Kitt Peak Speckle Interferometry of Close Visual Binary Stars

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Abstract

Speckle interferometry can be used to overcome normal seeing limitations by taking many very short exposures at high magnification and analyzing the resulting speckles to obtain the position angles and separations of close binary stars. A typical speckle observation of a close binary consists of 1000 images, each 20 milliseconds in duration. The images are stored as a multi-plane FITS cube. A portable speckle interferometry system that features an electron-multiplying CCD camera was used by the authors during two week-long observing runs on the 2.1-meter telescope at Kitt Peak National Observatory to obtain some 1000 data cubes of close binaries selected from a dozen different research programs. Many hundreds of single reference stars were also observed and used in deconvolution to remove undesirable atmospheric and telescope optical effects. The data base of well over one million images was reduced with the Speckle Interferometry Tool of PlateSolve 3. A few sample results are provided. During the second Kitt Peak run, the McMath-Pierce 1.6- and 0.8-meter solar telescopes were evaluated for nighttime speckle interferometry, while the 0.8-meter Coude feed was used to obtain differential radial velocities of short arc binaries.

1. Introduction

Binaries is a term that William Herschel coined when he discovered that some of the double stars he had been observing were revolving around each other and hence were gravitationally bound pairs (Herschel 1803, Hoskin 2011). The term *visual* was later added to distinguish the more widely separated astrometric binaries from the generally much closer spectroscopic and photometric (eclipsing) binaries.

The resolutions of conventional visual binary observations were seeing limited until Labeyrie (1970) devised speckle interferometry as a way to circumvent seeing limitations and realize the full diffraction-limited resolution of a telescope. The light from a close binary passing through small cells in the atmosphere produces multiple binary star images which, if observed at high enough magnification with short exposures (typically 10 to 30 milliseconds), will "freeze" out the atmospheric turbulence and thus overcome seeing-limitations. Although the multiple double star images are randomly scattered throughout the image (often superimposed), their separation and position angle remains constant, allowing these two parameters to be extracted via Fourier analysis (autocorrelation).

For images larger than a few arc seconds across, however, the rapid jitter of the binary speckle images is no longer correlated. Speckle interferometry is not effective beyond isoplanatic patch, but close binary stars are always well within the isoplanatic patch. The Fourier transforms of hundreds or thousands of short exposures are averaged to greatly improve the signal-to-noise ratio.

Harold McAlister (1977) used high-speed Tri-X film cameras on the 2.1- and 4.0-meter telescopes on Kitt Peak to observe close binaries. Obtaining Fourier transforms of thousands of film images was a labor-intensive process. His film camera was soon replaced with an intensified CCD (ICCD) camera and Osborne portable computer (McAlister *et al.,* 1982). The speckle observations by McAlister, William Hartkopf, and others at Georgia State University were an order of magnitude more precise than visual observations, making speckle the preferred observational technique for close binaries (McAlister, 1985). The status of speckle imaging in binary star research is reviewed by Horch (2006).

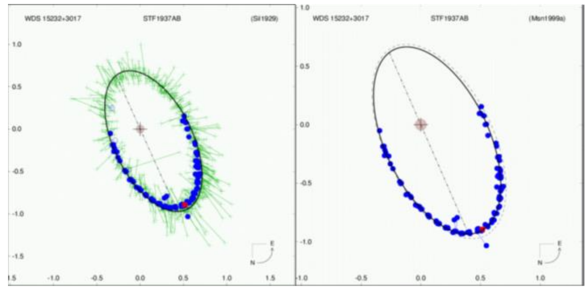

Figure 1. Close binary orbit of η CorBor with and without visual micrometer (green) observations. Speckle observations are blue dots.

The power of speckle interferometry can be seen from orbital plots and solutions. An orbit of a close binary based primarily on visual observations is not nearly as precise as one based solely on speckle observations. In the example of η CorBor provided by William Hartkopf, the new orbital solution based on the speckle observations alone (right solid line), compared to the earlier solution that included visual micrometer measurements (right dashed line) changed the estimated mass by 14%, astrophysically a very significant improvement! The consistency of the 20 different speckle telescope/detector combinations is remarkable.

Since speckle interferometry observational limits are set by telescope resolution (aperture diameter) rather than seeing, it is natural for smaller telescopes to concentrate on wider binaries, while larger telescopes observe binaries between their seeing and resolution limits. Although a number of smaller telescopes are permanently equipped for speckle observations, larger telescopes are not, so observers must bring their own "visitor" instruments.

An ICCD speckle camera, similar to Georgia State University's camera, was built and installed on the 0.66-meter refractor at the U.S. Naval Observatory (USNO) in Washington. A second, identical camera was then built and used in the USNO's "off campus" observational program. The USNO's highly successful speckle observations of close binary stars with a portable ICCD speckle camera on larger telescopes inspired us to develop an even more portable system based on the Andor Luca electron-multiplying CCD cameras (Genet 2013).

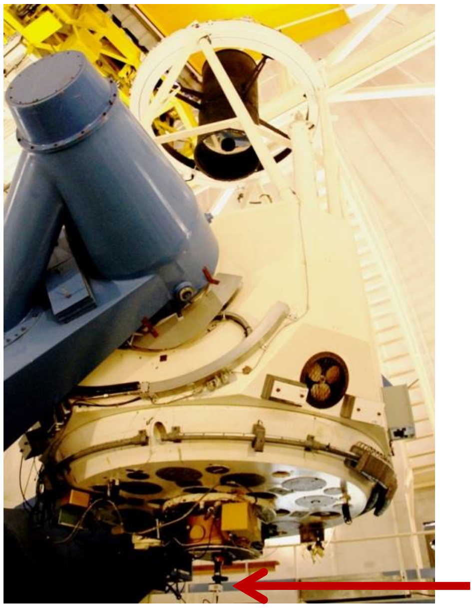

Figure 2. The 2.1-m f/7.6 telescope at Kitt Peak National Observatory dwarfs our portable speckle camera.

