

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.

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 remain 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).

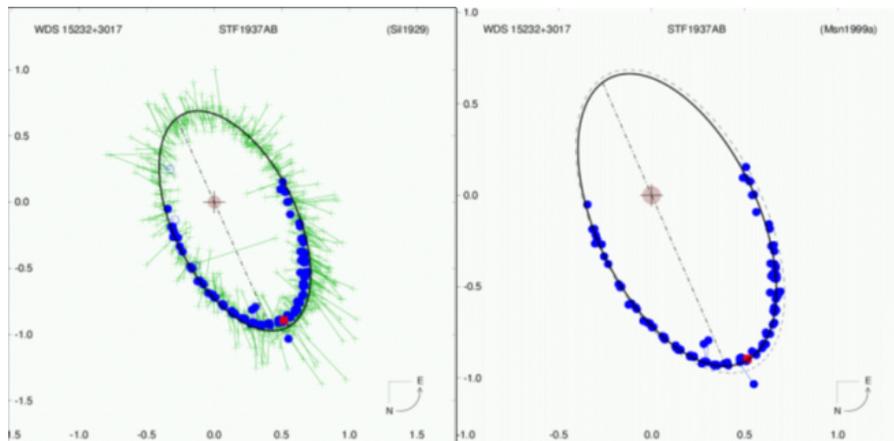


Figure 1. Close binary orbit of η Cor Bor with and without visual micrometer (green X) observations. Speckle observations are blue dots.

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 Cor Bor provided by William Hartkopf (Figure 1), 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 (Figure 2).

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 (Figures 3, 4).



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

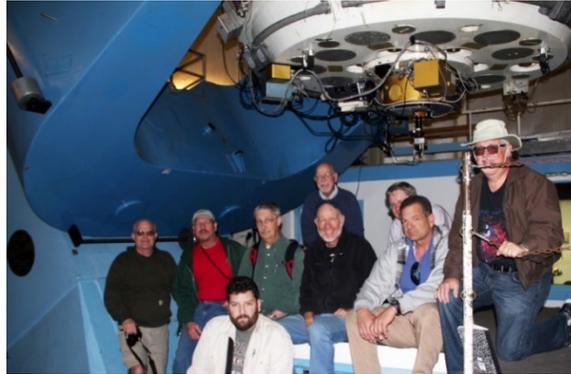


Figure 4. Nine of the 20 observers on the April 2014 run: Jones, Smith, C. Estrada (front), Green, Genet, Wiley (rear), Clark, R. Estrada, and Harshaw.

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 Interferometric 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 Kiyayeva *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 Interferometric 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 Interferometric Measurements of Binary Stars*).

Unconfirmed double star candidates

- (10) Hipparcos unconfirmed doubles, now some 1874 in number (Figure 5). 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.

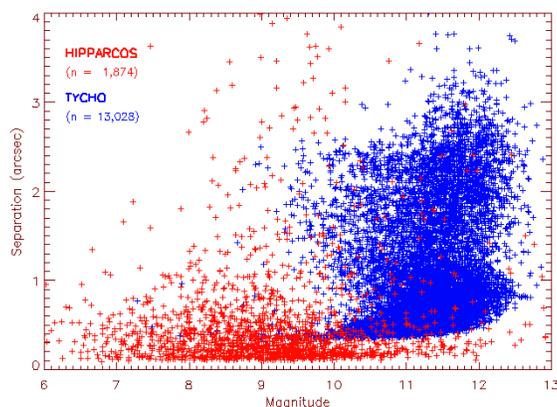


Figure 5. Plot of unconfirmed Hipparcos and Tycho doubles.

- (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 Kiyaveva (Russia), Francisco Rica (Spain), Henry Zirm (Germany), and Todd Henry (US).

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.

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 in Figure 6).

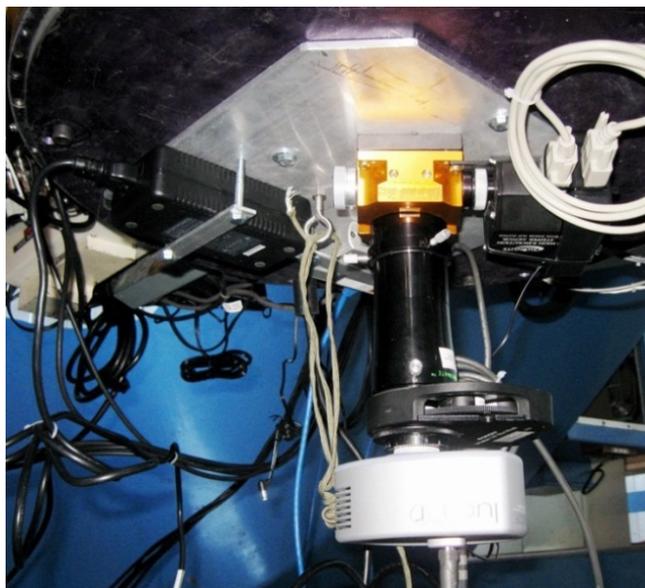


Figure 6. Our speckle interferometry system installed at the Cassegrain focus of the 2.1-meter telescope.

Observations

Preparing for and making observations at a large telescope with sizeable teams is a major technical, organizational, and logistical undertaking (see Figure 7). 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" Kitt 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.

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.

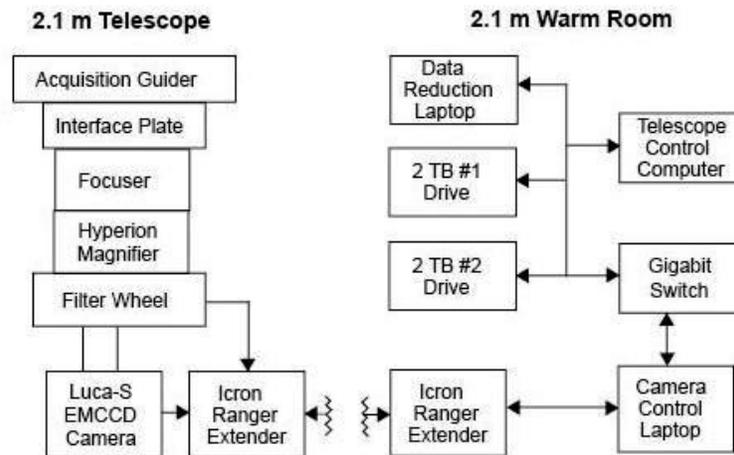


Figure 7. The original speckle system block diagram.

With many specifics of the science research programs and equipment engineering details worked out, our proposal for the second semester of the 2013-14 academic year 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.

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 (Figure 9, 10).

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.

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.

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.

Regular observations then began from the warm room and continued all night, every night, until well past astronomical twilight (Figure 8, 9). One does not lose observing time at Kitt Peak by shutting down early!



Figure 8. Four undergraduate and one graduate student make the observations in the first run: Plummer, Wallace, Patel, Teiche, and Chaney.



Figure 9. 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 (Figure 10).

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 10. 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.

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 PlateSolve 3 and using its semi-automatic feature greatly speeded up the data reduction.

Acknowledgments

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 Interferometric 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. 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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