DSLR Double Star Astrometry Using an Alt-Az Telescope

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Abstract: The goal of this project was to determine if the double star's angular separation and position angle measurements could be successfully measured with a motor driven, alt-azimuth Dobsonian-mounted Newtonian telescope (without a field rotator), and a digital single-lens reflex (DSLR) camera. Additionally, the project was constrained by using as much existing equipment as much as possible, including an Apple MacBook Pro laptop and a Canon T2i camera. This project was additionally challenging because the first author had no experience with astrophotography.

Introduction

Double star (DS) observations throughout the last 200 years have used a variety of devices to measure the position angle and angular separation such as the Lyot-Carmichael micrometer, Bi-Filar micrometer, and astrometric reticle eyepieces. Separation measurements using reticle eyepieces are limited by seeing conditions and wide angular separations. Rapid scintillation can lead to erroneous readings on the linear scale of the astrometric eyepiece. The digital age has introduced photographic methods involving charged couple devices (CCD) and complementary metal-oxide-semiconductor (CMOS) image sensors. Astronomers have usually recommended equatorially-mounted telescopes, rather than alt-azimuth (alt-az) mounts, due to the problem of field rotation encountered with the latter type. Field rotation can alter the actual measured position angle as the DS is allowed to drift across the field of view. High field rotation is observed in the north (0°), south (180°), and toward the zenith. Low field rotation is observed in the east (90°) and the west (270°). The magnitude of the field rotation is dependent upon the cosine function of the azimuth direction [1].

To circumvent these problems and still use the alt-az mounted telescope, DSLR photographs can be taken of a DS and the digital information can be reduced with a variety of commercially available software to obtain the position angle and angular separation. With short exposure times, both the field rotation and scintillation effects can be minimized, and an accurate reading obtained. Exposure times have to be carefully selected to avoid being under or over exposed. Under exposure of double stars is often accompanied by too few reference stars. Over exposure of the star image is clipped at the maximum thus reducing the subpixel resolution that is possible with correct exposure.

Instrumentation and Software

The telescope used in this study was an 18 inch f/4.5 Newtonian manufactured by Obsession (Figure 1), equipped with a ServoCAT GOTO drive. The DSLR was a Canon T2i with an 18-megapixel CMOS sensor providing 14-bit RAW image files and 8-bit JPEG files. It features an enhanced LiveView mode that simplifies focusing on the stars. Accurate focus was accomplished by using a Bahtinov mask [2]. Frey used a MacBook Pro equipped with OS 10.8.4 and a partitioned hard drive with Microsoft Windows 7. Software used in this project included ImageJ [3], IrfanView [4], and Herbert Raab's Astrometrica [5] to obtain right ascension (RA) and declination (Dec) values of each star. The data was processed by Frey using an Excel spreadsheet [6] and yielded the position angle and separation. Frey also used PlateSolve3, software being developed by Dave Rowe of the Pinto Valley Observatory, that reduces double star FITS, BMP, PNG, GIF, and JPG files and converts them directly to position angle and angular separation values.

Haworth used AIP4WIN V2.4.8B [11] software to

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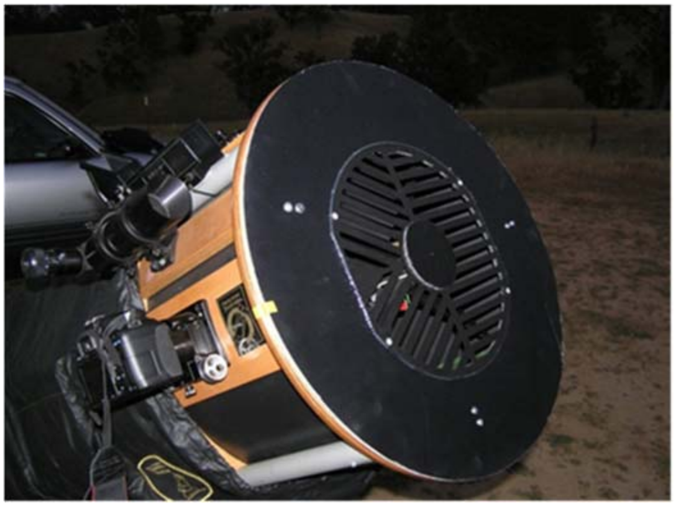

Figure 1. Obsession telescope with a Bahtinov mask and Canon T2i DSLR camera.

