Thirteen Potential Short-Arc Binaries Observed at Kitt Peak National Observatory

Richard Harshaw
Brilliant Sky Observatory, Cave Creek, AZ

Russell Genet, Jacob Hass, and Kevin Phung,
California Polytechnic State University, San Luis Obispo, CA

Abstract Many hundreds of close double stars were observed via speckle interferometry at Kitt Peak National Observatory in 2015. This list of doubles was compared with a list of potential short-arc binaries developed by Harshaw, and 13 matches were found. The Kitt Peak observations were added to past observations and it was concluded that while some doubles showed a sufficient curve in their trajectories to be likely short arc binaries, others were likely mere optical doubles.

Introduction

Short-arc binaries are double stars that are starting to show an arc in the plot of their measurements as a function of time. They can be identified by plotting the measurements at various epochs on an X, Y graph by converting the position angle (theta, θ) and separation (rho, ρ) into Cartesian coordinates using the following transforms:

$$X = \rho * \sin(\theta) \text{ and } Y = \rho * \cos(\theta)$$

With the X, Y position of each measurement known, the data can be plotted using a tool such as Excel. A sample plot can be seen in Figure 1.

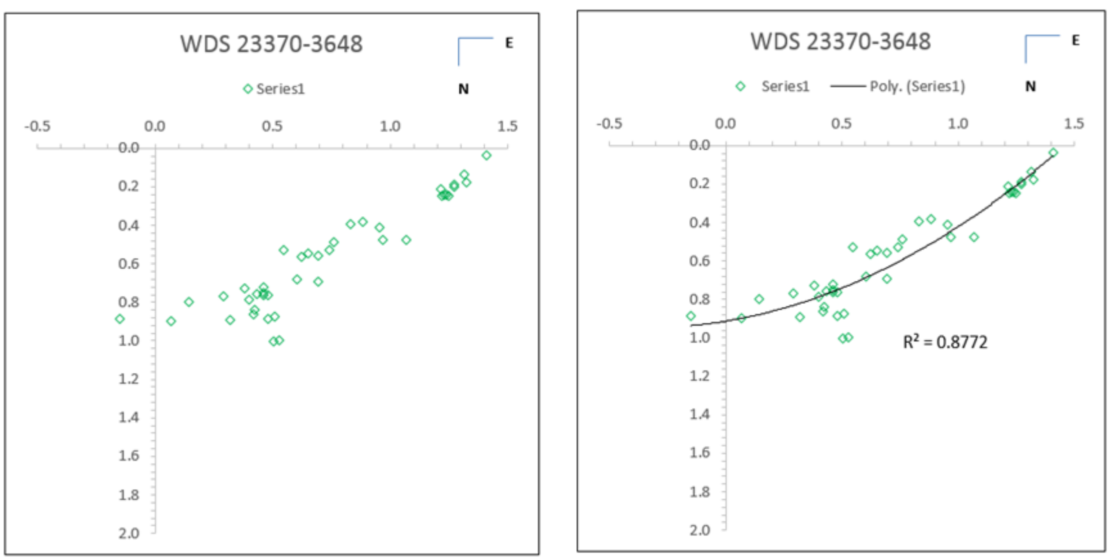

Figure 1. A sample of raw data left, along with raw data with a trendline superimposed on it, right.

The data points are starting to show a departure from the straight line expected with a linear (optical) pair. The companion is moving from left to right. We can then utilize Excel's Trend function to generate a polynomial trend line that best fits the data as seen in Figure 1.

The R^2 value is a measure of the tightness of the fit between the points and the trend line. A perfect fit would be indicated by a value of 1.00, and no fit would be 0.00. The value of 0.08772 is very strong and suggests we are observing a true binary, even though the orbit has not yet been derived.

One of the shortcomings of Excel's trend function is that it assigns equal weight to all points. For analyzing binary star measurements, equal weights is not the best method as some measurements are better than others and hence deserve greater weight in the least squares solution.

The discovery of short arc binaries by means of plotting the measurements over time is a useful tool to identify good candidates for binary status and, possibly, orbital solutions. This is especially true of those short arc binaries that are extremely close in terms of ρ (under 5" of arc). However, even wide pairs can show the trace of an arc in the data plots. A short arc does not necessarily translate into a short period. A short arc simply means the data is starting to show a departure from linearity, a good sign that the pair may be physical.

The Work Done at Pulkovo Observatory

A group of astronomers at the Pulkovo Astronomical Observatory has specialized in short-arc binaries for many years (Kiyaeva *et al*. 2008 and 2012). Uniform sets of photographic observations of the short arcs of wide double stars have been obtained with their 26-inch refractor (Figure 2) for over 50 years starting in 1957. This historic telescope is now automated and has been making CCD observations since 2003. It might be noted that the Struves (both father and son) used a large refractor at the Pulkovo Observatory for their discoveries of thousands of double stars. Although this telescope was destroyed during World War II (as was all of the Pulkovo Observatory), a new refractor was built, and the main building of the Pulkovo Observatory was restored in a project led by architect Alexandr Brjullov.

