWHM, this doesn't seem to be the best approach.

The problem of stars being "too close" is easy to visualize, when you think of stars that are nearly equal in brightness. If there is a significant brightness difference (i.e. a faint secondary), then required separation (to not be "too close") is larger than if the pair has nearly equal brightness. The gradation between these two situations is illustrated in Figure 4.

Since it is fairly easy to "eyeball" the fact that there is indeed a second star, even in the extreme case of Figure 4(c), it seems reasonable to conclude that the desired information about that secondary star is contained in the image. The challenge is to find some other way to extract the information from an image of a pair that is too close to be reliably measured with aperture astrometry.



(a) With an equal-brightness pair, it is relatively easy to place a measuring aperture over one single star; and to tell where the "boundary" between the stars lies.

(b) When the secondary star (arrowed) is noticeably fainter than the primary, it is difficult to place the measuring aperture. The fainter the star, the more difficult it is to avoid "contamination" of the secondary star's centroid with light from the halo of the primary star.

(c) When the secondary star (arrowed) is so close to the primary that there isn't a well-defined "valley" between them, an aperture astrometry method is doomed.

Figure 4: The problem of small separation and large magnitude difference.

7. PSF fitting for very close and unequal-brightness pairs

In an attempt to extract position information from pairs that are too closely separated to reliably measure with aperture photometry; and to deal in a repeatable way with pairs that present a large delta-magnitude, I constructed a simplistic approach to PSF modeling.

There are two common a-priori models of the point spread function in widespread use: the Gaussian and the Moffat models. The Gaussian model assumes a PSF of the form:

$$I(r) = I_0 \exp\left[-\frac{r^2}{2\sigma^2}\right] \qquad \text{Eq. 2}$$

The Moffat model assumes a PSF of the form:

$$I(r) = \frac{I_0}{\left[1+\left(\frac{r}{\alpha}\right)^2\right]^\beta} \qquad \text{Eq. 3}$$

The Moffat function is a good theoretical model of the PSF of atmospheric turbulence, which is usually the primary contributor to the observed PSF on the CCD images. Mathematically, the Moffat function becomes Gaussian in the limit as $\beta \rightarrow \infty$ (Trujillo, et al, 2001). Hence, I chose to base my PSF-fitting algorithm on the Moffat function.

Most of my images show slightly elliptical star images. These betray the imperfection of my telescope's mount and minor tracking/guiding errors, since the long axis of the star images align with the RA direction. In order to model this fact of life, I modified the Moffat function to have different widths in the x- and y-directions:

$$I(r) = \frac{I_0}{\left[1+\left(\frac{x}{\alpha_x}\right)^2+\left(\frac{y}{\alpha_y}\right)^2\right]^\beta}$$

where α_x and α_y are the widths in the x- and y-directions, respectively.

I then assume that a small sub-image that contains only the two stars of the binary pair can be modeled with reasonable accuracy by:

$$I(x,y) = I_P(x_P, y_P) + I_S(x_S, y_S) + C$$

where (x_P, y_P) are the coordinates of the primary star,

(x_S, y_S) are the coordinates of the secondary star,

I_P and I_S are Moffat functions whose peak intensities (in ADU/pixel) represent the primary and secondary stars, respectively, and

C is an additive constant.

This simple model ("two Moffat functions and a constant") is the basis of my PSF fitting approach. The mathematics of finding the best Moffat fit to a real PSF is complex (Bendinelli et al, 1988). However, it turns out that Microsoft Excel can be pressed into service as a "brute force" iterative method to determine the parameters of a two-star model that is the best fit to the observed image. I extract a small sub-image (typically 30 X 30 pixels) that contains the two stars of the binary pair (and no other objects), turn this into a 30 X 30 matrix of ADU values, and then use Excel's "Solver" utility to find the model function that minimizes the squared error of "modeled minus observed":

$$\chi^2 = \sum_{x,y} \left[I(x,y) - O(x,y)\right]^2$$

Where $O(x,y)$ is the array of observed ADUs in the measured image, and the summation extends over all pixels in the array.