Our speckle camera is the primary instrument on the 0.25-meter SCT telescope at the Orion Observatory. Our first "off campus" visitor speckle runs were made with our camera on the 0.5-meter PlaneWave Instruments CDK telescope at Pinto Valley Observatory, providing us with twice the resolution. Double stars with a separation of 0.5 arc seconds were observed. The 2.1-meter telescope at Kitt Peak National Observatory was chosen to continue our quest for observing ever closer binaries, allowing us to observe binaries with separations of 0.1 arc second and periods of well under one decade.

Two bright-time, week-long observing sessions on the 2.1-meter telescope at Kitt Peak spread six months apart provided good coverage of close binary stars in the sky visible from Arizona. On the first run, October 15 to 23, 2013, the first eight nights were totally clear nights, while the last night was partially cloudy. On the second run, April 10 to 16, 2014, although the first two nights were primarily cloudy, the last five nights were completely clear. This gave us a total of 13 completely clear nights for our observations.

Although the Principal Investigator (Genet) stayed full time for both runs, most of the observers participated for just half a week; thus not too much school- or work-time was missed. The 27 observers (the coauthors of this paper) were an eclectic mix of undergraduate and graduate students, and advanced-amateur and professional astronomers.

Figure 3. Seven of the 12 observers on the October 2013 run: Genet, Plummer, Patel, Teiche, Trueblood, Wallace, and Chaney.

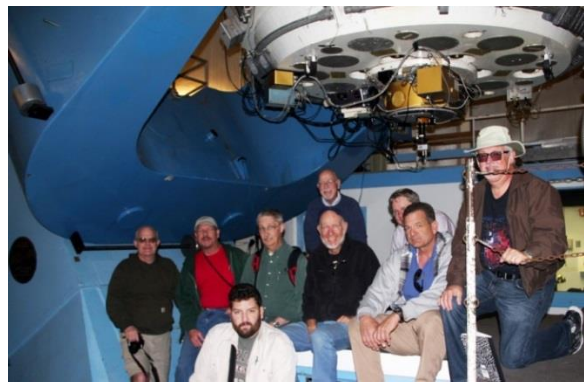

Figure 4. Nine of the 20 observers on the April 2014 run: Jones, Smith, C. Estrada (front), Green, Genet, Wiley (rear), Clark, R. Estrada, and Harshaw.

2. Research Programs

Our research has concentrated on five classes of double stars: (1) known binaries with published orbits; (2) candidate "binaries" without published orbits that exhibit indications of binarity; (3) unclassified double stars that could be either chance-alignment optical doubles, common proper motion pairs, or binaries; (4) unconfirmed double star candidates (not known if they are even double stars); and (5) special requests by other astronomers. The *Washington Double Star Catalog*, the *Sixth Catalog of Orbits of Visual Binary Stars* (including the accompanying plots of past observations), and the *Fourth Catalog of Inteferometric Measurements of Binary Stars* were all formatted as Excel spreadsheets and used to search for candidates for our various target lists. Each class is described below.

Known binaries with published orbits

(1) Long-period, slow-moving binaries with many past speckle observations. Extensive observations of some of these binaries were used as

calibration binaries in the first run and also to establish within- and between-night variances.

(2) Short-period Grade 1 and 2 binaries used as calibration binaries in the second run, to establish within- and between-night variances, and to contribute further speckle observations to these well-observed binaries (Malkov *et al.*, 2012).

(3) Both long and short period binaries where recent speckle observations suggested that the orbital parameters could use refinement, as it appeared from the plots that the recent observations were heading "off the track."

(4) Both long and short period binaries with plots that suggested that the current published orbits were woefully inadequate. We termed these "bad orbit binaries."

(5) Both long and short period binaries that had few or no past speckle observations and it was clear that additional speckle observations would significantly contribute to refining their orbits.

Candidate "binaries" without published orbits

(6) Short-arc, long-period binary candidates with extensive past visual observations but, in some cases, with few or no speckle observations. When plotted, short-arc binaries have enough previous observations that an arc is evident. These arcs are likely to be segments of an elliptical orbit. In more developed cases, where a significant portion of an ellipse is available, traditional orbital solutions can be derived. When the arc is too short to accurately build a solution, the apparent motion parameters (AMP) method, an approach developed by A. Kiselev *et al.* (2003, 2009), can be applied. AMP estimates the sum of the component masses from their relative radial velocities, known parallax, and projected separation. Other papers by Kiyaeva *et al.* (2008, 2012), Harshaw (2014), and Genet *et al.* (in preparation) also speak to this important indicator of binary systems. AMP utilizes the known position angle and separation, as well as measures of the apparent relative velocity in micro-arcseconds per year, the position angle of the relative motion, and the radius of curvature (Kiselev *et al.*, 2003). Parallaxes are derived from Hipparcos, a mass estimate of the system from spectral classes, and relative radial velocities from one-time spectrographic radial velocity measurements of each component of the system. Additional important work in this area has been done by F. Rica of Spain (2011, 2012).

(7) Short-arc, short-period binary candidates found by searching through the *Fourth Catalog of Inteferometric Measurements of Binary Stars.* Typically these close binary candidates do not have any past visual observations, and only have Hipparcos and a few speckle observations. They are placed on our target list if the past observations show a significant change in position angle within the few decades speckle observations have been made.

Unclassified double stars

(8) Few past visual observations

(9) Few past speckle observations (*Fourth Catalog of Inteferometric Measurements of Binary Stars*)

Unconfirmed double star candidates

(10) Hipparcos unconfirmed doubles, now some 1874 in number. Many approach 0.1 arc seconds in separation (the limit for Hipparcos). These are potential double stars discovered by Hipparcos that have not yet been confirmed by follow-up observations. While many of these may have been false detections, others may end up being binaries of special interest. See Perryman (2012) for details on Hipparcos binaries.