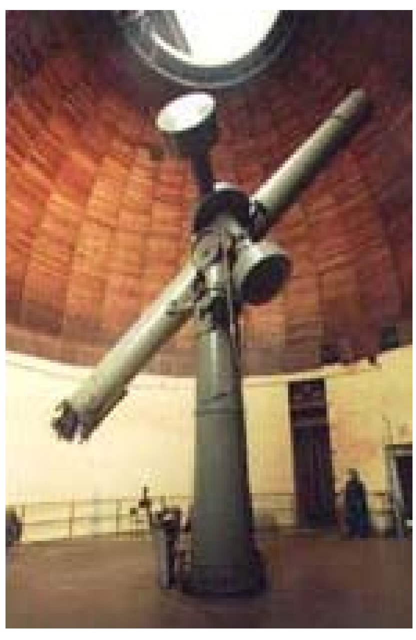

Figure 2. The 26-inch refractor at Pulkolov Observatory. It has been used by Alexey Kiselev, Olga Kiyaeva, and their colleagues to make extensive observations of wide double stars for over a half century.

Survey of 5,500 Double Stars

In 2012, Harshaw began a systematic survey of the double stars in the Washington Double Star Catalog (WDS), looking for good short arc binary candidates. The WDS was downloaded from the US Naval

Observatory and imported into Excel. From there, filters were set up to find pairs that met the following criteria: eight or more measurements and no solutions for orbits or linear cases. Approximately 5,500 double stars passed this filter. Data requests were then sent to the US Naval Observatory and the detailed measurement histories of all of these pairs were obtained.

An Excel spreadsheet was created that translated the values for ρ and θ into Cartesian coordinates. The values of θ were adjusted for precession of the equinoxes using a transformation graciously provided by William Hartkopf of the US Naval Observatory. The transformation is given by

$$(0.00552 * \sin(\theta)/\cos(\mathrm{Dec})) + 0.000278 * \mathrm{PM} * \sin(\mathrm{Dec}) * (T_F - T_L)$$

where Dec is the declination of the primary, PM is the proper motion in right ascension of the primary, T_F is the year of the first measurement, and T_L is the year of the most recent measurement.

Because many of the pairs for which data was requested are multiple stars, some 9,000 graphics were generated. The measurement plots were then sorted into the following categories:

Type	Count
Short arc binaries	964
Linear pairs	961
Proper motion pairs	1,803
Suspected orbits	122
Unknowns	16

Table 1. Classification of stars by type of data plot.

The total count does not come to 9,000 cases because many of the tertiary companions (and beyond) had too few measurements to get meaningful results, and several cases simply defied categorization.

Linear pairs were stars that showed nearly straight lines in their data plots, with some of these lines spanning more than 100 seconds of arc and with R^2 values of the trend lines exceeding 0.9.

The proper motion pairs were stars with either common proper motion (less than 10% difference between proper motion vectors), similar proper motion (with up to 50% difference in the proper motion vectors), and different proper motion (all other cases).

Most of the suspected orbit plots were forwarded to William Hartkopf for analysis, and 10 orbits were computed as a result (Hartkopf, 2013). The results of the project were published in the JDSO (Harshaw, 2014).

Close Short Arc Binaries and Speckle Interferometry

The short arc binaries that are of the greatest interest to us are those with separations under 5" of arc. Such pairs probably have periods measured in human lifetimes (or at most a few hundred years) and are thus pairs for which it may be possible to soon solve orbits. However, separations this close require extremely accurate measurement, beyond the reach of more common approaches such as filar micrometry and CCD imaging. Such analysis is best done with speckle interferometry or other high resolution methods (such as adaptive optics).

The stars twinkle at night. This twinkling is caused by small pockets of turbulence in the atmosphere, pockets called Fried Cells. These cells are small—on average, the size of a small grapefruit—and are composed of air masses at slightly different temperatures. These gas bubbles at slightly different temperatures diffract the light traversing them by amounts proportional to the temperature and density. The end result is that the pristine isoplanatic wave front of starlight that impinges the upper atmosphere is scattered. David Fried first proposed these cells in 1965. In 1966, the Soviet government tasked Andrei Kolmogorov and a team of physicists to find a way to undo the chaos induced in starlight so that images of satellites flying over Soviet territory could be enhanced, thus allowing their identification. Kolmogorov and his team discovered that by treating the ground based image with Fourier transformations removed the chaos and allowed images to be vastly improved.

For four years implications of this discovery for astronomy remained unexplored. But in 1970, the French astronomer Antoine Labeyrie found a way to apply the Russian discovery to astronomy in a process that can be known as speckle interferometry. This process makes use of thousands of ultra-short exposures (often less than 40 ms) to "freeze" the atmosphere so that the chaos is reduced to a minimum.

Labeyrie's original work was done with photographic film and took a great deal of time to do. It was also limited to bright stars and large telescopes since photographic film is a fairly inefficient collector of photons. But since Labeyrie's original work, CCD's came into their own (and lately, a new generation call the EMCCD or electron multiplied CCD), thus obviating the need for right pairs and large telescopes. In fact, speckle can be performed with amateur class instruments (Harshaw, 2015a).

It has been learned that when performing speckle analysis on a double star, results can be greatly improved by determining the Fourier transform for a single nearby star and applying the results of the single star to the double star image. The single star should be of approximately the same magnitude as the double star as close to it in the sky as possible—4° or less is a good goal. Also, to ensure consistent atmospheric quality, the single star should be imaged within 10 minutes of the double star. The single star is known as a deconvolution star.

The powerful capabilities of the EMCCD coupled with modest research grade telescopes (4 meter and smaller) make precision analysis of short arc binary candidates a viable scientific endeavor.

