Speckle Interferometry of Close Doubles on the Mount Wilson 60” Telescope A Live Virtual Star Party

Calla Marchetti[1], Ivan Altunin[1], Kingsley Panigrahi[1], Emersen Panigrahi[1], Sophia Panigrahi[1], Sophia Risin[1], Elliott Chalcraft[1], Ryan Caputo[1], Kalee Tock[1,2], Rachel Freed[2], Reed Estrada[3], Chris Estrada[4], Rick Wasson[5], Dave Rowe[6], Richard Harshaw[2], Blake Estes[7], and Tom Meneghini[7]

1) Stanford Online High School
2) Institute for Student Astronomical Research (Sonoma), CA
3) Northrop Aviation
4) Institute for Student Astronomical Research (Lancaster), CA
5) Orange County Astronomers
6) PlaneWave Instruments
7) Mount Wilson Observatory

Abstract: Speckle data were collected on four different nights in May and June of 2020 using three different telescopes: Mt. Wilson Observatory 60-inch telescope, the Orange County Astronomers 22-inch Kuhn telescope, and the Arizona Sonoran Desert Observatory of Glendale 11-inch telescope. Three of those observation events involved students from multiple locations throughout the world participating over Zoom. Later, students met with astronomer mentors online to reduce the data. Eight double star targets with separations ranging from 0.144 to 2.880 arcseconds were measured and reported here, including the triple system A 1609.

Introduction

Close pairs are especially interesting to double-star astronomers because their orbits tend to be faster. For some, a full orbit is observable in its entirety over the course of a human lifetime. However, many known close binaries are difficult to resolve, and some have dim companions. Therefore, measuring them necessitates the use of large telescopes or advanced techniques. In spring of 2020, a student observing run was organized by Stanford Online High School (SOHS) and the Institute for Student Astronomy Research (InStAR) for the purpose of using speckle interferometry to measure several close pairs. Although the in-person session was cancelled due to COVID-19 restrictions, the project was conducted online, with students participating via Zoom in the data collection and subsequent reduction.

Instrumentation

The three telescopes used for this project were the Mt. Wilson Observatory (MWO) 60-inch, the Orange County Astronomers (OCA) 22-inch Kuhn telescope, and the Arizona Sonoran Desert Observatory of Glendale (ASDOG) 11-inch telescope. These instruments are shown in Figure 1.

The MWO 60-inch telescope has a “bent” Cassegrain f/16 configuration with a 24-meter focal length and was used here without a Barlow. Completed in 1908, the mirror alone weighs 1,900 pounds. It was famously used by Harlow Shapley to create a map of the Milky Way Galaxy, which established our Sun’s position on its periphery. It was also the first telescope to image star-like condensations in the “spiral nebulae” (Simmons, 2020). This opened the field for later work by Edwin Hubble, who used the 100-inch telescope on Mount Wilson to collect images of Cepheid variable stars, confirming the “spiral nebulae” as separate galaxies and challenging Shapley’s initial position that the Milky Way was the extent of the Universe (Trimble, 1995).

For this project, the historic telescope was mated to a ZWO ASI 1600MM back-illuminated, cooled CMOS camera with a Baader R-filter, attached to the telescope via a flip mirror and several T2 threaded adapter tubes. The configuration is shown in Figure 2.

Received September 24, 2020

Speckle Interferometry of Close Doubles on the Mount Wilson 60" Telescope
A Live Virtual Star Party

Figure 1: Left to right: MWO 60-inch telescope, OCA 22-inch Kuhn telescope, ASDOG 11-inch telescope.

Figure 2: (Left) Red filter on the ZWO camera; (Right) ZWO ASI 1600 Camera attached to a flip mirror with an eyepiece at the top.

The 22-inch aperture OCA Kuhn telescope is also historic in that it has belonged to the Orange County Astronomers astronomy club since being built by club members, led by William Kuhn, in the 1980s. Initially, the very heavy telescope, which has an Equatorial Fork mount, was operated manually, but, over the years, the telescope has been modified so that it is now computer-controlled. A 2x Barlow was employed so that the f/8 Cassegrain optics effectively became f/16. The speckle camera used was a ZWO ASI 290MM, so that the resulting image pixel scale was 0.0736"/pixel. For this imaging session, the filters were Clear (as in CCD imaging "Luminance", used only for finding) and Sloan (SDSS) g' r' i' z' (Generation 2) from Astrodon.