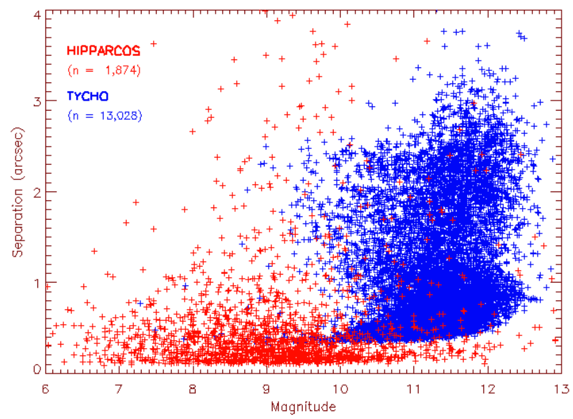

Figure 5. Plot of unconfirmed Hipparcos and Tyco doubles.

(11) Tycho unconfirmed doubles, currently some 13,028 in number, most greater than 0.5 arc seconds in separation (nearly the limit for Tycho, as only 1192 have a separation less than 0.5 arc seconds). We prepared this list but did not observe any on our Kitt Peak runs as they appeared to be more appropriate targets for smaller telescopes (they should be good candidates for the 17.5-inch automatic speckle interferometry system we are building).

(12) Hubble guide stars that were rejected because they did not provide a solid lock-on. This rejection could have been due to binarity.

Special requests

(13) A number of doubles were observed for Oleg Malkov (Russia), Olga Kiyaeva (Russia), Francisco Rica (Spain), Henry Zirm (Germany), and Todd Henry (US).

3. Portable Speckle Camera

Small-format, regular CCD cameras take about a second to read out a single image that has been accumulated over many seconds or minutes. The readout noise is typically 10 electrons RMS—very small compared to the accumulated light levels. While such cameras can be used to make speckle observations if they are capable of making 10 millisecond exposures, their readout time would be very long in comparison to their exposure time. A typical binary speckle observation consists of 1000 images. Each image typically has an exposure of 20 milliseconds for a total data cube exposure time of 20 seconds. If each image (frame) took 1 second to read out, 1000 frames would take almost 20 minutes, resulting in a very poor duty cycle (about 2%).

A number of small-format, high-speed, frame-transfer CCDs are available for about $500 that can read out one frame at high speed while another frame is being exposed. Continuous readout-while-exposing at speeds of 50 frames/second are not uncommon, allowing these cameras to have a duty cycle approaching 100%. While these cameras are quite useful for obtaining speckle observations of many brighter close binaries, their high-speed charge-to-voltage converters induce significant noise compared to the low signal levels inherent in 20 millisecond, highly magnified speckle images. An image intensifier can be used to boost the signal level, allowing these low-cost cameras to reach fainter binaries. When the image intensifier is integral to the CCD camera (often coupled with short optical fibers), then one has an intensified CCD (an ICCD).

Another way the signal can be amplified before it reaches the charge-to-voltage converter (which is inherently noisy at high speed) is to clock the output charge (electrons) from the pixel array through a final gain register. A high voltage is applied in an avalanche region in the semiconductor (the pixels in the gain register), and as the charge is transferred from one pixel to the next, extra electrons are knocked out of the lattice, causing amplification similar to a photomultiplier. This electron multiplication (EM) boosts the signal to a level where the high speed read noise is insignificant, making EMCCD cameras very attractive for speckle interferometry. The amplification process does introduce some noise, however, so electron multiplication is not advantageous at normal readout rates (Smith *et al*., 2008).

Similar to other CCD cameras, EMCCD cameras are available in both front- and back-illuminated versions. Andor Technologies, for instance, makes the very compact, front-illuminated, Luca-R camera (which costs about $14K). It has a quantum efficiency of about 50% and can be accessed via USB. The Andor Luca-R camera we used for observations on the 2.1-meter telescope at Kitt Peak cooled to -20° C within seconds, had a dark noise of only 0.05 electrons/pixel/second, and a read noise well under 1 electron RMS. Andor also makes a much larger, back-illuminated, iXon camera which costs about $40K. It has a quantum efficiency of 90%, but must connect to a PCI card with a fairly short cable (5 meters) on a nearby computer. This can require either mounting a PC on the telescope or running a special fiber-optic link which Andor can supply. It might be noted that Andor recently started manufacturing high-speed sCMOS cameras with USB-3 outputs that cost less than $12K. We hope to evaluate one of these cameras for use in close visual binary speckle interferometry in the near future.

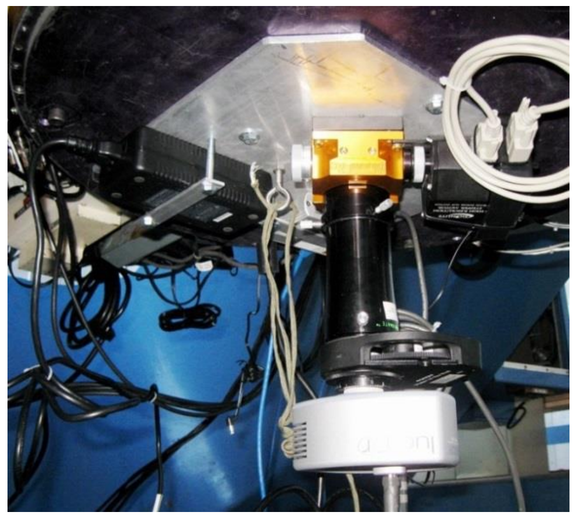

Figure 6. Our speckle interferometry system installed at the Cassegrain focus of the 2.1-meter telescope.

Although the Luca-R EMCCD camera was the heart of our overall speckle camera system, it also included magnification with a 2-inch x2 OPT Barlow in front of a Moonlite focuser and a 2-inch x4 TeleVue PowerMate after the focuser (Genet 2013). An Orion 5-position filter wheel immediately preceded the Luca-R camera. All observations were made through a Sloan i' filter (Astrodon second generation Sloan filter).

4. Observations

Preparing for and making observations at a large telescope with sizeable teams is a major technical, organizational, and logistical undertaking. Preparations for the Kitt Peak observing runs began over a year prior to the first run when the Principal Investigator (Genet) visited Richard Joyce and Di

Harmer, experienced experts on the 2.1-m telescope, at the Kitt Peak National Observatory headquarters in Tucson. Drawings of the telescope were examined, and a discussion on interfacing a guest instrument to the telescope was initiated.

