Speckle Interferometry of Close Visual Binaries

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Abstract Speckle interferometry circumvents atmospheric seeing limitations, facilitating astrometric observations of visual binaries with small separations. Some of these closely-spaced binaries have short periods, allowing complete orbits to be obtained in just a few years. Speckle observations of close visual binaries have been made by an eclectic group of student, amateur, and professional astronomers with an EMCCD camera on two smaller telescopes and then on both 2.1- and 0.8-meter telescopes at Kitt Peak National Observatory. Advanced technologies to increase the reach of speckle interferometry are also being pursued by this group, which includes a number of engineering faculty and students. These technological advances include full automation to increase the quantity of observations in an economical manner, and masks adapted from exoplanet imaging to disperse the bright primary starlight away from "discovery zones" so that faint secondary stars can be detected. Consideration is being given to the development of a large, four-meter-class, dedicated automatic sparse-aperture telescope for high spatial-resolution speckle interferometry. This sparse-aperture telescope may only cost about one-hundredth the cost of an equivalent filled-aperture telescope.

Close Visual Binaries and Speckle Interferometry

Astrometric orbits can be used to establish the "dynamical mass" (the sum of the two individual stellar masses) of a binary if the distance to the binary is also known. Knowing this distance allows an angular separation—the semi-major axis of the elliptical orbit—to be translated into an actual physical separation. Kepler's Third Law can then be applied to determine the dynamical mass sum.

However, what is needed to develop and refine stellar evolutionary models is the individual component masses, not the combined dynamical mass. Astrometric orbits, when combined with radial velocity curves, allow the summed dynamical mass to be parsed into individual stellar masses. Most of the visual binaries' orbits established prior to 1980 had periods of many decades or even centuries. Thus there was little overlap between these astrometric binaries, with their long periods and slow movements, and the radial velocity curves of spectroscopic binaries, with their short periods and high velocities.

What was needed were more astrometric orbits of shorter-period, faster-moving binaries so that spectroscopic radial velocity curves would be available for the same binaries to provide complete, individual-mass solutions. Unfortunately, most such short-period binaries have angular separations that are less than the seeing disk. With normal imaging, atmospheric jitter causes these binaries to jump about at high speed, hopelessly smearing images of binaries with separations below the typical seeing limit of about one arc second or more. This causes them to appear as a single star.

In 1970, Anton Labeyrie, a French astronomer, beat the seeing limit by taking hundreds of very short-exposure images of close double stars with a high-speed film camera (Labeyrie 1970). Each exposure contained many distinct binary star images randomly superimposed on each other. Although atmospheric jitter caused the images to radically change from one exposure to the next, Labeyrie found that as long as both stars were within the "isoplanatic patch" (which typically has a diameter of about five arc seconds), their jitter was correlated. By taking the Fourier transform of each image and processing many images in Fourier space, the most frequent position angles and separations in the images became apparent.

These were, of course, the position angles and separations of the double star being observed, although there was an inherent 180° ambiguity in the position angle. By the end of the 1970s, Harold McAlister and his associates were making high speed film camera observations of very close binaries on the 2.1- and 4.0-meter telescopes at Kitt Peak National Observatory (McAlister 1985). They obtained, for the first time, astrometric orbits on many spectroscopic binaries with existing radial veracity curves, thus yielding individual stellar masses for those all too few binaries that also had known distances. High-speed Tri-X film was not an easy medium to use, however. With the advent of early microcomputers and intensified CCD (ICCD) cameras, observations were made from the warm room at the 4-meter telescope instead of the Cassegrain cage as shown in Figure 1.