The third telescope used for this project is located in the suburbs of Phoenix at the Arizona Sonoran Desert Observatory of Glendale (ASDOG). This Celestron 11-inch aperture telescope belongs to Jimmy Ray and has a Celestron German Equatorial Mount. It is mated to a ZWO ASI290MM camera. Despite having significant light pollution, ASDOG is well-suited to speckle interferometry, which is less impacted by light pollution than most other forms of astronomy.

Target Selection

The targets were selected in part to test the capabilities of the telescopes used. Even with excellent seeing, starlight is generally smeared out such that the "seeing limit" is at least 3″. This means that two stars would need to be at least 3″ apart in order to resolve them in typical seeing conditions. However, speckle interferometry enables observers to operate below the seeing limit and obtain diffraction-limited information about the positions of the stars. The closest possible separation for double star astrometry using a red filter and the speckle interferometry reduction technique is therefore given by the Rayleigh limit shown in Equation 1:

$$\text{Rayleigh limit} = 1.22\frac{\lambda}{d} = 1.22\frac{650\ \text{nm} \cdot \frac{1\ \text{m}}{10^9\ \text{nm}}}{d\ \text{in} \cdot \frac{1\ \text{m}}{39.37\ \text{in}}} \cdot \frac{360^\circ}{2\pi\ \text{rad}} \cdot \frac{3600''}{\text{degree}}$$

Equation 1: Rayleigh limit for 650nm wavelength using a telescope of aperture d, where d is given in inches.

A comparison between the Rayleigh limit and the closest-separation pair imaged in this study for each of the telescopes used is shown in Table 1.

Speckle Interferometry of Close Doubles on the Mount Wilson 60" Telescope
A Live Virtual Star Party

Observatory	Aperture (inches)	Rayleigh limit (″)	Closest separation imaged in this study (″)
MWO	60	0.107	0.144
OCA	22	0.293	0.367
ASDOG	11	0.585	2.880

Table 1: Rayleigh limit along with the closest separation double star imaged by each of the telescopes in this study.

Observing Sessions

Rick Wasson used the OCA Kuhn telescope to image STF 1527, WRH12, and HU572. Jimmy Ray and Richard Harshaw used ASDOG to image STF 1670AB, with multiple students participating via Zoom. A team including Rick Wasson, Dave Rowe, Reed and Chris Estrada, MWO Director Tom Meneghini, Telescope Operator Blake Estes, Rachel Freed, and Kalée Tock gathered at MWO for an engineering run and then for an imaging session three weeks later, with students participating via Zoom on both occasions.

Fire Capture software was used to control the camera and acquire the speckle images during all of the observing sessions. For each of the selected double star targets, short speckle exposure lengths were estimated based on the magnitude of the double stars, seeing and wavelength. Drift calibrations were performed to determine the pixel scale and camera angle. In most cases, reference stars were observed in order to conduct deconvolution, which removes the effects of optical aberrations and some atmospheric effects. The deconvolution requires the reference stars to be single stars, ideally within 4 degrees of the target. It is important to collect the reference star data used for deconvolution within about 10 minutes of acquiring the target star to reduce the chances of a change in atmospheric conditions between the two measurements.

Speckle interferometry had not been done using the MWO 60-inch telescope before the engineering run of May 24. At that observing session, the bright star Arcturus initially did not come into focus on the camera detector. Focus was apparently inside the focuser, and immoveable. Tom Meneghini and Blake Estes later discovered that the focus problem was caused by a malfunction jamming the mechanism which supports and moves the secondary mirror, which is the way the telescope is focused. As a work-around, a set of lenses was employed. This brought focus out to the camera, but also reduced the effective focal length and caused considerable optical distortion. Therefore, the data collected during the engineering run were ill-suited for analysis, though the speckle process was still demonstrated for the Zoom audience.