One interface problem was that the guest instruments needed a 22-inch diameter plate to fasten to the large opening on the telescope's acquisition-guider unit. A sturdy 22-inch diameter plate, even if made from aluminum, would be difficult to transport to Kitt Peak on an airplane. This problem was solved when Hillary Mathis located a ½-inch thick aluminum plate that had been made by an early observer for a somewhat different guest instrument. This plate already had the holes that exactly matched the acquisition-guider's bolt circle, a somewhat large hole near the center, and three instrument fastening holes spaced 120 degrees apart. Our visitor speckle camera was assembled on a 12 x 12-inch x ¼-inch thick aluminum plate with three holes spaced to match those on the "used" Kit Peak interface plate.

Another interface problem was connecting the USB camera on the back of the telescope to a laptop in the warm room. This problem was solved by connecting an Icron Ranger USB-to-Ethernet unit at the telescope to its mating Ethernet-to-USB unit in the warm room with a 50-foot Cat-5 cable we brought with us to run between the two units.

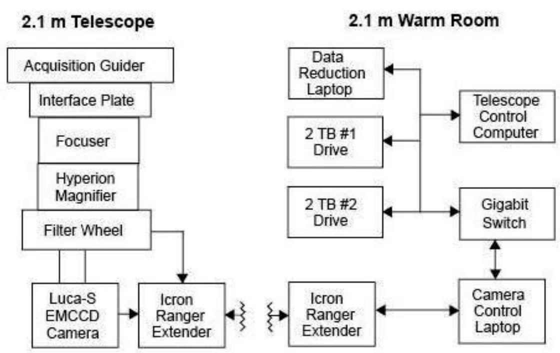

Figure 7. The original speckle system block diagram.

Our original plan for our visitor system used a very compact and sturdy Hyperion eyepiece projection system for magnification. However, we ended up using two Barlow lenses instead because we wanted to be certain that we had sufficient back focus. A 2-inch diameter x2-power Barlow lens in front of our focuser (actually extending up slightly into the back of the telescope's acquisition-guider unit) extended the focal plane, while a 2-inch x4 TeleVue Power mate completed the magnification. A local area network (LAN) connected equipment in the warm room. This LAN had to be hard wired because Wi-Fi routers are not allowed on the mountain because they could interfere with a radio telescope. Our original plan for a hardwire connection to the telescope control system proved to be impractical.

With many specifics of the science research programs and equipment engineering details worked out, our proposal for the second semester of 2013 was submitted in March of 2014. Although obtaining time on Kitt Peak telescopes is highly competitive (they are oversubscribed), the Telescope Allocation Committee awarded us nine nights in October.

Figure 8. Smith fastens our camera to the large-diameter interface plate for the monsoon engineering checkout.

Knowing that there is many a slip between the cup and the lip, arrangements were made to bring our visitor speckle camera to Kitt Peak during the monsoon engineering down-time at the end of July (2013) for a form, fit, and function check. Four of us (Genet, Smith, Clark, and Wren) attended the engineering checkout. Genet brought the disassembled camera on the plane with him. Smith assembled the camera and fastened it to the large interface plate. Two Kitt Peak telescope specialists, Mathis and Hensey, then mounted the assembly to the back of the acquisition guider.

Once we were awarded time on the 2.1-meter telescope, we began forming the two observational teams, one for the first half of the run and the other for the second half. This way most of the observers just had to come for four or five nights, although Genet and Smith stayed for the entire run.

Figure 9. Mathis and Genet wire up the speckle camera after it was mounted to the telescope.

Detailed target lists had to be developed. Single reference stars also had to be selected. For our second run in April, Smith developed a semi-automated reference star selection routine. These various lists were then merged into the final target list spreadsheet that was divided into two-hour RA segments. By observing targets in two-hour segments, we were able to make most of our observations within an hour of the meridian at minimal air mass. Finally, Smith developed a target cache for the 2.1-m telescope control computer that allowed us to efficiently move to target coordinates without having to key them in.

Figure 10. Hansey, Weise, and Mathis install our speckle camera on the first Kitt Peak run.

Each observing run began with the mid-morning installation of our camera on the back of the telescope. Cables were connected, computers powered up, and the operation of the system confirmed. The first half of the first night on each run was devoted to focusing the telescope and co-aligning the telescope's acquisition camera with the speckle camera. This was surprisingly difficult on both runs as the field-of-view of the science camera is only a few arc seconds, making both focus and co-alignment difficult. Dave Summers, a highly experienced Kitt Peak telescope operator, not only gave us instructions on operation of the telescope, but helped us achieve focus and co-alignment.

Figure 11. Four undergraduate and one graduate student make the observations in the first run: Plummer, Wallace, Patel, Teiche, and Chaney.

Regular observations then began from the warm room and continued all night, every night, until well past astronomical twilight. One does not lose observing time at Kitt Peak by shutting down early!

Figure 12. First team in the warm room during the second run: (standing) R. Estrada, Ridgely, Genet, (sitting) Clarke, Frey, and C. Estrada.

There were three primary observing positions: the telescope operator (TO), camera operator (CO), and run master (RM). After initialization (and a bit of practice), the three team members were able to work closely together in a highly coordinated fashion to observe a target every four or five minutes.

In a very simplified version of what transpired, the RM chose the next object to observe from the target list and called out the telescope cache ID. The

TO located the target in the cache and made it in the "next to observe" target; then, as soon as the CO finished the integration on the previous target, the TO initiated telescope slewing. On arriving at the target, the TO used the telescope's fine motions to move the star displayed on the acquisition camera's video to the location marked for the science camera. The TO then moved the slider mirror to the position that allowed light to fall through to the science camera, and passed control to the CO (who also had a control paddle). The CO fine-tuned the centering of the target, adjusted the gain and integration time of the EMCCD camera, initiated the exposure, and called out the camera sequence number, which was entered by the RM into the run log.