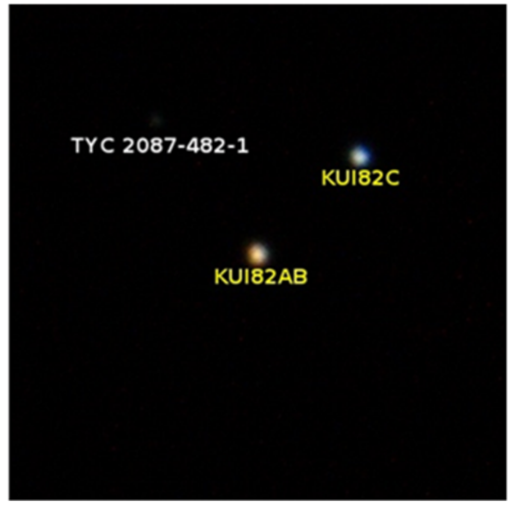

Figure 2. This is KUI 82AB,C , discussed in the text.

determine the angular separation and position angles. The images used were RAW CR2 files from images taken by Frey. Haworth used AIP4WIN because it reads RAW Canon DSLR images, it plate solves the positions of the double stars, and will give repeatable star centroid determination for both round and non-round star images. Haworth's computer is a MacBook Pro running OS X 10.8.5, Mountain Lion, running a Parallels desktop for a Mac Virtual machine to run Windows 7 Professional SP1, Windows XP Professional SP3 and Ubuntu 12.04.1 LTS.

Each Canon CR2 image file was ~30MB (too large to send by email) so the authors exchanged images by using Xoom Data Services, Inc. LargeFilesASAP, a free large file transfer service.

Locale and Observing Conditions

The photographs were taken at Santa Margarita Lake in San Luis Obispo County near Santa Margarita, CA at 35.34 degrees North latitude and 120.50 degrees West longitude. Observations were conducted over the period March 21- May 30, 2013. Observing conditions varied over this period. Most observing sessions involved low humidity and good seeing with only moderate scintillation. The marine layer from the Pacific Ocean was never a problem.

Procedure: Astrophotography and Data Reduction

A fairly detailed account will be given for the double star photography and software analysis because most astrophotographic methods incorporate equatorially mounted telescopes using CCD devices. Also, traditionally, PCs have been used, rather than Apple Macintosh computers because astrometry software is usually PC based. The authors' hope is, by outlining these steps, that amateur astronomers with alt-az telescopes and DSLR cameras are able to do serious double star research. The following summarizes the camera, telescope, and computer operations carried out.

Camera Settings for the Canon T2i

Disengage the auto flash and autorotation. Set the picture style for zero saturation. Set the mirror lockup. If your camera has a reduced noise effect setting, engage it. Set the camera to take both RAW (CR2) and JPG images simultaneously. Set the timer for 2-second delay and/or use a shutter cable. Set the shooting mode to Tv. Begin with 1.0-second exposures at ISO 800. Verify that the camera date and clock settings are accurate within one second. Replace the lens with a 2-inch T-ring.

Telescope Setup

Insert the camera into the focusing tube and align the bottom of the camera with the optical path from the primary mirror. Align the telescope with reference stars using the Live View of the camera. Be sure the reference stars are centered on the camera's LCD screen. Place a Bahtinov mask on the front of the telescope and center a bright star's image, again using the Live View. A hand-held magnifier will assist you in positioning the Bahtinov image on the screen. Rotate the focusing knob until the central diffraction spike is centered on the star. Focus until the central spike is located symmetrically between the other two diffraction spikes. See Figure 3 [2]. Remove the Bahtinov mask. Slew to the first double

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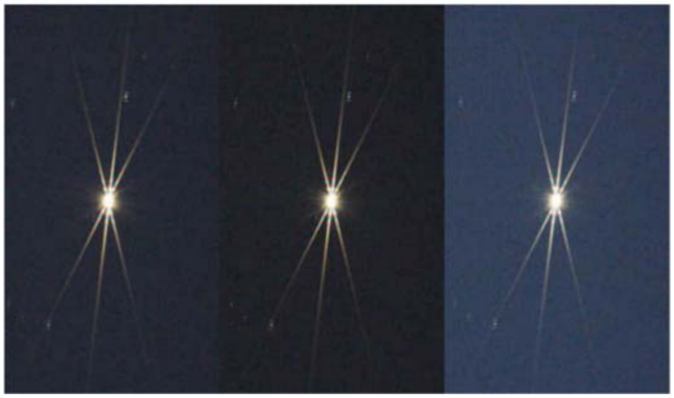

Figure 3. Bahtinov diffraction images. The central image shows the proper orientation of the central spike to attain maximum focus. (Wikipedia, http://en.wikipedia.org/wiki/Bahtinov_mask.)

star. Be sure it is centered on the LCD. This is important as field rotation is less at the center of the image and increases the farther away from the image center. Take an initial image of the double star.