Goal of this Project

Speckle images of 13 short arc candidates previously acquired at Kitt Peak National Observatory using the 2.1 m telescope were analyzed with speckle reduction software with the goal of helping to confirm the emergence of the arcs in these stars or (if the data leads elsewhere) the removal of the star from the short arc list and reassignment to a different category. It may even be that new data collected may help determine the orbit of one or more of these pairs. By plotting new measurements with the existing data, it is thought that the project might help to reveal true binaries, common proper motion pairs, or optical doubles.

Selection of the Stars for Observation

Thirteen pairs were chosen for observation based on the preliminary results of the plots of their measurements. Table 2 lists the pairs that were chosen.

WDS	Discoverer Code
00287+3718	A 1504AB
00373+5801	BU 1097
00405+3627	COU1051
02250+2529	COU 357
02270+3117	HO 216
03356+3141	BU 533AB
03401+3407	STF 425
20177+2025	J 2308BC
20419+1931	COU 226AB
21352+2124	BU 74
22214+4148	A 411
22395+4123	BU 277AB,D
23267+4103	COU1845

Table 2. Target List for Kitt Peak 2013

Equipment and Procedures

Observations were made on the 2.1-meter telescope at Kitt Peak National Observatory in October 2013. A speckle interferometry camera that consisted of two Barlow lenses, a focuser, filter wheel, and an Andor Luca electron-multiplying CCD (EMCCD) camera were brought to Kitt Peak and installed on the telescope. The speckle camera system has been described in some detail by Genet (2013) and is shown installed on the telescope in Figure 3. The heart of the camera was the Andor Technologies Luca (EMCCD) camera, which provided low-noise readouts at high speed.

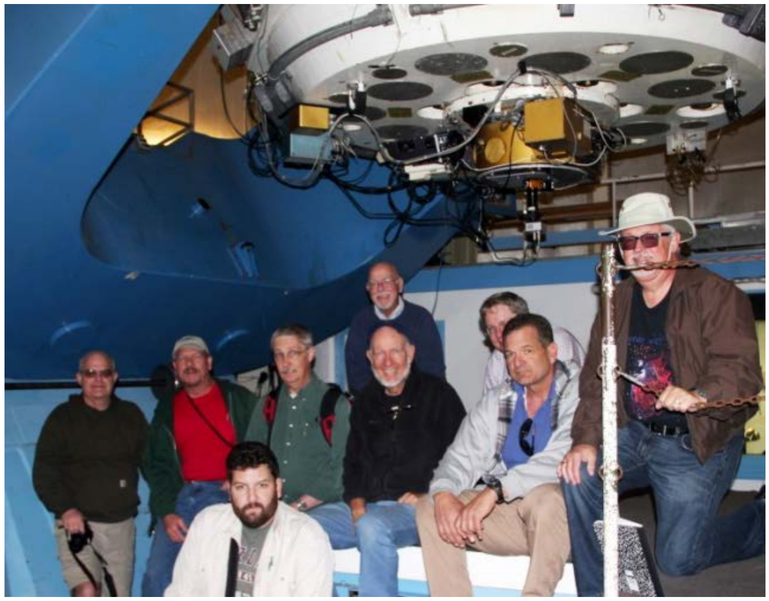

Figure 3: Observational team poses under the 2.1-meter telescope at Kitt Peak.

Speckle interferometry observations were made of several hundred known close binaries as well as a few close double stars that showed some movement and could be optical doubles, common proper motion pairs, or short arc binaries. The telescope and camera were operated from a warm room near the telescope over eight nights by two teams of observers. The warm room and an observer are shown in Figure 4. Over 1000 double stars were observed, along with several hundred single stars used for deconvolution during reduction.

Figure 4: Concordia University student takes a break from operating the telescope.

Reduction of the Data with Plate Solve 3.33

Plate Solve 3.33, a data reduction program written by David Rowe of PlaneWave Instruments is the program used to reduce the data and make the measurements (Rowe and Genet 2013). Plate Solve processes each frame in a FITS cube (a stack of 1,000 FITS images) and generates the Fourier Transforms needed to build the power spectrum and from that generate the autocorellogram. When used with a deconvolution star, the accuracy is quite high.

An example of a raw autocorellogram can be seen in Figure 5 of the star WDS00287+3718. Figure 5 also shows Plate Solve's astrometry function after the autocorellogram has been cleaned up a bit.

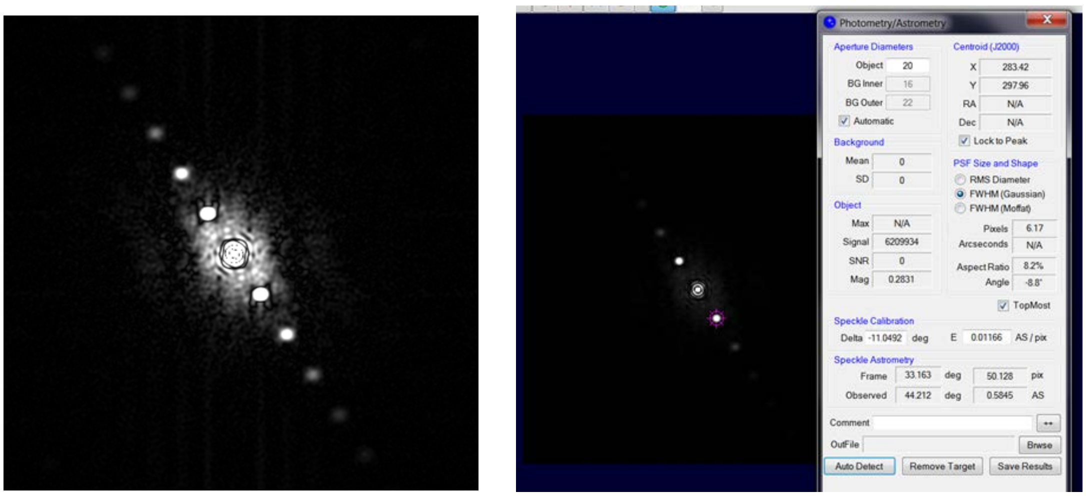

Figure 5. A raw autocorellogram of WDS00287+3718, left, and the star after processing.