The malfunction was corrected, providing a large amount of back-focus (more than 11 inches) for the June Star Party. In fact, during the MWO observing run on June 14th, triple star A1609AB, C was analyzed live using Dave Rowe's Speckle ToolBox (STB) and shared with the Zoom audience. As the evening progressed, the team developed a routine of calling out SAO numbers to Telescope Operator Blake Estes at the control console, who entered these into The Sky software and then pointed the telescope to the correct coordinates. From there, the engineering team performed fine adjustments with the fine guidance hand controller situated at the telescope to locate and center the star in the camera field of view.

Results

Of the original targets, all were successfully resolved except for 14267+1625 A2069, whose separation was predicted to be very close to the diffraction limit of the MWO 60-inch telescope. The pixel scale was approximately 0.03″ per pixel, so the 3-4 pixels that separate the two centroids would not have provided adequate sampling for confident measurements. A2069 was chosen initially because it had a predicted separation 0.108″ for 2020.0, but by the time the system was measured the prediction was approaching 0.101″, which is below the MWO 60-inch telescope Rayleigh limit shown in Table 1. Therefore, the binary was not resolved but "elongated", as shown in Figure 3. This elongation indicates that the separation of A2069 was less than 0.107″, the Rayleigh limit for the MWO telescope.

The systems that were resolved were analyzed with autocorrelation and bispectrum analysis using STB 1.14. One of the systems, STF 1609AB, was a triple system. The autocorrelation and bispectrum results of this system are shown in Figure 4.

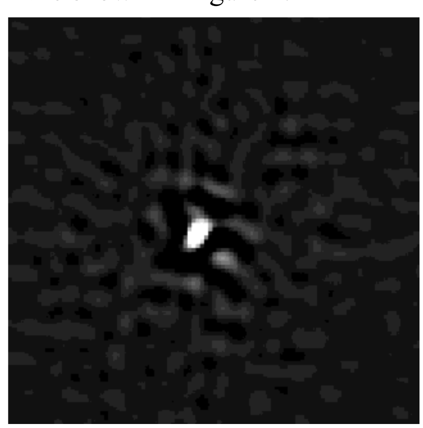

Figure 3: Elongated bispectrum image of A2069

Speckle Interferometry of Close Doubles on the Mount Wilson 60" Telescope
A Live Virtual Star Party

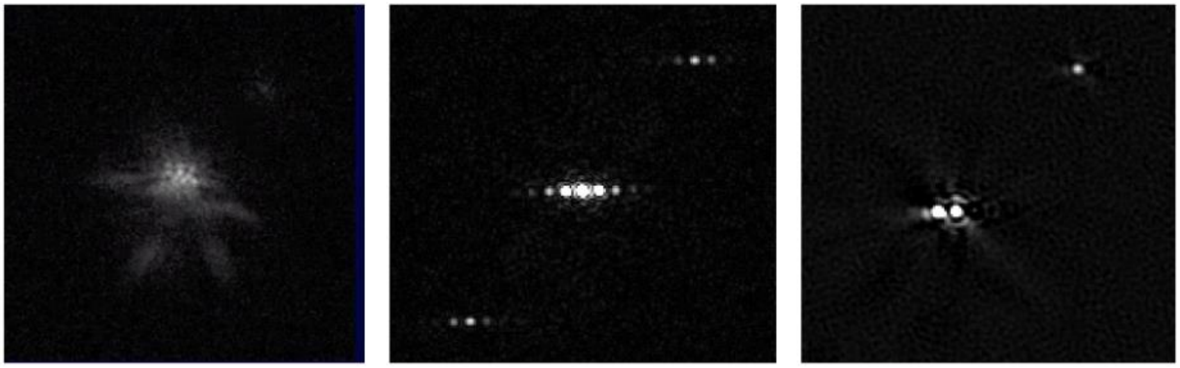

Figure 4: A 1609ABC Single image (left), autocorrelation (center) and bispectrum reconstructed image (right). In the Autocorrelation, the two nearly equal components (AB) create correlations with the C component as well (upper right and lower left).