7.1 Validation Checks:

I made a couple of tests to confirm both the general logic of the (fairly complicated) Excel spreadsheet and the ability of the Solver to converge on an accurate solution.

First, I created a purely synthetic image of two well-separated Gaussian point spread functions, and asked Solver to create a model $I(x,y)$ that represented the image. This worked perfectly – with the least-square solution being identical to the synthetic image properties (positions, intensities, and FWHM of the PSF's). I then repeated this numerical experiment using two synthetic stars that were barely separable by "eyeball" (separation < 1X FWHM), similar to Figure 3(c). Again, starting with this synthetic image, the Solver was able to determine the parameters that were used to create the best solution.

Second, I created synthetic images that contained additive Gaussian noise (with no noise correlation between pixels), and repeated the numerical tests. Even with noise levels that are much higher than observed on real images, the Solver was able to unravel the positions, intensities and PSF widths of the two stars.

With these validation activities complete, I tried a couple of verification tests, by measuring pairs whose motion is well-known (referred to as "calibration systems" in the WDS).

7.2 Verification Checks:

As with other astrometric projects, the essential requirement for double star measurement is accuracy. It is reasonable to strive for repeatability of ± 0.1 arc-sec in measurements of multiple images of a single pair, and any measurements with errors (random or systematic) of more than about 0.5 arc-sec may be of marginal value. If the error is larger than an arc-second, then the measurement may be worse than useless – it may confuse future observers, and may noticeably degrade any future orbit calculations.

Because of the mess of conversions and calculations that my PSF-fitting approach entails, there was certainly the potential for some goof-up creeping into the procedure. I didn't want to risk reporting measurements that would later be embarrassing!

The WDS includes some pairs whose motion is reasonably well-determined. These are called "candidate calibration systems", and they can be used as verification checks of the whole project sequence of imaging, PSF fitting, and astrometric analysis. I selected two candidate calibration systems that were conveniently placed, and which were close enough to test the ability of PSF fitting to separate stars that were separated by not much more than the FWHM of the images. The results were heartening, as shown in Table 1. These verification checks give me confidence in my software, procedures, and results.

Star	ρ (arc-sec)	θ (deg)
STT 547 AB		
ephemeris	5.951	185.5
measured	6.0 ± 0.3	187.5 ± 2.2
STF 422 AB		
ephemeris	6.688	271.3
measured	6.8 ±0.2	271.5 ± 1.4

Table 1: Verification Results of "two-Moffat function" PSF fitting technique.

7.3 Consistency of Various programs

I measured several pairs of stars using MPO Canopus, Astrometrica, and my Excel-based PSF fitting, to confirm that the results were consistent regardless of the program used. These results shown in Figure 5 confirm that all three programs are consistent when the stars are well-separated. One aspect that isn't illustrated in this Figure is that as the separation shrinks, the aperture astrometry results can be quite sensitive to the size of the measuring aperture – too large an aperture and the program cannot distinguish one star from the other, and too small an aperture makes it hard to get a meaningful centroid position. The PSF-fitting method can be reliably extended to pairs as close as $\rho \approx$ 1X FWHM, and can also handle very large delta-magnitudes.

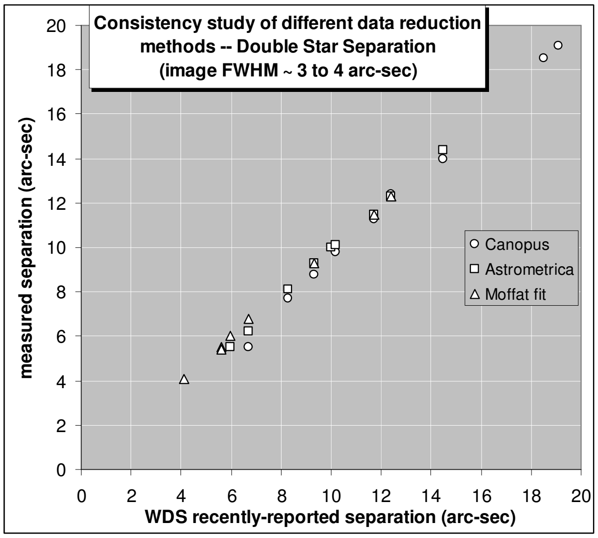


Figure 5: Various methods of measuring pairs' separation are consistent, for separations > 2X FWHM. PSF fitting can reliably distinguish stars separated by ~ 1X FWHM.