Figure 13. The telescope operator has four screens, several programs, and numerous switches and analog displays to contend with. C. Estrada quickly became one of the top telescope operators.

Besides the TO, CO, and RM, who were totally occupied in the "production-line," fast-paced observational procedure, sample observations were reduced as an on-going check on the quality of the observations. At any given moment, one or two operators would be in training, or relief observers would be standing by, ready to take up an operating station while several folks headed for the dining room for a coffee break.

5. Reduction

PlateSolve 3 (PS3) is a general purpose program developed for stellar astrometry by one of us (Rowe). Given an image with a sufficient number of stars—but without any information as to plate scale, camera angle, RA, or Dec—PS3 quickly determines the plate scale, camera angle, and the RA and Dec of the image center. Besides this unique plate solving capability, PS3 also has many other capabilities such as viewing FITS headers, subtracting darks and flat fielding, aligning and combining images, lucky image analysis, and the double star speckle interferometry reduction process described below.

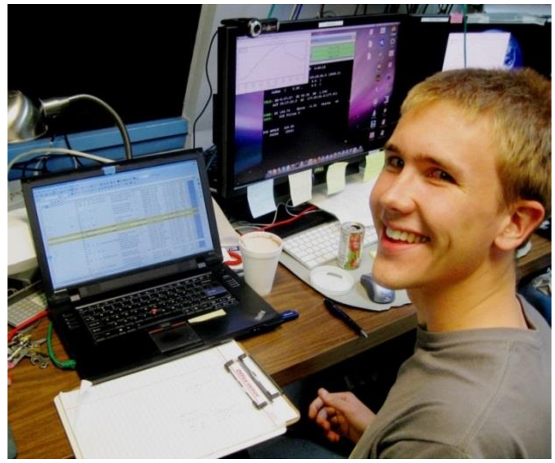

Figure 14. Weise was the primary Run Master for the first team in the October run.

The raw FITS data cubes (from the October run on the 2.1-meter telescope at Kitt Peak National Observatory in October 2013) occupied 1.4 terabytes. PS3 preprocessing of a gigabyte data cube resulted in a single power spectrum image of about 1 megabyte. In this way, the entire data set from the October run pre-processed into about 1.5 gigabytes, allowing transfer via the Internet. Preprocessing consists of taking the Fourier transforms of all of the images in a cube and then obtaining the average of these transforms. Not only does preprocessing produce manageable file sizes, but after preprocessing the computer time required for each reduction is just seconds instead of minutes.

Although preprocessing can take many hours, it only needs to be done once and it runs unattended. On a Windows-7 machine with a 2 GHz processor, it takes approximately 2 minutes to preprocess a FITS cube with 1000 512x512 images. For a long, multi-night run there can be upwards of 1000 data cubes, so preprocessing can take more than 24 hours.

For a run on a specific telescope, the filters, as described below, can often be set once (perhaps after some experimentation) and then left alone for the reduction of an entire run. Proper setting of the two Gaussian filters should optimize the detection and measurement of the double.

Gaussian Lowpass Filter A telescope's optical system is a spatial low pass filter where the low pass cutoff frequency (in pixels) is a function of the wavelength, the f/ratio of the telescope, and the size of the pixels. The Airy disk radius, R, is given by

$$R = 1.22\ \lambda F/D$$

where Lambda is the wavelength and F/D is the focal ratio of optical system. In pixels, this is

$$R(\text{pixels}) = 1.22\ \lambda\ (F/D)/h$$

where h is the pixel dimension.

As an example, take the pixel dimension to be 10 microns, the wavelength to be 0.8 microns, and the focal ratio to be 50. The Airy disk radius will be approximately 5 pixels. The Fourier transform of the Airy disk will have most of its energy within a spatial frequency, fc, given by

$$fc = N/(2R)$$

where N is the size of the image and R is the radius of the Airy disk, all values in pixels.

In the spatial frequency domain, there is very little signal content higher than this frequency. However, at frequencies higher than fc there is considerable noise from the electronics, from the sky background, and from photon shot noise from the object. Therefore, to improve the signal-to-noise ratio and to reduce unwanted interference from the electronics, it is useful to apply a low pass filter with a cutoff proportional to this spatial frequency. Thus, the cutoff frequency, fc (pixel radius), is given by:

$$fc = (hN) / (2.44\ \lambda\ F/D)$$

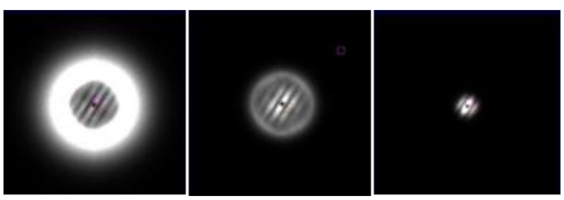

Figure 15. On the left, the Gaussian lowpass filter was set too wide (70 pixels), allowing high frequency noise to be included. On the right, it was set too narrow, cutting off useful information. In the middle it was set just slightly larger than the spatial cutoff frequency imposed by the telescope's aperture.

The purpose of the Gaussian highpass filter is to remove, as much as possible with a simple filter, the broad tail of the point spread function (PSF) that is due to seeing and optics. This filter removes the lowest-frequency information in the image and is typically set between a 2 to 5 pixel radius. It is set empirically to give the best auto-correlation.

The use of deconvolution reference stars not only sharpens the double star image, it also removes much of the telescope's optical aberrations, including the effect of the central obstruction. In addition, if the reference star is taken close in time and located near the double star, deconvolution will remove much of the atmospheric dispersion and broad tail due to the effects of seeing. Deconvolution will help in almost all instances.

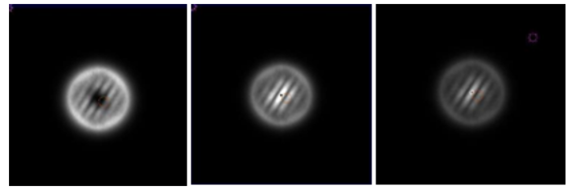

Figure 16. On the left, the Gaussian Highpass filter was set too wide, not only cutting out the bright central peak, but also much of the fringe pattern. On the right, the filter was set too narrow, allowing the bright central peak to shine through. The center is set correctly.