In the Astrometry dialog, the camera angle of -11.0492° and pixel scale of 0.01166" per pixel have been entered, and Plate Solve displays the solution—44.212° and 0.5845". (The last values, measured in 2009, were 43.0° and 0.60").

Plate Solve has a function that can let the analyst build a CSV file of all results for the session, a file that can be opened in Excel or other spreadsheet programs. It also saves a JPEG image of the solution for use later.

Camera Angle and Pixel Scale Calibration

The camera angle and pixel scale were determined after the observations based on binaries with published orbits. Three separate and independent calibration analyses were conducted.

The first calibrations estimates of the camera angle and pixel scale were made by students at Arroyo Grande High School within weeks of the Kitt Peak observing run. Although full reduction of the Kitt Peak data had not been made yet, REDUC, a speckle autocorrelation program written by Florent Losse was used to estimate the camera angle, Δ, and pixel scale, E, for the run at Kitt Peak National Observatory. Five fairly wide binaries were observed during the run. REDUC, in its "calibration" mode was used to reduce a single observation of each of the five binaries on the night BU 1292 was observed.

Inputs to REDUC were: (1) the interpolated values of position angle, θ, and separation, ρ, based on the January 2013 and 2014 predictions in the Sixth Catalog of Orbits of Visual Binary Stars, and (2) the five FITS data cubes, one from each of the five wide binaries. The values used in the calibration, as well as the calibration results (and supplemental information on visual magnitudes reported in the Washington Double Star Catalog) are given in Table 3.

WDS	V1	V2	θ2013	θ2014	θ Obs	ρ2013	ρ2014	ρ Obs	Seq #	Δ	E
01532+1526	8.75		260.5	260.6	260.580	1.093	1.092	1.0922	942	-11.66	0.01136
03122+3713	8.02	8.29	125.9	125.8	125.820	2.845	2.852	2.8506	964	-11.53	0.01177
03362+4220	8.84	9.54	342.7	343.5	343.342	0.724	0.722	0.7224	983	-11.02	0.01216
04041+3931	7.38	9.35	54.6	54.2	54.279	1.502	1.52	1.5165	1002	-11.36	0.01119
23595+3234	6.47	6.72	338.2	338.9	338.762	2.324	2.347	2.3425	923	-11.15	0.01176

Table 3. Calibration Data

The camera angles, Δ, and pixel scales, E, were averaged, and their standard errors (of the mean) calculated on a spreadsheet. The results were: Δ = -11.3° ±0.1 and E = 0.0116”/pixel ± 0.0002.

The second calibration estimates were made by D. Wallace and R. Genet during a workshop at the University of Hawaii’s Institute for Astronomy, Maui.

Repeated speckle interferometry observations were made of five relatively wide binary stars on a number of nights to assess the within- and between-night precision of the observations. These observations were also used to estimate the camera orientation and pixel scale, and the overall accuracy of the observations as compared with orbital ephemerides.

All observations were made with a portable speckle camera system that featured an Andor Luca-R EMCCD camera, which has 9 µ square pixels, and x8 magnification (Genet 2013). The camera was mounted on a 2.1-meter telescope at Kitt Peak National Observatory. All integrations were 10 ms in length taken through a Sloan i’ filter. Observations were made with 1x1 binning and 512x512 Regions of Interest (RoIs) that were read out in the “Kinetic” frame-transfer mode. A total of 295 data cubes, each consisting of 1000 frames, were obtained over seven nights.

WDS	θ Ephem	θ F	Δ Ephem	ρ Ephem	ρ F	E Ephem
01532+1526	260.58	248.985	-11.595	1.0922	96.0698	.01137
03122+3713	125.82	114.308	-11.512	2.8506	242.236	.01177
04041+3931	54.279	43.691	-10.588	1.5165	128.945	.01176
23965+3234	338.762	327.582	-11.18	2.3425	198.879	.01178
		Mean	-11.22		Mean	.01167
		St Dev	.4571		St Dev	.0002
		St Er Mn	.2286		St Er Mn	.0001

Table 3. Calibration Results

Results

The results of the observing run for the 15 short arc binaries selected appears in Table 4. In the table, the column headings are as follow:

WDS No—the WDS number of the system
Discoverer and Comp—the discoverer code and components (if not AB)
Meas θ-- the value of θ (position angle) measured
Meas ρ-- the value of ρ (separation) measured
Last θ —the last given value of θ
Last ρ —the last given value of ρ
Resid θ —the residuals between last θ and measured θ
Resid ρ —the residuals between last ρ and measured ρ
Last—the year of the last measure on record