8. Making measurements:

I found that making measurements of "unconfirmed" or "neglected" pairs is a surprisingly time-consuming effort, but that it has rewards that make it worth the effort. The activity divides roughly into three phases: finding the pair, imaging, and data reduction.

The WDS contains accurate RA, Dec coordinates for most of the pairs, so finding them on a star chart and pointing your telescope in the correct direction, isn't normally a problem. (There are pairs that are "dubious", "unconfirmed", or "uncertain" – pairs that may not be at their reported position, or may not exist at all. These provide opportunity for some detective projects).

8.1 Imaging

The imaging activity is straightforward. The idea is to be meticulously well-focused, select an exposure duration that achieves a balance between good signal level but no saturation, and to take advantage of nights where the seeing is very stable. A high level of sky-glow doesn't affect the astrometric measurement, so this is a good activity to fill your full-moon nights! Haze or thin clouds also don't interfere with the astrometric measurements; in fact, it may be that the very best seeing occurs on nights of slight haze.

Regarding signal level, I try to get $\mathrm{SNR}_{peak} > 20$ on the secondary star, without saturating the primary star. I keep a curve of predicted exposure vs. magnitude to achieve SNR $\approx$ 100 in various filters (from photometry projects), so I can use this to get a first-guess of the appropriate exposure duration for each pair. However, the reported magnitudes of some "neglected" pairs are of uncertain reliability, so I use the old photographer's habit of making a series of images at various exposure durations. For example, for an "equal brightness" pair, I might use exposures of 1 sec, 3 sec, and 9 sec. If there is a wide difference in brightness between the primary and secondary star, I might also do a 30 sec and 1 min exposure. The idea is that at least one (and often two) exposure durations will result in the desired combination of good SNR but no saturation. At each exposure duration, I take at least 6 images. That way, if one or two are spoiled, I still have several "good" ones for measurement.

To filter or not to filter? That is a fair question. Some references recommend the use of filters to avoid the atmospheric-dispersion spectral spreading of star images. However, if measurements are made at relatively low air mass ($X<1.5$, i.e. at least 40 degrees above the horizon) that effect isn't important. Another reason to consider using filters is that the right filter may reduce the magnitude difference (due to the inherent color difference of the components of the pair). In general, a large magnitude difference makes it harder to measure the pair.

Using a "clear" filter allows the shortest exposures, and using a short exposure minimizes the risk that tracking/guiding errors or "image wander" from atmospheric turbulence may smear the image. I've made a few tests to compare the results of using a V-band filter versus a clear filter; aside from the need to use longer exposures, I found no advantage of the V-filter in terms of repeatability of the measured (ρ, θ). Hence, I've generally used the clear filter for my images.

I normally autoguide if the exposure is going to be longer than 15 seconds or so. This is primarily because of the poor tracking of my mount; but it is also a contributor to good results in the case of bright primary and faint astrometric reference stars (described below).

Images are processed in the normal way: flat frame, bias and dark correction. Then each image is examined for defects such as tracking/smearing, focus problems, adequate SNR and no saturation. The "good" images are then used for astrometric analysis.