Deconvolution is based on the following mathematical properties: (1) the recorded image of a very short exposure is the convolution of the uncorrupted image of the object with the PSF of the telescope plus the instantaneous atmosphere, and (2) the convolution operation can be implemented by taking the inverse Fourier transform of the product of the Fourier transforms of the uncorrupted image and the point spread function (PSF) of the telescope plus instantaneous atmosphere. Symbolically:

$$F(I) = F(O)\ F(T)$$

Where F( ) denotes the Fourier transform, I is the actual image recorded, O is the "perfect" image of the object, and T is the PSF of the telescope plus instantaneous atmosphere.

Speckle interferometry is based on averaging a large number of very short exposures which "freeze" the atmospheric seeing, allowing us to take the average of the above equation in transform space. If we let $\langle I \rangle$, $\langle O \rangle$, and $\langle T \rangle$ denote the averages of the Fourier transforms of I, O, and T, as defined above, then we can calculate an approximation for the Fourier transform of the object's power spectral density (PSD) as:

$$\langle O \rangle = \langle I \rangle / \langle T \rangle.$$

Taking the inverse Fourier transform of $\langle O \rangle$ yields an approximation to the object's autocorrelation with the telescope and atmosphere removed. This process is called deconvolution.

To perform this operation we need an estimate of $\langle T \rangle$, the autocorrelation of the telescope plus atmosphere. A convenient way to obtain this estimate is to obtain a speckle cube of a nearby single star. The most effective deconvolution will be based on single star speckle observations that are very near the object from the point of view of the atmospheric conditions and telescope pointing. We feel that it is good practice to observe a single reference star that is as near as possible to the double star in both time and space. The reference star must, of course, be bright enough to have a high signal-to-noise ratio after speckle preprocessing.

Although the speckle interferometry tool in PlateSolve 3 can be operated entirely by way of user GUI inputs, a semi-automatic reduction option using a comma-separated variable (.csv) file speeds up the reduction process. The csv file allows PS3 to automatically load each double star file as well as the corresponding single star file. With hundreds of targets and corresponding reference stars to process, looking up individual files can be tedious.

An added benefit of this mode of reduction is that, based on information contained in the csv file on the "expected" position angle and separation of the two stars (from last observed catalog values or calculated values), PS3 places a red circle at the "expected" solution location. This allows the 180° ambiguity inherent in autocorrelograms to be resolved. It also gives immediate visual feedback on how close the automated PS3 solution is to the "predicted" position. If the automated PS3 solution is not the best solution, one can intervene and provide a more appropriate manual solution

The reduction autocorellogram is the "picture worth a thousand words." The primary star is always at the exact center. The secondary star is displayed as two fainter images exactly 180° apart. If semi-automatic reduction is employed, as it was for the double shown in the figure below, then a "predicted" position will be indicated with a circle (in this case offset from the lower secondary at the 5 o'clock position toward the bottom). The large circle around the lower secondary is the object aperture. It should encompass all or most of the secondary's image. Once satisfied with the solution, the "set target location" option can be clicked if manual, and the circle with the X and eight short radials will appear. If this is an automatic solution, the X circle will automatically appear.

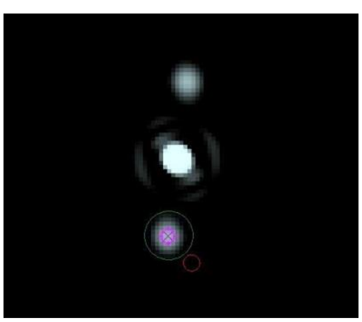

Figure 17. Autocorellogram of a typical "easy" solution.

6. Sample Results

The first published results from our Kitt Peak runs were by two student teams at Cuesta College. The teams consisted primarily of advanced-placement students from Arroyo Grande High School who were taking ASTR 299, Astronomy Research Seminar, at Cuesta College on the side (Genet, Johnson, and Wallen 2010). The first team's paper was on WDS 01078+0425 BU 1292 (Adam *et al.*, 2014a). They chose this binary because all past observations were visual (micrometer) and they would be publishing the first speckle observation.

Figure 18. The six high school students on the BU 1292 team.

The student team reduced the data with Florent Losse's REDUC, as the PS3 speckle tool was still in development. They reduced data for five well-observed binaries for calibration purposes, and then reduced the first ever speckle observation (made for them during our first Kitt Peak run just a week earlier). Their "calculated" point (the Kitt Peak observation) was added to a plot of previous observations, as was the predicted position based on interpolations of the ephemerides for the night of observation. Their analysis suggested that the published orbit of 285.3 years was off by about 3.2 years and was closer to 282.1 years.

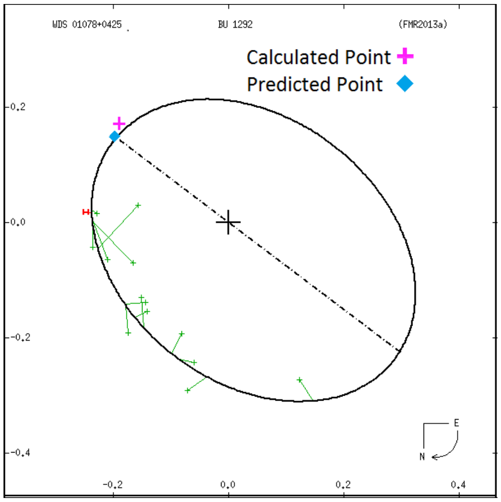

Figure 19. High school student observation of BU 1292.

The second team chose a binary where three recent speckle observations had significantly departed from the predicted orbital path (Adam *et al.*, 2014b). They wanted to see if the speckle observation made at Kitt Peak continued this departure or returned to the predicted path. As can be seen from their plotted observation, the departure continued.