System	Date	Tele-scope*	Number of Fits Cu-bes	Position Angle (°)	Standard error on PA (°)	Separa-tion (″)	Standard Error on Sep (″)
STF 1527 WDS 11190+1416	2020.34	OCA 22	4	302.24	0.13	0.493	0.012
WRH 12 WDS 12349+2238	2020.34	OCA 22	4	8.02	0.28	0.352	0.015
HU 572 WDS 13091+2127	2020.34	OCA 22	4	329.40	0.59	0.554	0.006
STF 1670AB[1] WDS 12417-0127	2020.36	ASD 11	1	356.17	NA	2.880	NA
TOK 406 WDS 14382+1402	2020.45	MWO 60	1	14.36	NA	0.144	NA
A 1609AB WDS 13258+4430	2020.45	MWO 60	1	87.39	NA	0.256	NA
A 1609 AC	2020.45	MWO 60	1	220.69	NA	2.618	NA
A 1609AB, C WDS 13258+4430	2020.45	MWO 60	1	222.27	NA	2.647	NA
A 2069 WDS 14267+1625	2020.45	MWO 60	1			<0.107	

**OCA 22: Orange County Astronomers 22-inch Kuhn telescope.*
MWO 60: Mt. Wilson Observatory 60-inch telescope.
ASD 11: Arizona Sonoran Desert Observatory of Glendale, Celestron 11-inch telescope.
[1] STF 1670AB's was measured with STB1.05 autocorrelation only, because STB1.14 does not work without a reference star.

Table 2: Measurements of position angle and separation for the eight star systems studied here.

The astrometric measurements obtained are summarized in Table 2. Note that it was not possible to report standard errors for the measurements of all of the pairs, as only a single fits cube was obtained in several cases. Ideally, it would be best to average the results from about five 1000-frame fits cubes. For the OCA 22-inch telescope, the astrometry was averaged from fits cubes taken in four Sloan filters. A comparison of each measurement to its corresponding residual, based on the orbital ephemeris predicted by Bill Drummond's spreadsheet, is shown in Table 3 (Drummond, 2020). Note that most of these stars were not resolved by Gaia DR2 (except for A1670AC and A1609AB,C), so it was not possible to compare the measurements to each pair's corresponding measurement in Gaia DR2.

	System	Position Angle (°)	Residuals (°)	Separation (")	Residuals (")
STF 1527	Predicted	302	--	0.46	--
	Autocorrelation	302.52	0.52	0.490	0.030
	Bispectrum	302.24	0.24	0.493	0.033
WRH 12	Predicted	9.1	--	0.325	--
	Autocorrelation	8.06	-1.04	0.406	0.081
	Bispectrum	8.02	-1.08	0.352	0.027
TOK 406	Predicted	6.2	--	0.129	--
	Autocorrelation	12.94	6.24	0.141	0.012
	Bispectrum	14.36	8.16	0.144	0.015
STF 1670AB	Predicted	357	--	2.975	--
	Autocorrelation	356.17	-0.83	2.880	-0.095
	Bispectrum	--	--	--	--
HU 572	Predicted	328	--	0.554	--
	Autocorrelation	327.72	-0.28	0.533	-0.021
	Bispectrum	329.4	1.4	0.554	0
A 1609AB	Predicted	89.3	--	0.244	--
	Autocorrelation	87.7	-1.56	0.256	0.011
	Bispectrum	87.39	-1.91	0.256	0.012

Table 3: Predicted position angles and separations based on Bill Drummond's spreadsheet and the WDS Sixth Orbit Catalog Orbital Elements.

For the pairs observed at the OCA 22-inch telescope (STF 1527, WRH 12, and HU 572), the use of multiple filters made possible the bispectrum analysis of approximate delta magnitude (Δm = mB-mA) values at different wavelengths, as shown in Table 4. The uncertainties of delta magnitude in bispectrum may be large, particularly when only a single observation is made and the colors are not transformed to a standard photometric system, as is the case here.