WDS No.	Discoverer and Components	Date	Meas θ	Meas ρ	Last θ	Last ρ	Resid θ	Resid ρ	Last
00287+3718	A 1504 AB	2013.805	44.117	0.5829	43	0.6	-1.117	0.0171	2009
00373+5801	BU 1097	2013.805	254.088	0.4949	307	0.6	52.912	0.1051	2008
00405+3627	COU 1051	2013.808	90.671	0.4648	72	0.4	-18.671	-0.0648	2007
02250+2529	COU 357	2013.805	115.067	0.2967	152	0.3	36.933	0.0033	2007
02270+3117	HO 216	2013.805	5.663	1.3747	331	1.3	34.663	-0.0747	2007
03356+3141	BU 533 AB	2013.805	221.214	1.0297	246	1.1	24.786	0.0703	2012
03401+3407	STF 425	2013.805	60.4	1.8823	104	1.9	43.6	0.0177	2012
20177+2025	COU 219 AaAb	2013.802	108.527	0.4249	115	0.5	6.473	0.0751	2007
20419+1931	COU 226 AB	2013.802	37.978	0.3546	4	0.4	-33.978	0.0454	2008
21352+2124	BU 74	2013.802	60.808	0.239	315	1	254.192	0.761	2005
22214+4148	A 411	2013.805	232.636	0.2552	229	0.3	-3.636	0.0448	2008
22395+4123	BU 277 ABxD	2013.805	221.102	0.4302	220	0.4	-1.102	-0.0302	2012
23267+4103	COU 1845	2013.8021	359.759	0.9206	0	0.9	-359.759	-0.0206	2010

Table 4. Results of the analysis of 13 short arc candidates.

Discussion

Each star is discussed below in detail. In all measurement plots, the Excel trend line is superimposed, but the reader is reminded that Excel's trend function assigns equal weight to each data point.

WDS 00287+3718 (A 1504 AB)

Figure 6 shows a plot of the historical data for this pair with the Kitt Peak measurement shown as a new marker. The ephemerides for the orbit (as given in the 6th Orbit Catalog) project theta of 44.5° (2014) and rho of 0.593" (2014).

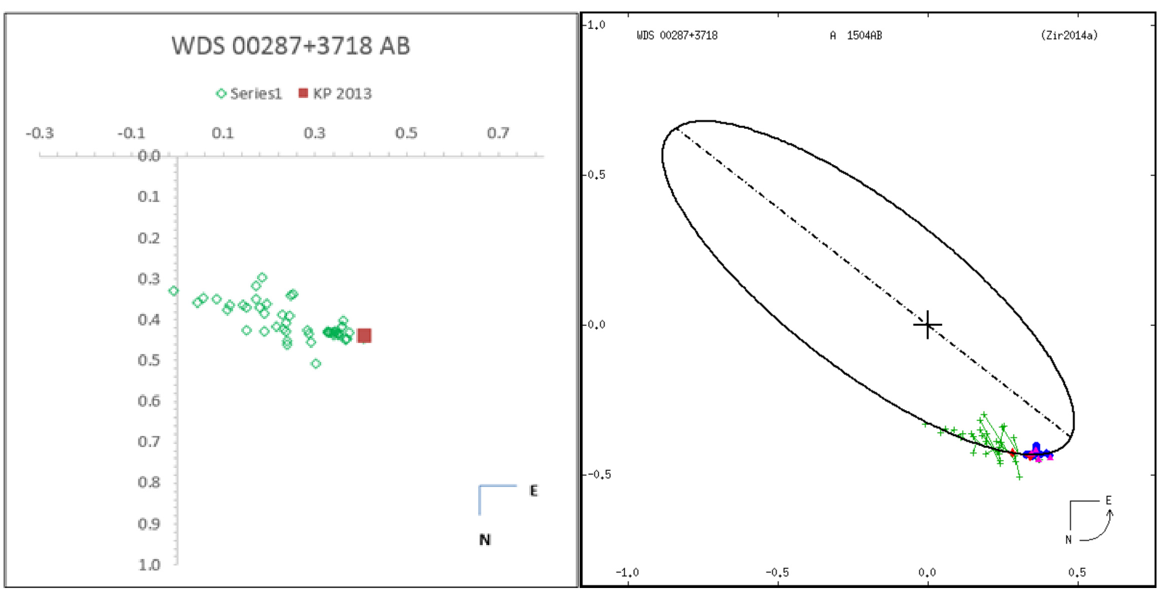

Figure 6. A plot of WDS00287+3718 AB left, along with the orbital plot from the 6th Orbital Catalog.

The orbital solution by Zirm 2014 leads to an ephemerides prediction of 44.5° theta and 0.593" rho. The measure obtained at Kitt Peak shows residuals of 0.383° theta and 0.010" rho.

WDS 00373+5801 (BU 1097)

The data plot is shown in Figure 7.