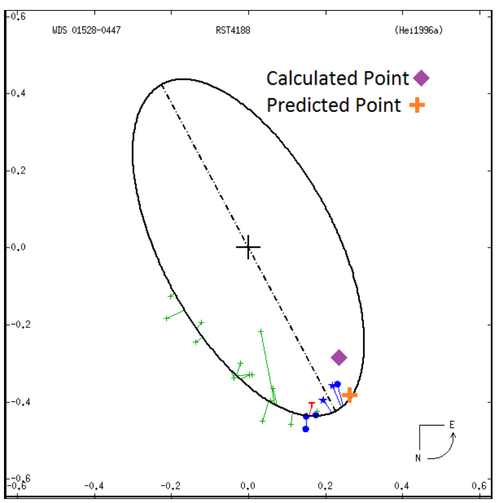

Figure 20. Plot of observations of WDS 01528-0447

We are still in the process of reducing and analyzing the observations from the second Kitt Peak run. While most of our observations reduced well, some were too close to obtain a good solution (usually well under 0.1 arc seconds). Many of the solutions were easy, however, and the semi-automatic feature of PS3 immediately gave good solutions without any human intervention.

An example of an "easy" solution is WDS 14492+1013, A2983. This known binary has 67 reported past observations, has magnitudes of 9.36 and 9.27, with a reported K2V spectral type. We used HIP 68708 as our reference deconvolution single star (magnitude 6.70, K0).

With a camera angle of 0.28° and pixel scale of 83.68 pixels/arcsecond (our preliminary calibration values), our reduction with PS3 yielded a position angle, θ, of 318.59°, and a separation, ρ, of 0.180″. With a period of only 10 years, this is a rapidly moving binary. Its last reported position angle, θ, in 2009 was 214°. A simple linear interpolation from the annual January 0 ephemerides in the *Sixth Catalog of Orbits of Visual Binary Stars* to the night of observation yielded θ of 318.96° and ρ of 0.175″, reasonably similar to our observed values.

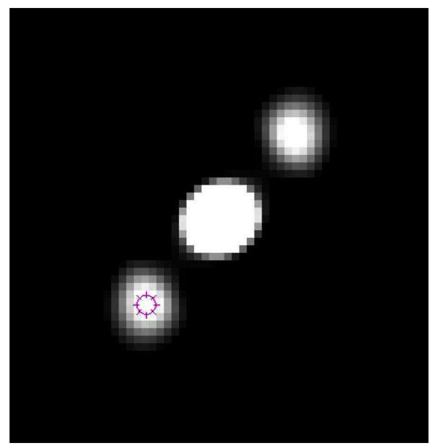

Figure 21. PS3 autocorellogram of WDS 14492+1013 A 2983. The autocorellogram has been magnified so that the individual pixels can be seen, each which is only slightly more than 0.01 arc second square.

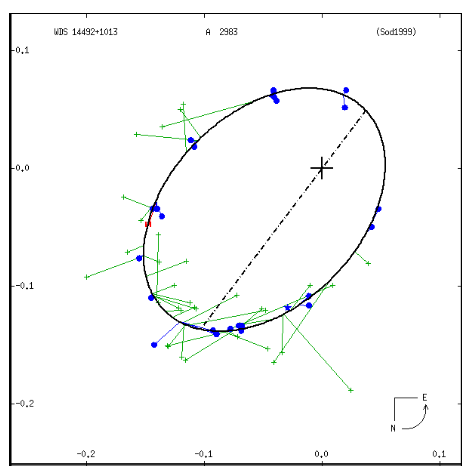

Figure 22. Plot of the past observations of WDS 14492+1013.

As can be seen from the plot of past observations, the visual observers with their micrometer observations were significantly challenged, while this was an easy binary for speckle interferometry on larger telescopes.

7. McMath-Pierce 1.6-meter Experiment

One of the challenges faced with the 1.6 meter McMath-Pierce solar telescope was acquiring double stars with our very narrow field-of-view science camera. The 1.6-meter telescope projects an image of the sun that is approximately 76 cm in diameter at an image scale of 2.36 arc seconds per mm. Our challenge was centering a double star on the Andor Luca-S EMCCD science camera with its 658 x 496 pixels of 10 μm, resulting in a chip that is only 6.58 x 4.96 mm in size. We ran a series of tests to determine how accurately the McMath-Pierce 1.6 meter can acquire and re-acquire a target (Harshaw *et al.*, in prep.).

We found that this telescope is precise for its size and intended solar use. Our experiment consisted of placing a target reticule (a “cross hair” drawn on a foam core circle with a felt tip marker) on the telescope’s north port and observing target acquisition through a low-light-level security camera.

Figure 23. Branston places the reticule on the observing table (Branston, P. Boyce, Harshaw, and Wiley)

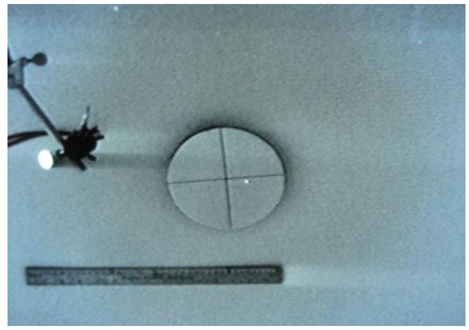

Figure 24. The reticule experiment on the 1.6-meter McMath-Pierce telescope.

Figure 24 shows the first star, Sirius, in the slewing tests at 3 o’clock. The 1.6 meter placed Sirius within 1 arc minute of the reticule. Once Sirius was centered, a command was given to the telescope’s control computer to “zero” the encoders on Sirius and the slew tests began. Slews were made to Procyon, Pollux, Arcturus, Spica, and back to Sirius. In each case, the 1.6 meter placed the target star within 2 arcminutes of the reticule (and in most cases, much less than that). Also at each target star, slews to the north and south (of 10° and 2°) were made to test the hysteresis in heliostat’s drive system. In all cases, the 1.6 meter returned to the target star with errors of less than 30 arcseconds. This convinced the team that the 1.6 meter can acquire speckle targets. A second series of tests is being planned for late May 2014 that should let us build a telescope pointing model that could be used for speckle acquisitions.