Filter Center WL FWHM	Sloan g'2 475nm 149 nm	Sloan r'2 630nm 133 nm	Sloan i'2 770nm 149 nm	Sloan z'2 ~900nm ~160 nm
STF 1527	0.68	0.55	0.70	0.73
WRH 12	1.51	1.84	2.04	2.21
HU 572	0.76	0.62	0.65	0.87

Table 4: Delta magnitude (secondary - primary) of STF 1527, WRH 12, and HU 572 in multiple Sloan filters. For each filter, the center wavelength and full-width-half-max (FWHM) bandpass are given in the headings. For the IR long-pass z'2 filter, the long WL end is determined by the detector sensitivity limit, which is assumed to be 980 nm.

Analysis

Delta magnitude normally decreases as the filter wavelength increases, but as seen in Table 4, the opposite was the case for STF 1527. This would suggest either that the primary is a red giant or that the secondary is a red dwarf. The system being 1400 lightyears away makes it too far for a white dwarf to be visible, especially with such a bright primary, and the WDS says the primary is spectral type A0IV. This confirms that it is a sub-giant running out of hydrogen and beginning to leave the main sequence. Most likely, both components were originally type B stars, but the primary was a more massive, hotter, earlier B type. Now the primary has run out of fuel first, expanded, and cooled down to type A0, it's redder than the B companion but enlarged to still be about 2 mags brighter.

As seen in Figures 5 - 10 below, the measurements of all pairs reported here fall within 0.1 arcsecond of their predicted locations. In most cases, this corroborates both the accuracy of the orbits and the accuracy of the measurements. Specifically, our points for STF1527, STF1670AB, HU572, and A1609AB are all close to their predicted orbit points. However, there is a scattered trend with respect to time in the plotted

Speckle Interferometry of Close Doubles on the Mount Wilson 60" Telescope
A Live Virtual Star Party

measurements of WRH 12 (Figure 6 at right), as demonstrated by the interspersed locations of the darker and lighter points on the historical data plot. Therefore, it remains somewhat unclear whether the corresponding locations between the measurement point and predicted point are coincidental. Similarly, for TOK 406, the four earliest-date points of the historical data file had to be quadrant-flipped in order to match their positions on the WDS orbital plot, as shown in Figure 7. A new paper in prep by Tokovin may soon update the orbital elements of this system (Tokovin, 2020).

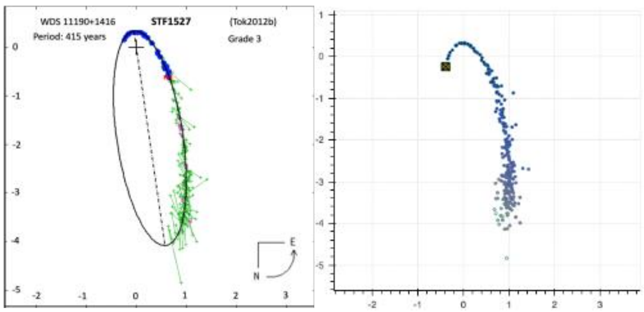

Figure 5: Left: WDS orbital plot of STF 1527. Right: the historical data along with the measurement (green square), and the prediction based on the WDS orbital ephemeris (orange square). For this system, the "measured" and "predicted" points are nearly identical, so the two position markers are overlapping.

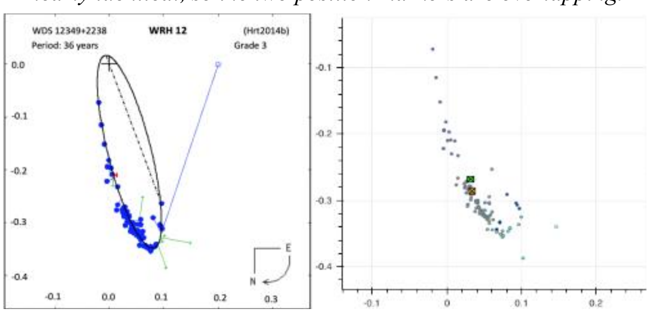

Figure 6: Left: WDS orbital plot of WRH 12. Right: the historical data along with the measurement (green square), and the prediction based on the WDS orbital ephemeris (orange square).