8.2 Bright primary, faint secondary

There are some pairs composed of a very bright ($V<6$) primary, a faint secondary (Δm in the range 4-7), and relatively faint field stars. This situation presents two special problems: (a) balancing the exposure to avoid saturation of the primary while getting an acceptable SNR > 25 on the secondary, and (b) getting astrometric reference star images. The pair STF 422 is such a pair, and is of particular interest because it is a candidate "calibration system". The primary is magnitude 6, the secondary is magnitude 8.9, and virtually all of the field stars are magnitude 13 or fainter. That's an intensity range of 15:1 in the double star, and an intensity range of over 1000:1 between the primary star and the field stars. An exposure duration that avoids saturation of the primary, gives SNR < 20 on the secondary star, but doesn't show any astrometric reference stars. A longer exposure, to give reasonable SNR>10 on astrometric reference stars, saturates the primary star. What to do?

The solution that I used was based on an Excel spreadsheet that performs the least-squares determination of plate constants. With the autoguider working, I make a long-exposure image of the FOV, that shows a good array of astrometric reference stars. Then I make a series of shorter-duration exposures, that provide good images of the double star pair (but few if any astrometric reference stars). Since the autoguider keeps the 'scope pointed at the same location (within a pixel or so), the plate constants determined from the "long exposure" image can be applied to the "short exposure" images also.

The couple-of-pixels motion between the long exposure image and the double-star images is negligible, because the purpose of the calculation is to determine the distance between the two stars, not their absolute positions.

8.3 Finding the stars

Once the images are taken and astrometrically matched, it may still be a little tricky to identify the correct stars. For example, Figure 6 is the image of the field containing the pair ROE 94 (the “neglected double” that was my target for this image). I saw the obvious close pair at the center of the field of view, and thought, “there’s my target” ... but its coordinates weren’t right. The NASA ADS enable me to find the original discovery report (Roe, 1916), which gave the location of this star relative to the catalog star BD +50º3940. That enabled me to correctly identify the target. But what is that prominent close pair nearby? A check of the WDS identified two other pairs that are in this FOV. One was DBR 2, in the lower left. The other was HJ 1846, but the star identified by the WDS coordinates wasn’t a visual double. That prominent equal-magnitude double matches a recent WDS-reported measurement ρ,θ of HJ 1846, so this appears to be a case of a minor error in the WDS coordinates.

As this example illustrates, sometimes a little detective work is needed to sort out just what you’ve gotten in your image of a visual double star.

8.4 Data reduction & Precession Correction:

The determination of the (RA, Dec) coordinates of each star in the pair is a straightforward project for your astrometric software: match the image to a reference catalog (e.g. UCAC2 or USNO B-1), determine the plate constants of the image, determine the (x,y) coordinates of each star, and the use the plate constants to translate from (x,y) to (RA, Dec). Most astrometric software does most of these calculations without any complex operator interaction. This is the same procedure that you’d use in a project to update astrometry of an asteroid. The resulting (RA, Dec) coordinates for the stars (or the asteroid) are generally reported relative to the equinox and pole of the standard epoch (J2000).

Remember that the direction to the pole, and the position of the zero-point of RA, do gradually change as the Earth’s rotational axis precesses. Precession doesn’t affect angular separation (ρ), but it *does* affect the calculated position angle (θ). Given the very long data record for observations of some double stars (a century or more for some pairs), it is necessary to consider the effect of precession, and report the position angle with reference to an agreed-upon pole position. The proper approach (expected for observations that are published for addition to the