Computer Setup for MacBook Pro Using OS X 10.8.4

Activate Red Screen [7]. Download this initial image. Open ImageJ and select the JPG image. Go to the analysis menu, select "Measure." Using the square icon, click and drag until the square box is centered around the double star. Check to be sure the value is below 255. If it is 255, the maximum value possible, you must either decrease the ISO, decrease the exposure, or adjust both the ISO and exposure to avoid saturation of the image. Take another test image. Once the value is below 255 (try for 240-250) select the line icon from the menu. Click and drag the line through the two stars. Go to the analysis menu and choose "Plot Profile." Be sure two single peaks appear and that the tallest one does not have a flat top.

If the peaks are distorted, refocusing with the Bahtinov mask may be necessary. Once the Maximum is below 255 and the focus is sharp, take a series of 10-15 images in rapid succession to be used for angular separation and position angle determination. The more images taken increases the quality of the data set statistics.

Logbook Entry

Record, for each image taken: image number, date, object name, right ascension and declination, constellation, approximate time, exposure time, ISO, and ImageJ Max value. Later on you can get the exact time from the camera log. **Important: be sure the target double star has enough reference stars in the fov for proper analysis by Astrometrica, AIP4WIN, and PlateSolve3**. Eight to twelve reference stars will be sufficient for most images to obtain a reduction. Various programs use a number of star catalogs: PlateSolve3 uses UCAC4; where Astrometrica options are UCAC4, USNO-B1.0, PPMXL, and NOMAD.

Move onto the next double star and repeat this sequence.

Photo Analysis

Open iPhoto on the MacBook Pro and download all images from the camera. Get the exact time of each exposure by clicking on the "Info" button. Click on the RAW (or CR2) photo to be analyzed. DSLR RAW files are used by Astrometrica and AIP4WIN because the RAW CR2 files provide a greater dynamic range over JPG files which are limited to 256 levels. PlateSolve3 can process JPG files, directly. Go to the file menu and select "Reveal" in Finder, select "Original" file. Click and drag the file into a CR2 file folder on the desktop. Download all CR2 and JPG files onto a flash drive.

Data Reduction

Use three different software programs to convert the DSLR photo files to position angle and angular separation values for the ten double stars.

Astrometrica Reduction

Restart the MacIntosh using Bootcamp and open Microsoft Windows. Use Windows 7 for this procedure. Use IrfanView to convert CR2 files to TIF files then use ImageJ to convert the TIF files to FITS files. Open Astrometrica. Load the FITS file and determine the RA and Dec for the primary and secondary components.

Excel Spreadsheet: Setup a spreadsheet to convert the RA and Dec of the primary and secondary stars into angular separation and position angle. The best guideline is to follow Chapter 15 by Bob Buchheim in Argyle [6].

PlateSolve3 Reduction

Restart the MacIntosh using Bootcamp. Use the Windows 7 O/S as with Astrometrica, either 32-bit or 64 -bit Windows 7 will function properly. Since PlateSolve3 can use JPG files, it is unnecessary to convert to TIF or FITS files. Load the JPG files then plate solve the image. Then by setting the primary star as reference and the secondary star as the target, differential photometry converts the right ascension and declination of the two stars into position angle and separation.

AIP4WIN Reduction

The following describes Haworth's four-step process.

First, Cartes du Ciel [13] is used to verify the double stars and its orientation to north. Its orientation to north is used in the AIP4WIN astrometric tool to rotate the reference stars.

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Second, AIP4WIN is used to convert the Canon color CR2 file to a monochrome FIT file. AIP4WIN has two settings windows that need to be configured to read Canon CR2 files. The first window is the Bayer Array Color window that configures Bayer type red, green, green and blue for the Canon CR2 files. The second window is the DSLR and Bayer conversion Settings window that uses the Bi-Linear Interpolation for the DeBayerization algorithm (private communication with Richard Berry). Set the DeBayer to Convert Color to Gray Scale. Set all RGB scales to 1.0. The image pixel size is set to 4.3 microns and the monochrome image is saved as a FIT file.