8. McMath-Pierce 0.8-meter Observations

In addition to the main 1.6-meter solar telescope, the McMath-Pierce array includes a 0.8-meter “East” telescope consisting of a 0.91-meter heliostat, a 1.07-meter spherical primary, and a 0.61-meter secondary, yielding an effective aperture of 0.81-meters. Focal length is about 40.4 meters and the system works at f/50. The spherical primary is diffraction-limited at this f-ratio. With this instrument, the light is directed to an optical bench equipped with a flat that projects the light horizontally along an optical bench on which our speckle interferometry components were mounted (Fig. 25). Our components included a 25mm 68° Plossl eyepiece for rough acquisition, a wide-field acquisition camera (red Atik on the left) for finer acquisition, then on to the science camera by way of a flip mirror.

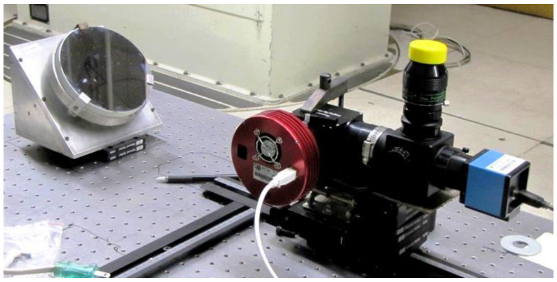

Figure 25. Speckle interferometry camera on the 0.8-meter telescope's optical bench.

A team consisting of P. Boyce, Harshaw, Jones, Wiley, and Branston spent five nights experimenting with different component configurations to evaluate the use of the 0.8-meter telescope for speckle imaging. The telescope is certainly useful for capturing speckle images (Fig. 26). We plan, in the future, to further evaluate the telescope's pointing accuracy, configure the optical system so that the acquisition camera will have a wider field-of-view, and develop software that will compensate for field rotation (Wiley *et al.*, in prep.).

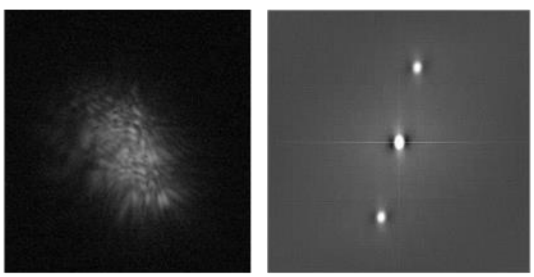

Fig. 26. STF1670AB (Porrima). Left: a single speckle frame. Right: Corellogram of 1,000 frames.

9. Coude Feed Spectroscopy

Besides obtaining over a half-million speckle images during our April run, we also obtained a few differential radial velocities of short-arc binaries on the auxiliary 0.8-meter Coude feed, which is part of the 2.1-meter telescope complex (housed in the same building). As the Coude feed telescope is independent of the 2.1-meter telescope, observations can be made on both telescopes simultaneously, which we did during the last three nights of our run. Green planned and made the spectroscopic observations.

Figure 27. Green and Kenney at the light entrance to the Coude feed.

Figure 28. Kenney and Genet in the spectrograph room below the 2.1-meter telescope

10. Conclusion

Our portable speckle system with its EMCCD camera as the sensor reliably observed close binaries on a 2.1-m telescope with separations down to 0.1 arc seconds. We found that using nearby, fairly bright single stars for deconvolution usually provided much better results than reductions without a reference star. Efficient operation required a telescope operator, camera operator, and run master, although additional observers were useful for quick-look reduction, relief operation, etc. Preprocessing the data with PlateSove 3 and using its semi-automatic feature greatly speeded up the data reduction.

11. Acknowledgements

Although they were unable to attend the Kitt Peak runs in person, William Hartkopf and Brian Mason at the U.S. Naval Observatory were instrumental in shaping the observing programs and preparing both proposals. Extensive use was made of the *Washington Double Star Catalog*, the *Sixth*

Catalog of Orbits of Visual Binary Stars, and the *Fourth Catalog of Inteferometric Measurements of Binary Stars,* catalogs maintained by Brian Mason and William Hartkopf at the U.S. Naval Observatory.

. Richard Joyce and Di Harmer provided extensive technical advice on the use of the 2.1-meter telescope. Hillary Mathis and Brent Hansey installed our camera during a one-evening mid-summer pre-run engineering checkout, as well as installing our camera on both the October and April runs. Dave Summers assisted with telescope operation on all of the runs. Daryl Willmarth set up the 0.8-m Coude feed spectrograph for us and provided instruction on its use. Ballina Cancio cheerfully handled dorm rooms, payment, and many logistical details for our unusually large number of participants. Lori Allen, Kitt Peak's Director, visited us during our October run and was encouraging with respect to our many student observers. Education and outreach are important to Kitt Peak.

We are also thankful for the generous and comprehensive support provided by the staff of the National Solar Observatory. Mathew Penn assisted in all phases of our run, while Mark Giampapa provided overall guidance. Ronald Oliversen, NASA Goddard Space Flight Center, generously shared some of his time on the McMath-Pierce 1.6-meter telescope with us and provided considerable help.

NASA, through the American Astronomical Society's Small Research Grant Program, funded the Orion Observatory's Luca-S camera, which was the backup camera for both runs. Andor Technologies loaned us a larger-format Luca-R camera for both runs.

Concordia University funded time on the Coude spectrograph in conjunction with a W. M. Keck Foundation astronomical grant.

Olga Kiyaeva at the Pulkovo Astronomical Observatory, as well as Francisco Rica in Spain, kindly supplied short-arc binary candidates. Olga Malkov at Moscow State University suggested targets that needed orbital refinement.

Joseph Carro assisted in formulating the target list for the known binaries. The *Journal of Astronomical Instrumentation* supplied our equipment block diagram. The Society for Astronomical Sciences provided an initial forum at their annual symposium for many of the ideas fleshed out in this paper (Genet *et al.,* 2013). We thank Vera Wallen for reviewing this paper prior to submission, and Robert Buchheim for formatting the paper.

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