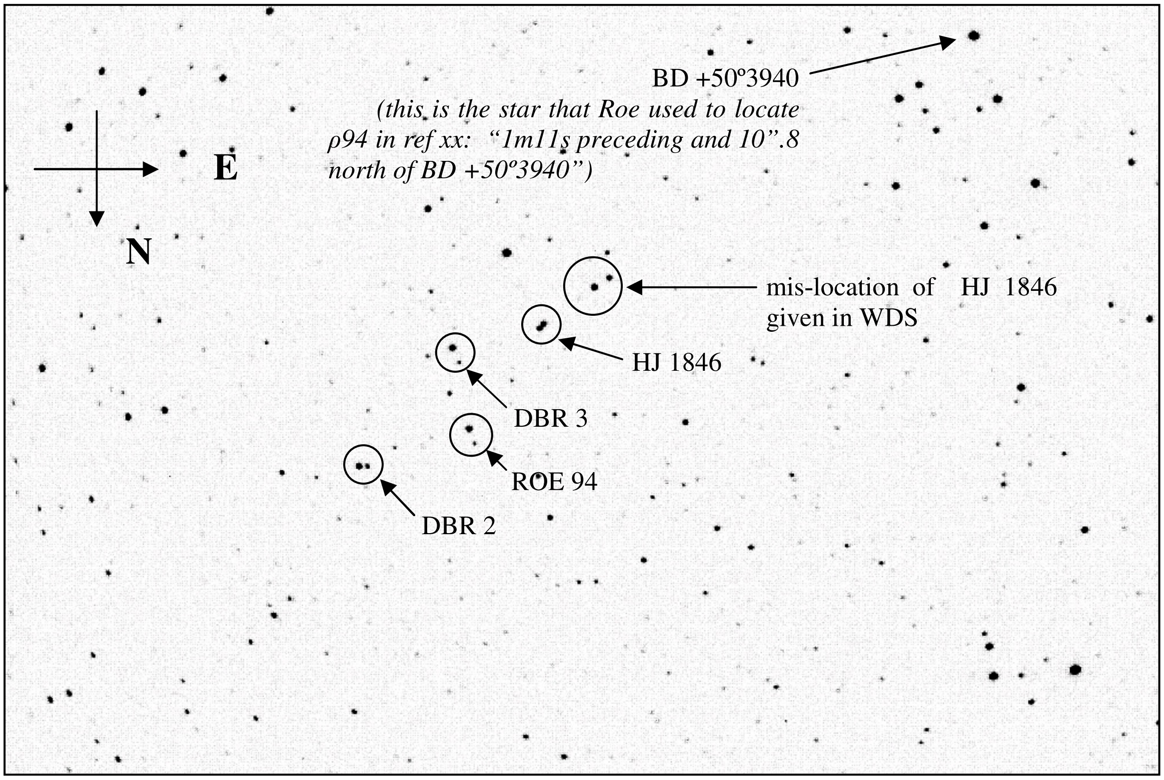


Figure 6: A "rich" field of double stars (centered at RA= 23:04:52 Dec= 51:19:24)

WDS) is that the position angle should be referenced to the *pole position and equinox of the date of observation* – not J2000 (Mason, 2008). You can understand the logic behind this convention if you think back to the use of a filar micrometer – the traditional instrument for double-star measurements. The first step in the process is to orient the fiber along the drift direction of a star (with the telescope drive turned off). Assuming that this is done with great care and accuracy, it automatically means that the position angle is measured relative to the pole of the date of the observation.

Since a CCD astrometric measurement will almost invariably be referenced to J2000 (because that is the reference frame in the astrometric star catalog), an additional step may be needed: precessing the observations to the pole and equinox of the date of the observation. This can be done in one of two ways: (a) first precess the stars' coordinates to the equinox of the date of observation, then calculate the position angle using these "precessed" coordinates; or (b) calculate the position angle with reference to J2000, then calculate the change caused by precession. Today, less than a decade removed from the standard epoch (J2000), precession has a very small effect (less than a half-degree) on position angle for pairs at declinations below ±70 degrees. However, if you are measuring pairs closer to the pole, the effect of precession can have a quite large effect – as much as several degrees (Wycoff et al, 2006).

This same effect (in reverse) must be considered when you are combining historic observations of a double star: all position angles in the WDS will be referenced to the pole orientation of the date of observation. In order to combine them into a single, consistent picture you will need to precess each measurement to the standard epoch. Again, for stars that are at modest declinations (below 70 degrees or so), and whose measurement accuracy is typical of visual/CCD accuracy, the effect of precession will be modest, even over time bases as long as a century.

The equations and methods for performing the precession calculations are given in Kaplan (2005).