Third, using the Image Display Control, the User Black/White Values are adjusted to show the image without the background noise. Usually only the White Point needs to be increased. The Control Zoom is adjusted to 25% or 20 % to see the complete image. The AIP4WIN astrometric tool is used to plate solve the image. Up to 24 reference stars are used in the plate solve of the image. The target stars are the double stars and they are not used as reference stars. The AIP4WIN astrometric tool allows you to manually start the plate solving process with the bright stars first. As more reference stars are chosen the plate solve measurements are refined and updated. At the end of the plate solving process you can save the details to a file. The USNO -A2.0 catalog with 526,280,881 stars with complete coverage of the sky was used for the plate solve reference stars.

Fourth, AIP4WIN measure distance is used to measure the separation distance (rho) and position angle (theta).

For double stars KUI 82AB,C a Python script was created by Haworth to calculate and plot the separation distance (rho) and position angle (theta) of double stars given the double stars RA and Dec in a CSV txt file. Also, the Python script will take multiple measurements and perform statistics on the data set and plot the result. The Python script was developed with the free Python Canopy Express programming environment. Haworth uses Canopy Express on computers with the Mac OS X and Windows 7 operating systems. Canopy Express simplifies using Python because it installs and manages the updates to over 30 preconfigured Python packages.

Data for Ten Double Stars

Table 1 shows the literature data and observed measurements of position angle and angular separation for the 10 double stars studied. The angular separations ranged from approximately 18-90 arc seconds. The difference in magnitudes between the primary and secondary stars ranged from 0.2-1.4 to ensure similar signal strength during software reduction. Frey's and Haworth's data were obtained using the outline presented in the procedure above. Most values in Table 1 are based on single image reduction for each double star. For

Table 1: *Position angle and angular separation for ten double stars. Literature values (WDS) and DSLR results are shown. *Values are averages of 3 reductions of same DSLR image. **WDS listed 3 different PAs for 2012: 311.9, 309.0, 314.1. Middle value was chosen for reference. ***Insufficient reference stars on image to obtain a solution. #Values are average of 5 reductions of different DSLR images.*

Object	Bessel. Epoch	Lit. Values (WDS)			Astrometric Results		AIP4WIN Results		PlateSolve3 Results	
		PA (degs)	Sep (asec)	Epoch	PA (degs)	Sep (asec)	PA (degs)	Sep (asec)	PA (degs)	Sep (asec)
STF 627 AB	2013.22	259.9	20.94	2012	256.84	21.52	260.1	21.3	260.27	21.30
STF 697 AB	2013.22	286.0	25.82	2013	284.06	26.75	285.97	26.08	284.54	25.88
STF 817	2013.28	73.1	18.65	2010	75.08	17.87	73.49	18.32	73.44	18.25
STF1347	2013.33	311.9**	21.18	2012	310.67*	20.92*	310.25	21.24	312.42	21.21
STF1369 AB	2013.33	149.4	24.96	2010	149.16	23.99	***	***	149.46	24.93
STF1399	2013.33	175.3	30.61	2009	175.46	30.30	175.47	30.7	175.57	30.53
S 686	2013.37	3.9	50.00	2012	4.84	50.08	4.20	49.99	4.23	50.08
STF2166 AB	2013.41	282.2	27.16	2012	282.74*	27.95*	281.66	27.25	281.83	27.33
KUI 82 AB,C	2013.41	312.8	49.87	2010	313.46#	50.13#	313.77#	50.09#	313.66#	50.15#
STF2185 AC	2013.41	250.1	90.01	2006	252.43	90.44	252.13	91.99	252.12	91.93

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Frey's Astrometrica observations, two are averages of three reductions of the same DSLR image; one is the average of five different DSLR images. Frey wanted to compare the statistics of Astrometrica's reduction of the same image several times versus a series of different images of the same target. All position angles are given in degrees, all angular separations in arc seconds. The literature values are based on the most recent entry in the Washington Double Star Catalog (WDS) [8] for that target.