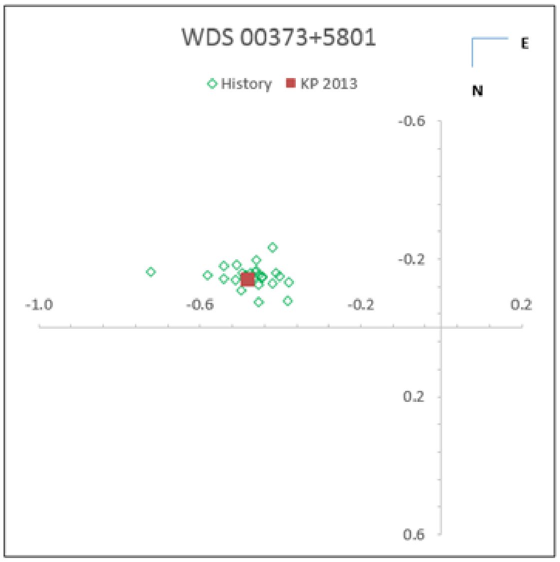

Figure 7. Plot of WDS 00373+5801

The parallax for the primary of this pair is given as 2.67 mas with an error of ± 1.03 mas. This is an uncertainty error of 38.5%, so it is best to not make any assumptions about this pair's distance and hence projected separations.

WDS 00405+3627 (COU 1051)

The data plot is shown in Figure 8.

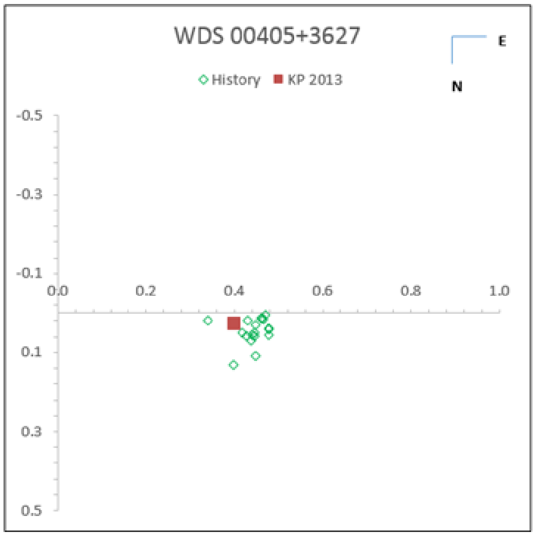

Figure 8. Plot of WDS 00405+3627

As in WDS 00373+5801, the parallax value for the primary is 3.85 mas with an uncertainty of 1.01 mas (26.2%), hence no conclusion about projected separations would be safe to make.

WDS 02250+2519 (COU 357)

The data plot is shown in Figure 9.

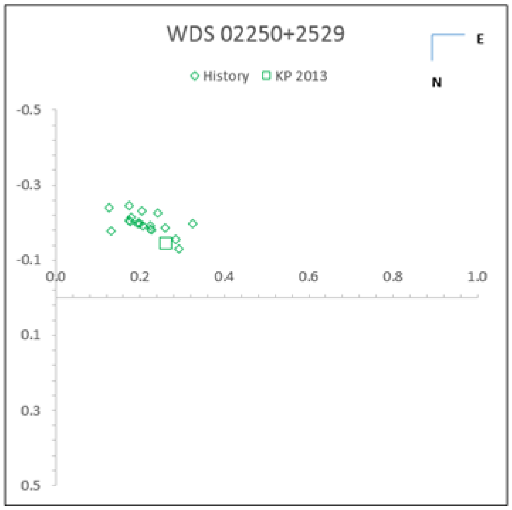

Figure 9. Plot of WDS 02250+2529

A parallax of 2.26 mas is shown for the primary, but the uncertainty is 41.6% (±0.94 mas), and only one star has proper motion values (the primary, at -10 mas RA and -3 MAS DEC).

WDS 02270+3117 (HO 216)

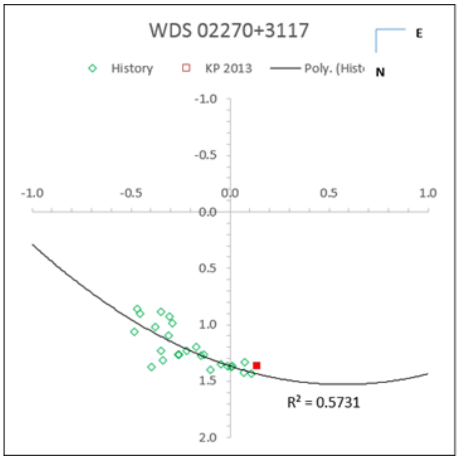

Figure 10. Plot of WDS 02270+3117

This pair is almost certainly physical. The parallax for the primary is 12.67 mas (with an uncertainty of only 8.05% or ±1.08 mas). This implies a mean distance of 78.9 parsecs, with the closest distance from the uncertainty being 72.7 parsecs and the farthest being 86.3 parsecs. There is a rather high proper motion for the primary, +80 mas RA and -35 mas DEC. The secondary PM is given as the same, but for such close pairs, such information is probably of low value (Hartkopf, 2014).

Assuming this pair to be physical, at 78.9 parsecs, the angular separation works out to 54 AU. Assuming a circular orbit for now, we can estimate the orbital period, and hence the stellar masses. Using the primary spectral type of F6 V (implying a mass of approximately 1.3 solar), we derive a period of 258 years with total system mass of 2.4 solar.