9. Reporting your measurements:

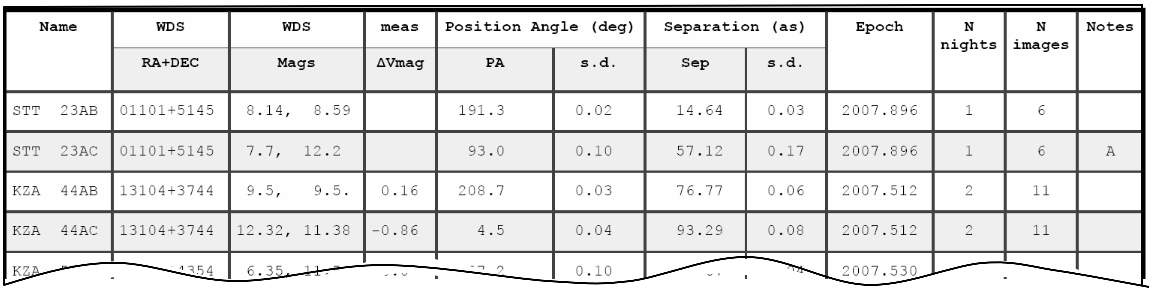
Like all amateur research projects, double-star measurements are only valuable if the results can be collated and provided in a form that is useful to the professional astronomical community. The USNO does not accept measurements directly from observers: the WDS is a compilation of published measurements. Happily, the University of South Alabama has begun providing the service of publishing a journal devoted to double-star topics, including reports of measurements. The Journal of Double Star Observations is published quarterly, and provides the entry portal for amateur observations to be incorporated into the WDS. The JDSO is freely available on the internet at www.jdso.org.

The heart of the typical JDSO article is a table of observations, similar to that shown in Figure 7. It may not be as aesthetically pleasing as the lightcurve of an asteroid, but it is just as valuable a contribution to astronomical science!

10. Results: Numbers and Emotions

There is a subtle satisfying emotion in completing the accurate measurement of a double-star pair that has been long neglected. It's fun to see if the stars have moved noticeably. Sometimes the motion is quite obvious, as in the case of MLB 102, shown in Figure 8. It is pretty amazing to be able to "see" the motion of the stars, with data that I've gathered in my backyard.

Examining and measuring "neglected" pairs is also a way of touching the past. During my first data reduction session, I gradually realized that some of these stars that I'd spent an hour or so with, had been ignored for decades. They were anonymous points of



Name	WDS	WDS	meas	Position Angle (deg)		Separation (as)		Epoch	N nights	N images	Notes
	RA+DEC	Mags	ΔVmag	PA	s.d.	Sep	s.d.				
STT 23AB	01101+5145	8.14, 8.59		191.3	0.02	14.64	0.03	2007.896	1	6	
STT 23AC	01101+5145	7.7, 12.2		93.0	0.10	57.12	0.17	2007.896	1	6	A
KZA 44AB	13104+3744	9.5, 9.5.	0.16	208.7	0.03	76.77	0.06	2007.512	2	11	
KZA 44AC	13104+3744	12.32, 11.38	-0.86	4.5	0.04	93.29	0.08	2007.512	2	11	
KZA	354	6.35, 11.			0.10			2007.530			

Figure 7: Typical report of double-star measurements published in JDSO.

light that had been overlooked by generations of astronomers. The professionals have moved on to cosmology and distant galaxies, the amateurs have advanced into CCD imaging, and so these pairs have been condemned to loneliness by their anonymity. They don't even have the derivative fame of lying near an attractive deep-sky object, where they might at least appear as the supporting cast that provides the crowd surrounding the highlighted galaxy or nebula. The few minutes of attention by an amateur astronomer in his backyard observatory may represent their only contact with humanity for a generation or longer. It's a new way of building a relationship with the stars, and of reaching back to the dedicated astronomers who made the earlier measurements. These lonely stars are something that I now have in common with a cadre of now-retired astronomers.