Statistical Analysis:

If astrometric reticle eyepieces are use to determine the position angle and angular separation of a double star, the observer must take many measurements to decrease the chance of bias and random error. The observations are fleeting and cannot be recovered. With DSLR or CCD techniques, a permanent record is obtained that can be accessed anytime for reexamination. Yet, "putting all your eggs in one basket", in this case, taking a single photo and basing your results on that, is inappropriate from a scientific approach. This initial study was undertaken with the goal of attempting DSLR double star evaluation so most double star targets have only a few recorded photos. Therefore statistical analysis was not carried out for the bulk of the observations.

However, one target, KUI 82AB,C, an optical double star in Hercules, was photographed five times in rapid succession. All FITS files were analyzed by Astrometrica (Frey) and by AIP4WIN (Haworth). JPG files were analyzed by PlateSolve3 (PS3). The standard deviations (SD) and standard errors of the mean (SEM) were calculated to determine the variance for the five different images. AIP4WIN and PS3 statistics show a tighter grouping. The position angles determined by Astrometrica's reduction of images 5971 and 5972 were significantly lower than the other three that caused the broader spread. See Table 2.

Figures 4A&B plot the right ascension in degrees on the X-axis and the declination in degrees on the Y-axis for five different DSLR images of KUI 82AB,C, reduced by Astrometrica. Note the exponential number on the far right of the X-axis. This value is to be added to the value indicated on the X-axis to get the actual value in degrees. A similar value is at the top of the Y-axis for declination. In the top image we see how the primary stars are grouped within a 6 arc second diameter circle. We also see a slight spread and change of position angle as the secondary stars are illustrated on the bottom.

Compare the data illustrated in Figures 4A&B with that in Figures 5A&B where the same five images were reduced by AIP4WIN instead of Astrometrica. Note that both the primary and secondary stars are grouped within a circle about 1 arc second in diameter. The AIP4WIN software [11] is better in converting the DSLR CR2 files into a tighter right ascension and declination display.

Figures 4 and 5 were created by Haworth using the Python script [12] given the right ascension and declination.

It was also noticed that every time an Astrometrica analysis was carried out only slight differences in the

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Table 2: *Standard deviation and standard error of the mean for 5 different image reductions of KUI 82AB,C*

		AIP4WIN Data		Astrometrica Data		PlateSolve3 Data	
Image	**Exposur (sec)**	**PA (degs)**	**Separ (asec)**	**PA (degs)**	**Separ (asec)**	**PA (degs)**	**Separ (asec)**
5970	2.0	313.741	49.83	313.75	49.75	313.64	50.09
5971	2.5	313.758	50.24	312.96	50.18	313.69	50.22
5972	2.5	313.652	50.45	313.00	49.86	313.55	50.44
5973	2.5	313.941	49.86	313.82	49.82	313.78	50.07
5974	3.2	313.756	50.06	313.77	51.03	313.65	49.94
Aver		313.770	50.09	313.46	50.13	313.66	50.15
SD		0.094	0.23	0.39	0.48	0.083	0.19
SEM		0.042	0.10	0.18	0.21	0.037	0.085
WDS		313	49.8	313	49.8	313	49.8

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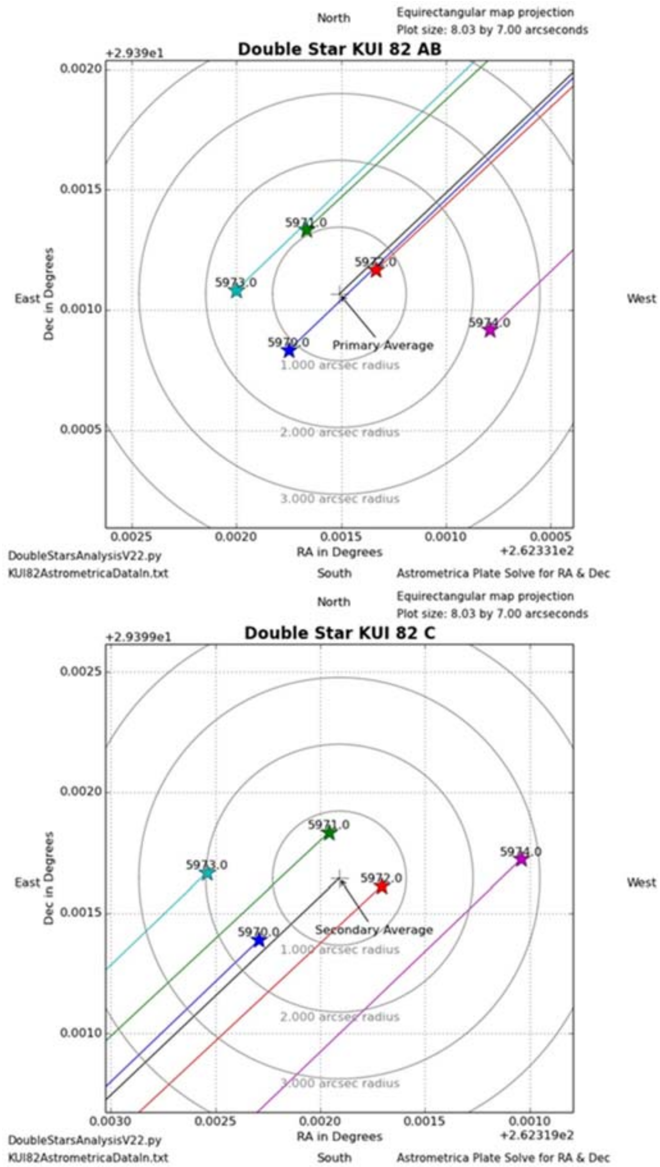