WDS 03356+3141 (BU 533 AB)

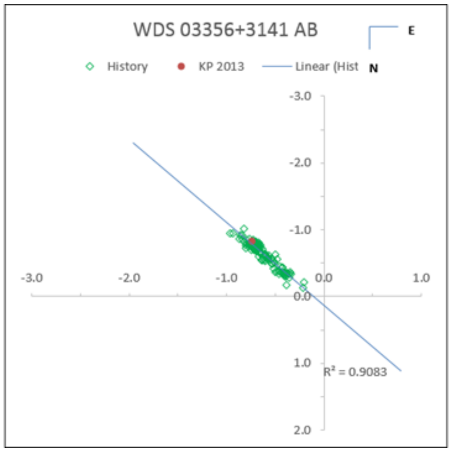

Figure 11. Plot of WDS 03356+3141 AB

Likely a physical pair, WDS 03356+3141 AB has a primary parallax of 11.63 mas (± 0.97 mas, or 8.3%), for an estimated distance of 86.0 parsecs (79.4 to 93.8 being within the range of uncertainty). The projected separation is at least 44 AU. Assuming the F4V primary to be approximate 1.25 solar masses. Due to linearity of the orbit, it is too early to tell if this is an optical binary or a gravitationally bound pair. If it is gravitationally bound pair it will have a very large elliptical orbit. Future observations are needed to distinguish this pair's orbit.

WDS 03401+3407 (STF 425)

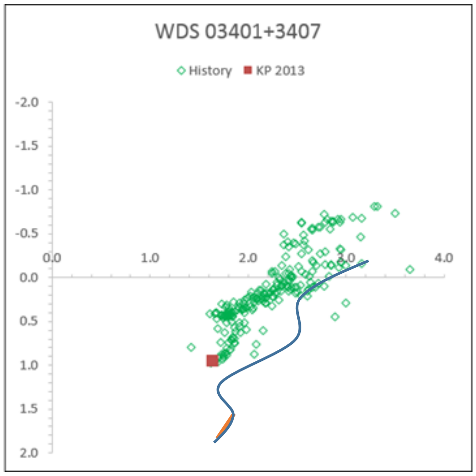

Figure 12. Plot of WDS 03401+3407

An interesting case, the parallax for the primary is 21.73 mas (±0.84 mas or 3.9%), implying a distance of 46.0 parsecs (with a range of 44.3 to 47.9 being possible). At 46.0 parsecs, the projected separation is 43 AU. The primary is F3V, so probably around 1.2 solar masses. Assuming a circular orbit, the period must be at least 186 years with a total system mass of 2.3 suns.

Proper motion data is only available for the companion, being -64 mas RA and +19 mas DEC, rather high values that would indicate a rather nearby star. The plot of the measurements suggests a periodic frequency to the companion's position, implying a possibly unseen companion.

WDS 20177+2025 (COU 219 AaAb)

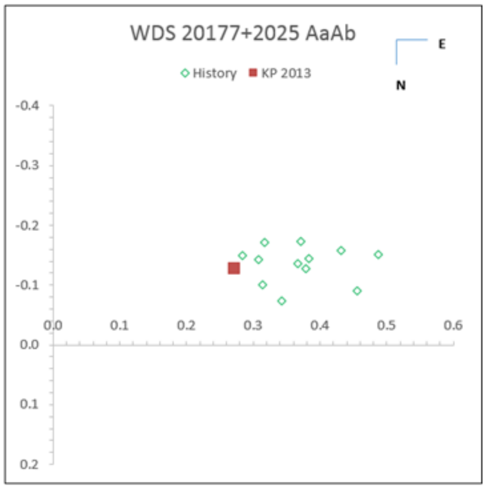

Figure 13. Plot of WDS 20177+2025 AaAb

No parallax data is available, and we only have proper motion for the primary (+7 mas RA, -2 mas DEC). The proper motion data suggests a star of some distance, but there is so much scatter in the historical data that it is not possible to determine the pair's nature yet.

WDS 20419+1931 (COU 226 AB)

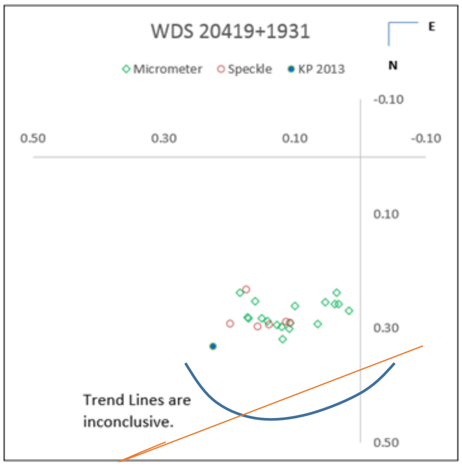

Figure 14. Plot of WDS 20419+1931

No parallax data is available, and we only have proper motion for the primary (+1 mas RA, -17 mas DEC). The proper motion data suggests a star of moderate distance, but there is so much scatter in the historical data that it is not possible to determine the pair's nature yet.

If the historical measures are indicating an arc, our measurement is not consistent with the history. If the pair is rectilinear, our measurement is more in line with that approach.

WDS 21352+2124 (BU 74)

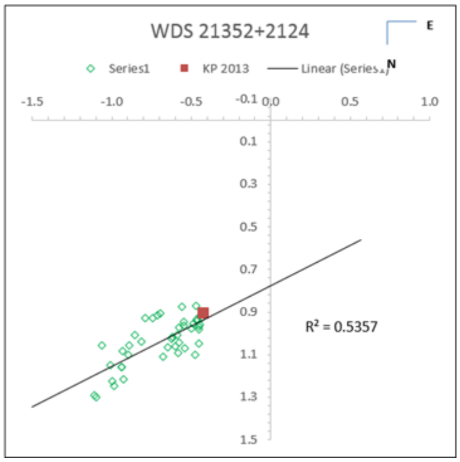

Figure 15. Plot of WDS 21352+2124

The primary has significant proper motion (+39 mas RA, -10 mas DEC). In addition, the parallax for the primary is known (11.74 mas ±0.93 mas), so we can project a distance of 85.2 parsecs to the primary (with a range from 79.0 to 92.4 being possible). The projected separation works out to 10 AU (about the size of the orbit of Saturn).