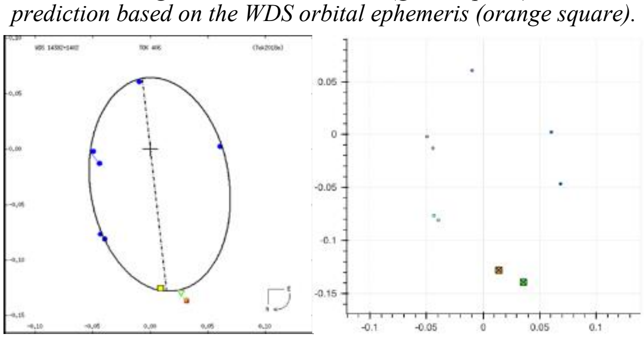

Figure 7: Left: WDS orbital plot of TOK 406 with the prediction in yellow, autocorrelation measurement as the open green triangle, and two separate bispectrum measurements in green and red on top of each other. Right: Data from the historical data file with the prediction in orange and the bispectrum measurement in green. Note that the earliest four points in this data set were quadrant flipped in the historical data file; they are here shown corrected.

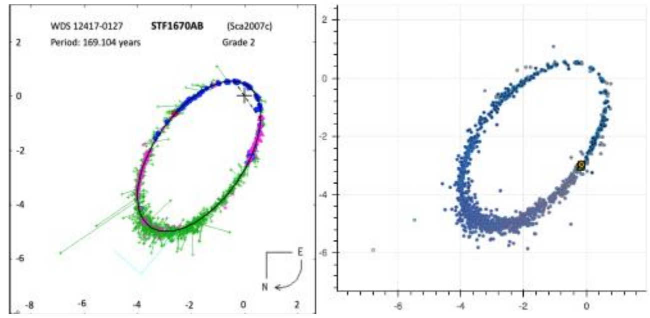

Figure 8: Left: WDS orbital plot of STF 1670AB. Right: the historical data along with the measurement (green square), mostly hidden behind the prediction based on the WDS orbital ephemeris (orange square).

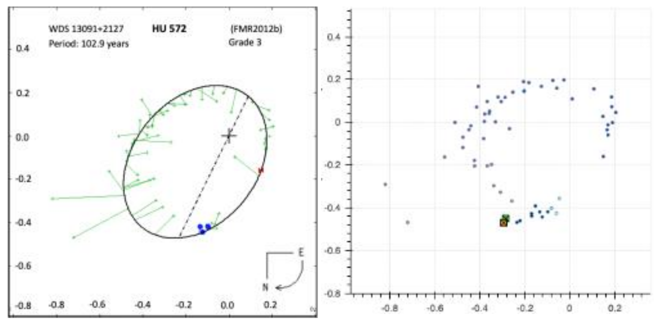

Figure 9: Left: WDS orbital plot of HU 572. Right: the historical data along with the measurement (green square), mostly hidden behind the prediction based on the WDS orbital ephemeris (orange square).

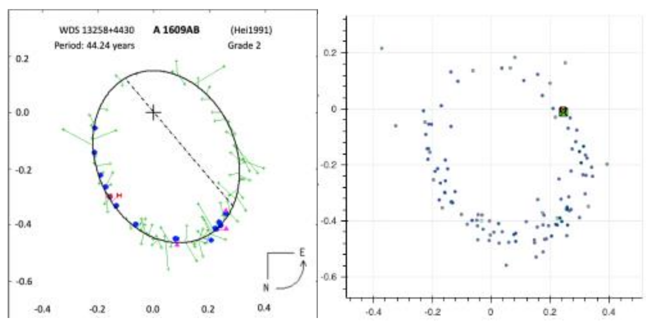

Figure 10: Left: WDS orbital plot of STF 1609AB. Right: the historical data along with the measurement (green square), mostly hidden behind the prediction based on the WDS orbital ephemeris (orange square).

Figure 11 shows the orbital plot for the system whose position angle and separation measurements are not reported here: A 2069. The secondary star's close proximity to periapsis on the night of our observation (predicted at 0.101″) was within the 0.107″ Rayleigh limit of the 60-inch MWO telescope.