Figures 4A&B. Right ascension and declination of the primary and secondary stars for KUI 82AB,C are plotted for 5 different DSLR images, 5970-5974, showing the grouping pattern. Files reduced by Astrometrica.

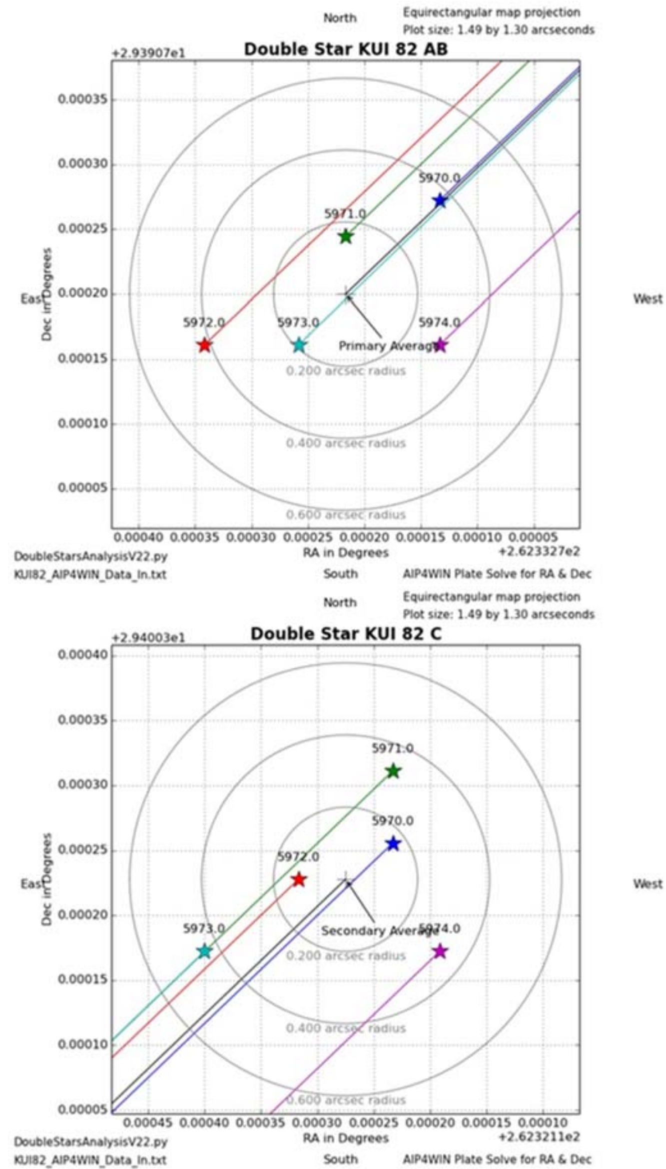

Figure 5A&B. Right ascension and declination of the primary and secondary stars for KUI 82AB,C are plotted for 5 different DSLR images, 5970-5974, showing the grouping pattern. Files reduced by AIP4WIN.