11. The need for more measurements

The standard catalog of visual double stars is the Washington Double Star Catalog. The WDS is available on-line from the US Naval Observatory, at http://ad.usno.navy.mil/wds/. Some of its pairs are far too close for CCD measurement, and some are located too far south for those of us in mid-northern latitudes. Still, if you sort the WDS to eliminate all stars whose last measurement was less than 3 arc-sec, and all pairs that lie south of Dec = -15°, you still are left with over 45,000 candidate target pairs. It usually isn't necessary to measure these double stars more frequently than every 10 years or so – they move very slowly! So theoretically, we could keep track of all of the amateur-accessible WDS stars by measuring only 4500 per year. That's 12 per night, 365 nights per year.

We are clearly not keeping up the required pace. The USNO's list of "neglected doubles" identifies over 800 pairs that are accessible to northern-hemisphere amateur CCD astrometrists (i.e. $\rho > 3$ arc-sec and delta-mag < 3) but which have not been measured in over 20 years. So – I urge you to consider adding some double-star measurements to your project list. It is a fine and useful activity that can be conducted on full-moon or hazy-night conditions.

References:

Roe, E. D. Jr., "New Double Stars and measures of Double Stars", *Astronomische Nachrichten*, volume 202, p.99 (1916)

Smolinski, J., and Osborn, W., "Measurement of Double Stars With a CCD Camera: Two Methods", Rev Mex AA (Serie de Conferencias) v 25, 65-68 (2006)

Trujillo, I., Aguierri J.A.L., Cepa, J., Gutierez, C. M., "The Effects of Seeing on Sersic Profiles. II. The Moffat PSF", *Mon Not RASC*, volume 328, issue 3, p.977 (2001).

Mason, B. D. personal communication (January & March, 2008)

Wycoff, G. L., Mason, B. D., Urban, S.E., "Data Mining for Double Stars In Astrometric Catalogs", Astronomical Journal, v 132, p 50 (2006 July)

Kaplan, G. H., "The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models", USNO Circular 179, US Naval Observatory (2005).

Bendinelli, O., Parmeggiano, G., Zavatti, F., "CCD Star Images: On the Determination of Moffat's PSF Shape Parameters", J. Astrophys Astr., v 9, p 17-24 (1988).

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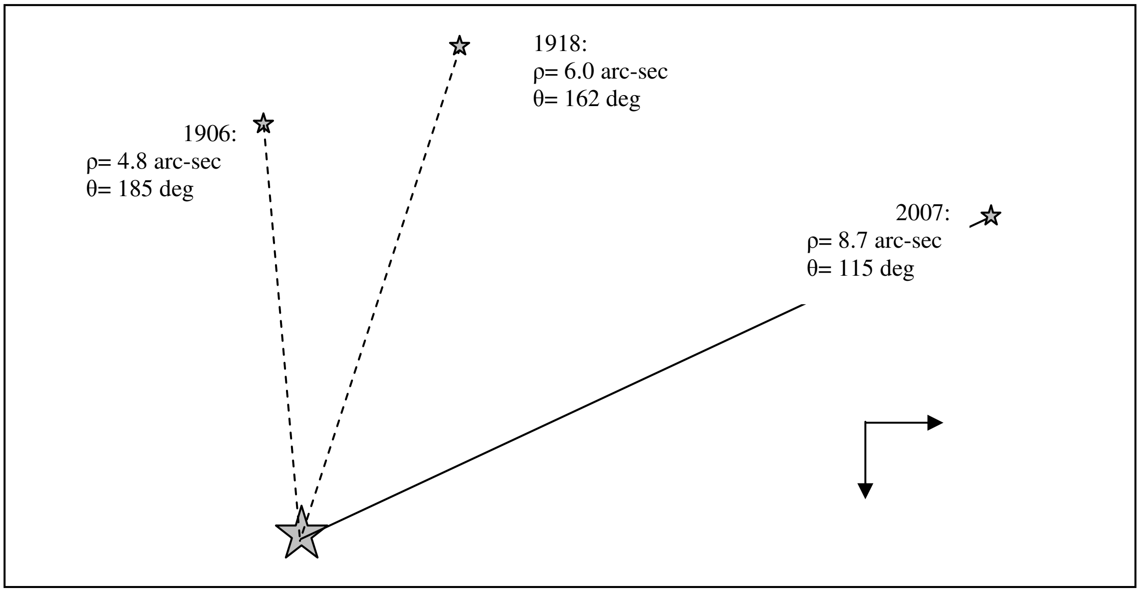