Speckle Interferometry of Close Doubles on the Mount Wilson 60" Telescope
A Live Virtual Star Party

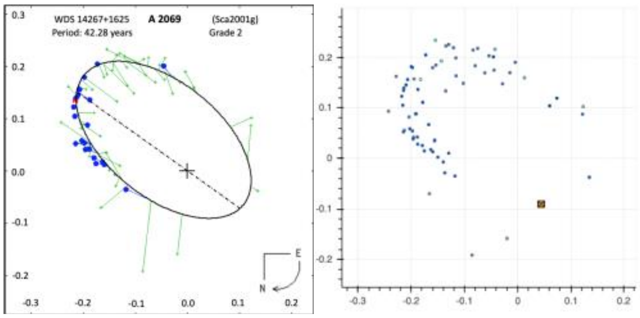

Figure 11: Left: WDS orbital plot of A 2069. Right: the historical data along with the predicted position of the secondary based on the WDS orbital ephemeris (orange square).

Conclusion

Using speckle interferometry enables reaching a telescope's diffraction limited resolution, making very close double stars accessible with a high speed camera. As a result of our study, 6 double star systems were successfully resolved using both bispectrum and autocorrelation methods. Of the successfully separated systems, observed separation values were very close to the predicted values and most were consistent with orbital solutions obtained from the WDS.

Acknowledgements

This research was made possible by the Washington Double Star catalog maintained by the U.S. Naval Observatory, along with the Stelledoppie catalog maintained by Gianluca Sordiglioni.

The team would like to acknowledge the generous support from Mount Wilson Observatory, for allowing us to do an engineering run in preparation for our Live Virtual Star Party Research Programs.

Thanks also to Jimmy Ray of the ASDOG Observatory for generously donating his time and his telescope for use in this project, and to the Orange County Astronomers for use of their telescope and facilities.

References

Dainty, J. C. 1981. Speckle Interferometry in Astronomy. Symposium on Recent Advances in Observational Astronomy, Ensenada, Mexico. 95-111.

Drummond, Bill, 2020. Personal communication.

Labeyrie, Antoine. 1970. Attainment of Diffraction Limited Resolution in Large Telescopes by Fourier Analysing Speckle Patterns in Star Images. Astronomy & Astrophysics. 6, 85-87.

Anderson, J.A., 1920, "Application of Michelson's Interferometer Method to the Measurement of Close Double Stars." Contributions from Mount Wilson Observatory, No. 185, ApJ, 51, 263-275.

Edelmann, Torsten, 2017. FireCapture2.6. http:// firecapture. Wonderplanets.de

Genet, R., Rowe, D., Meneghini, T., Buchheim, R., Estrada, R., Estrada, C., Boyce, P., Boyce, G.,Ridgely, J., Smidth, N., Harshaw, R., and Kenney, J., 2016, "Mount Wilson 100-inch Speckle Interferometry Engineering Checkout." JDSO, 12, 263-269, March 2016.

Harshaw, Richard and Rowe, David and Genet, Russell, 2017, "The Speckle Toolbox: A Powerful Data Reduction Tool for CCD Astrometry." JDSO, 13, 52-67, January 1, 2017.

Merrill, P. W., 1921, "Interferometer Observations of Double Stars", PASP, 33, 209.

Michelson, A.A., & Pease, F.G., 1921, "Measurement of the Diameter of α Orionis with the Interferometer", ApJ, 53, 249.

Rowe, David A. and Genet, Russell M., 2015, "User's Guide to PS3 Speckle Interferometry Reduction Program", JDSO, 11, 266-276.

Rowe, D., 2017, "WDS1.2 Search Program." Private communication.

Rowe, D., Genet, R., 2020. "STB1.13 Bispectrum Processing," in preparation for submission to JDSO.

Simmons, Mike, 2020. "Building the 60-inch telescope." Mount Wilson Observatory website, retrieved July 2020.

Tokovin, Andrei, Brian D. Mason, Rene A. Mendez, Edgardo Costa, Elliott P. Horch. "Speckle Interferometry at SOAR in 2019", in preparation.

Trimble, Virginia, 1995. "The 1920 Shapley-Curtis Discussion: Background, Issues, and Aftermath", Publications of the Astronomical Society of the Pacific, V. 107, pp. 1133.