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RA and Dec were observed if the same image was re-analyzed. This difference was due to the hands-on manipulation of Focal Length and Rotation indictated by the software to obtain the RA and Dec. It would be interesting to compare the SD and SEM for the position angle and separation values for KUI 82AB,C obtained from five different images and those obtained from analysis of five reductions of the same image. See Table 3.

Table 3 lists the same image, 5971, reduced five times with Astrometrica. This shows that the variance in the reduction of the same image multiple times is extremely small. Note that the SD for the Astrometrica separation and position angles in Table 3 for the same image (PA, 0.05920; Sep, 0.06199) are much smaller than the SD Astrometrica data obtained for reducing five different images (PA, 0.39297; sep, 0.47657) in Table 2. The SD for the five different images reduced by AIP4WIN (PA, 0.09437; Sep, 0.23460) more closely resembles the SD for the same five images reduced by Astrometrica, indicating a smaller variance in data processing using AIP4WIN.

Comparison of Past and Present Observations:

Brian Mason [8] provided all of the past position angle and separation data from the WDS for the ten double stars studied. The overall change in position angle (PA) from initial studies to the present is shown in Table 4. The position angle from past observations is plotted against the Besselian dates of those observations. The slope of the change in position angle was generated by using the Exponential Trendline feature in Microsoft Excel. Two of these plots are shown in Figures 6A&B.

A majority of the changes in position angle over the recorded periods differed by a small amount for the ten double stars. For the first eight double stars listed the range varied from 0.9 to 3.5 degrees. The latter two double stars showed more significant changes during the recorded period. Figures 6A&B show representative samples of both types of change. Figures 6A&B plot the Besselian year vs. position angle (degrees) on the left vertical axis and separation (arc seconds) on the right vertical axis. Note the fairly linear change in position angle for the two plots. Series 1 refers to the position angle changes; series 2 to the separation changes.

There is a measurable change in the position angle for KUI 82AB,C over the 100+ years of observations. A higher order equation should be used to determine the position angle for this system. However, by using the slope generated in the graph of Figure 6, a position angle can be projected from the most recent WDS reported values to the date of the observation made in this study. This can then be compared to the observed values in this study. For KUI 82AB,C, the most recent WDS position angle from 2010.6 was 312.8 degrees. If the PA slope determined from the Besselian date vs. PA graph is applied to the most recent WDS position angle value and

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***Table 3**: Standard deviation and standard error of the mean for 5 Astrometrica reductions of the same KUI 82AB,C image 5971.*

Iteration	RA primary	Dec primary	RA secondary	Dec secondary	PA degs	Separation asec
1	17 29 19.95	29 23 27.6	17 29 17.14	29 24 1.6	312.794	50.047
2	17 29 19.94	29 23 27.4	17 29 17.14	29.24 1.4	312.896	49.951
3	17 29 19.88	29 23 28.3	17 29 17.08	29 24 2.3	312.896	49.951
4	17 29 19.95	29 23 28.1	17 29 17.14	29 24 2.2	312.878	50.115
5	17 29 19.90	29 23 28.1	17 29 17.10	29 24 2.2	312.980	50.019
Average					312.889	50.017
SD					0.059	0.062
SEM					0.026	0.028
WDS					313	49.8