A projected period (based on a circular orbit) is 19 years with total system mass of 2.7 suns, the primary being an F5V star.

WDS 22214+4148 (A 411)

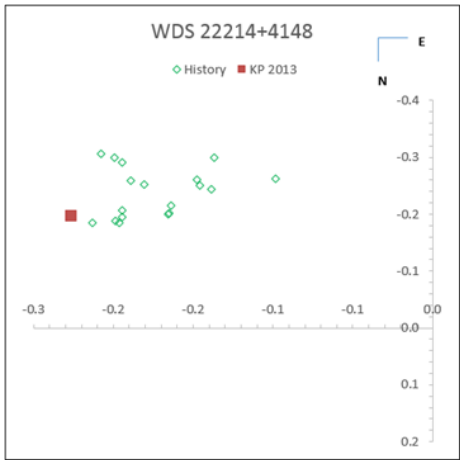

Figure 16. Plot of WDS 22214+4148

No parallax data is available, and we only have proper motion for the primary (-6 mas RA, -14 mas DEC). The proper motion data suggests a star of moderate distance, but there is so much scatter in the historical data that it is not possible to determine the pair's nature yet.

WDS 22395+4123 (BU 227 AB)

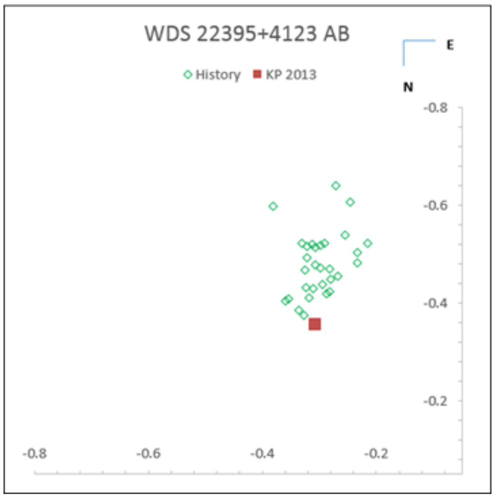

Figure 17. Plot of WDS 22395+4123 AB

The primary's parallax is given as 6.60 mas (±0.96 mas, or 14.5%), suggesting a distance of 151.5 parsecs (132.3 to 177.3 range). The projected separation at 151.5 pc is 33 AU.

The luminosity class of the primary is not given, only its spectral type of A2. But given its visual magnitude of 7.53, it can be surmised that the primary is at least 20 times as luminous as the sun and hence of likely A2 V. A circular orbit assumption yields an orbital period of perhaps 95 years and total system mass of 4.0 suns.

WDS 23267+4103 (COU 1845)

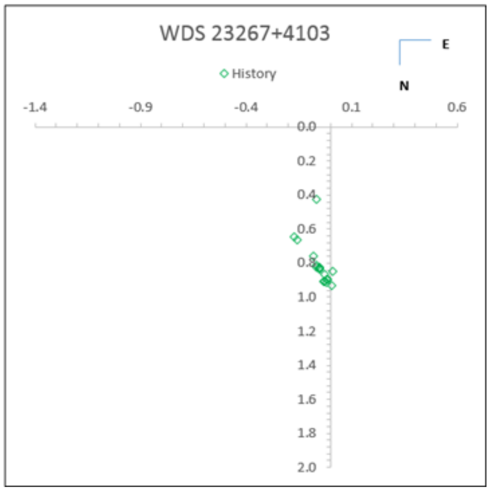

Figure 18. Plot of WDS 23267+4103.

The primary has significant proper motion (+36 mas RA, -15 mas DEC) and a parallax for the primary is known (10.46 mas ±0.76 mas), so we can project a distance of 95.6 parsecs to the primary (with a range from 89.1 to 103.1 being possible). The projected separation works out to 44 AU.

The luminosity class of the primary is not given, only its spectral type of A5. But given its visual magnitude of 7.9, it can be surmised that the primary is at least 5.5 times as luminous as the sun and hence of likely A5 V.

A circular orbit assumption yields an orbital period of perhaps 180 years and total system mass of 2.6 suns.

Conclusion

All measurements made during this observing run yielded results that fit well with recent trends in the data. Of the 13 stars studied, X showed a confirmation of arcing; Y showed traits of a linear pair; and 1 has a provisional orbit, and the measurement fit well with the orbital solution. Speckle interferometry continues to prove to be a powerful tool for the measurement of very close stars.

Acknowledgements

This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory.

References

Genet, R. 2013. Portable Speckle Interferometry Camera System. *Journal of Astronomical Instrumentation*, 2, 1340008.

Kiselev, A. A., Romanenko, L. G., and Kalinichenko, O. A. A Dynamical Study of 12 Wide Visual Binaries. AZ, 2009, Vol 53, No. 2, pp. 126-135.

Rowe, D. and Genet, R. 2015. User's Guide to PS3 Speckle Interferometry Reduction Program. *Journal of Double Star Observations*, 11, 266.