Figure 8: A modern measurement shows the motion of double star MLB 102, after 89 years of neglect.

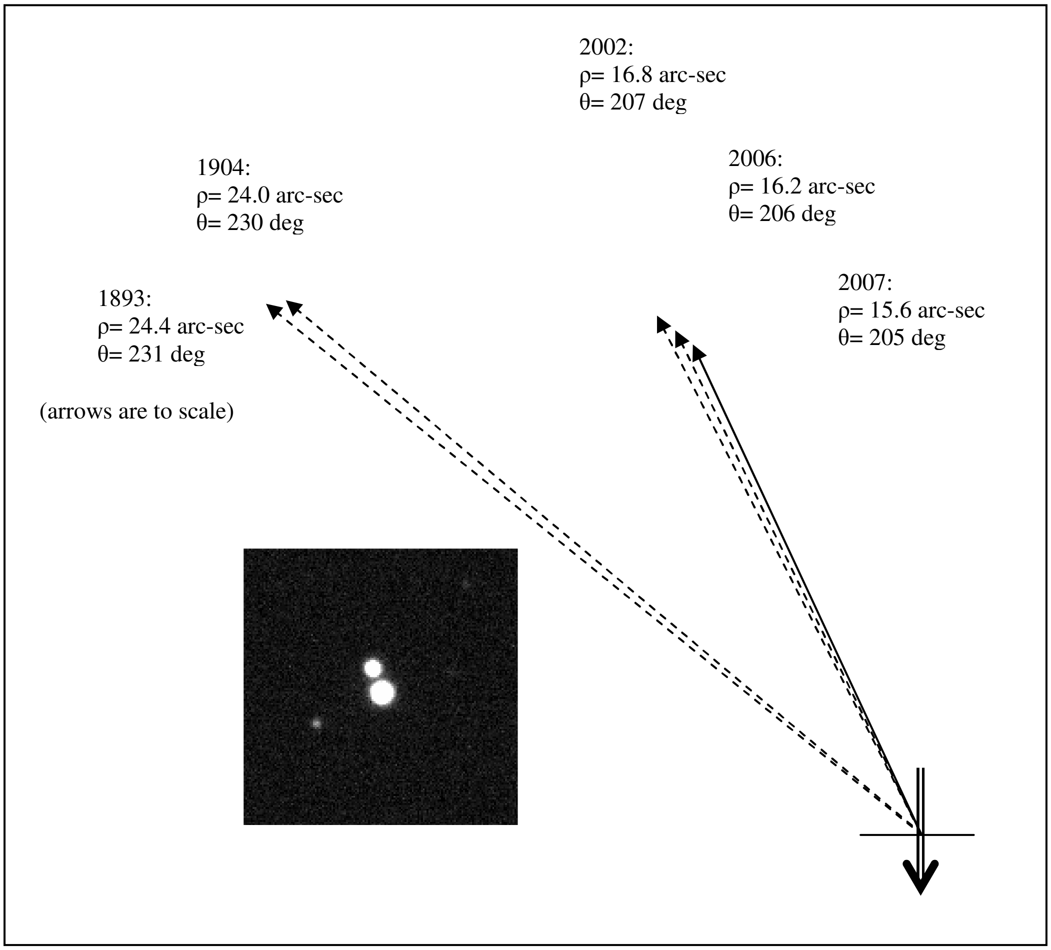

Figure 9: A new measurement of A 912 provides a bridge to the past, and confirmation of other early-21st century measurements.