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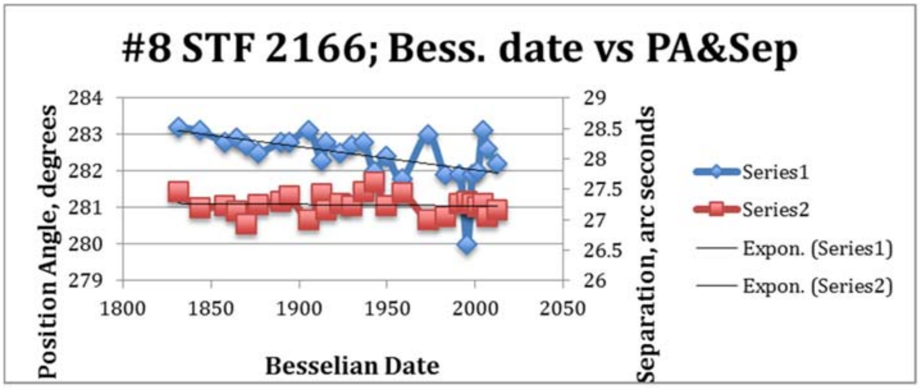
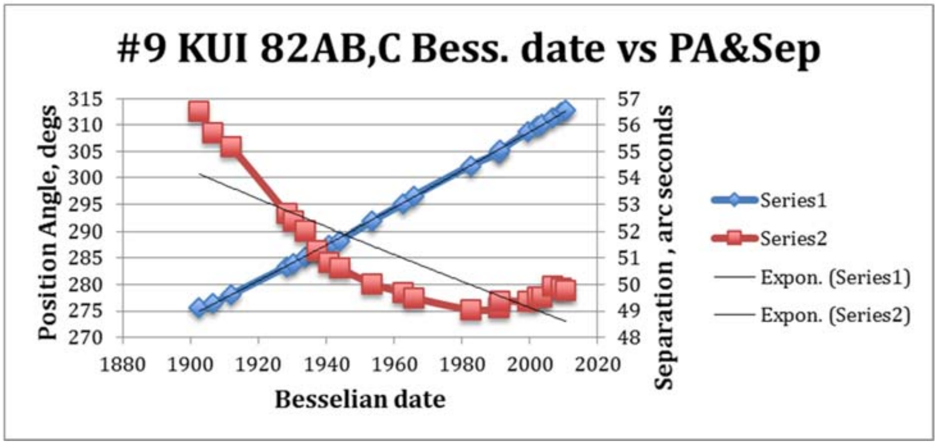
Table 4: *Change in position angle for the ten double stars observed from past to current study observations. * One outlier not counted in slope determination.*

Double Star	Period (years)	Change PA; max to min (degrees)	Slope: Bess. Date vs PA (degs/year)
STF 627AB	1799-2012	2.6	-0.0055*
STF 697AB	1828-2013	2.4	+0.0075
STF 817	1830-2011	2.8	+0.0064
STF1347	1825-2012	3.0	+0.0071
STF1369AB	1831-2012	3.5	+0.0125
STF1399	1827-2009	1.4	+0.0032
S 686	1825-2012	0.9	-0.0020
STF2166AB	1831-2012	1.4	-0.0056*
KUI 82AB,C	1902-2010	43.2	+0.3479
STF2185AC	1864-2006	59.7	+0.4348





Figures 6A&B: *(a) STF 2166, PA slope -0.0056, (b) KUI 82AB,C, PA slope +0.3479.*

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projected to the Besselian day the photograph was taken (2013.4, ~2.8 years), we get:

Change in PA of KUI 82AB,C = (2.8 yrs)(+0.3479 degs/yr) = +0.97 degrees

Add this to the most recent WDS PA value, we get:

Projected WDS PA in 2013.4 = 312.8 + 0.97 = 313.77 degrees
Astrometrica's value: 313.46 degrees
AIP4WIN's value: 313.77 degrees
PlateSolve's value: 313.66 degrees

The change in position angle for the initial 8 double stars between the last reported WDS value and the observations are too small to make this comparison.

Conclusions

This study has shown that using an alt-az motor-tracking telescope, a MacBook Pro computer with a partitioned hard drive using a Windows 7 operating system, and a Canon DSLR camera using short exposure times, accurate double star measurements of position angles and angular separation can be accomplished. Although multiple images of each double star were not taken in a majority of cases, fairly accurate measurements, that closely agree with literature values, can be obtained. Suggested future studies should concentrate on taking multiple images and stacking them, using this feature in the Astrometrica, AIP4WIN, and PlateSolve3 software. This will result in less noise in the photos, possibly leading to more accurate reductions. When selecting the double stars for study, the authors recommend examining visual sources like The SkyX [9] or Aladin [10] images to be sure sufficient reference stars are close by for successful reductions. Future studies might also consider using a Barlow lens in conjunction with the DSLR camera so binaries with smaller angular separations can be examined. The limiting factor here would be finding reference stars within the field of view during reduction.

Acknowledgements

The authors would like to express thanks to Joseph Carro and Brittany McCrigler for reviewing this paper and for their suggestions. Special thanks goes to Bob Buchheim and Tom Smith for assistance in setting up the spreadsheet for RA and Dec conversion to position angle and separation. Also a hearty recognition goes to Herbert Raab in Austria for his Astrometrica. The authors would like to thanks Dave Rowe of Pinto Valley Observatory for allowing us to test his newly developed PlateSolve3 software to reduce our data. And Tom Frey would like to express his gratitude to his co-author, Dave Haworth, for the many hours spent training him in the basics of astrophotography and software manipulation.

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