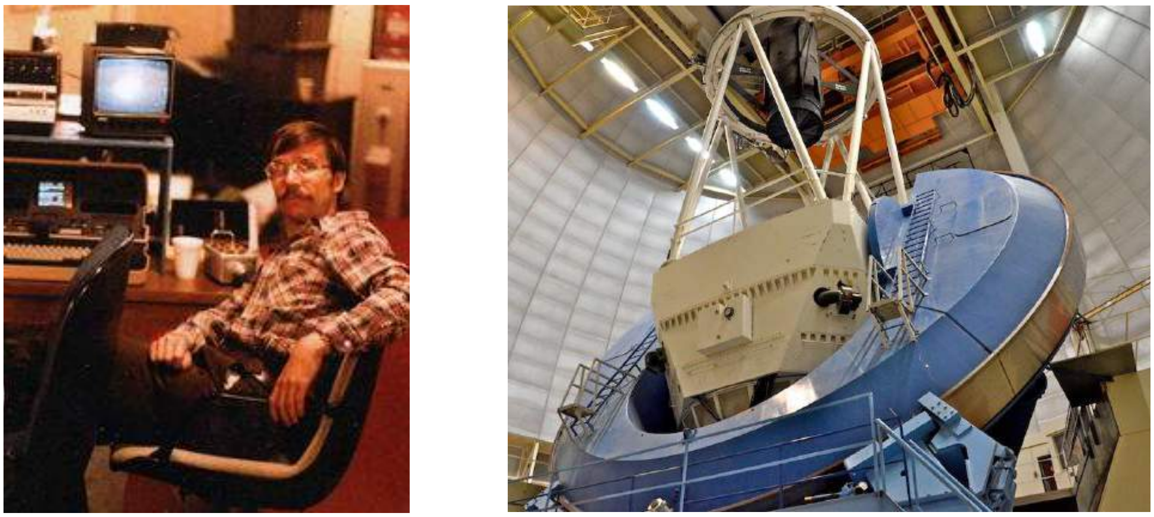

Figure 1. A young William Hartkopf (left) captures high-speed frames with an early Osborn portable computer from an intensified CCD (ICCD) camera located at the Cassegrain focus of the 4-meter telescope at Kitt Peak National Observatory (right). Similar observations were also made on the 2.1-meter telescope at Kitt Peak.

The European Space Agency launched the Hipparcos astrometric satellite in 1989 (Figure 2). At the time of its launch, the most capable computers on the planet did not have sufficient computational power to analyze the expected data. Trusting Moore's Law, they had the requisite capability when it came time, a few years later, to reduce and analyze their data (Perryman 2010).

Hipparcos provided accurate distances of about 100,000 stars, most for the first time. Binaries with astrometric (angular separation) orbits based on observations patiently built up over the decades and centuries, but previously at unknown distances, immediately became more valuable since the known distances finally allowed dynamical masses to be calculated. Hipparcos discovered large numbers of new binaries, suspected binaries, and close double stars, a rich source we are still actively mining decades later (Perryman 2012).

When, in the near future, the results from the European Space Agency's latest astrometric telescope, Gaia (Figure 3), become available, we will know the distances to many additional binaries. Furthermore, the already known distances to binaries will be refined by about a factor of ten (Eyer et al. 2013). Since distance uncertainty is often the major error source, recomputation of dynamical masses will significantly improve their accuracy. Not only will Gaia provide accurate distances, but, similar to Hipparcos, Gaia should discover a large number of binaries, suspected binaries, and close double stars. We may find this rich source of close binaries difficult to effectively follow up on unless we significantly improve our ability to obtain astrometric orbits of a large number of close visual binaries.

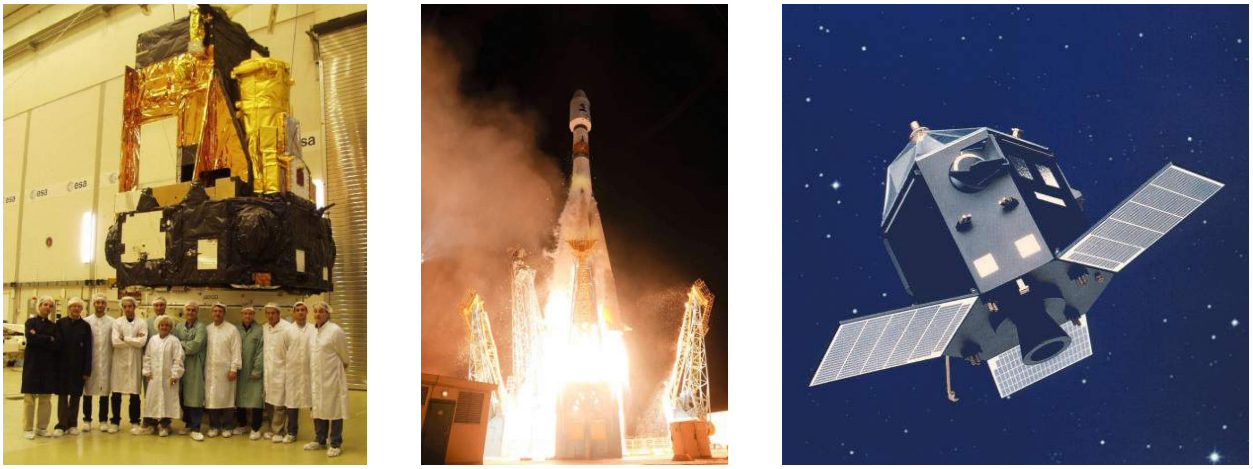

Figure 2. The European Space Agency's Hipparcos astrometric satellite.

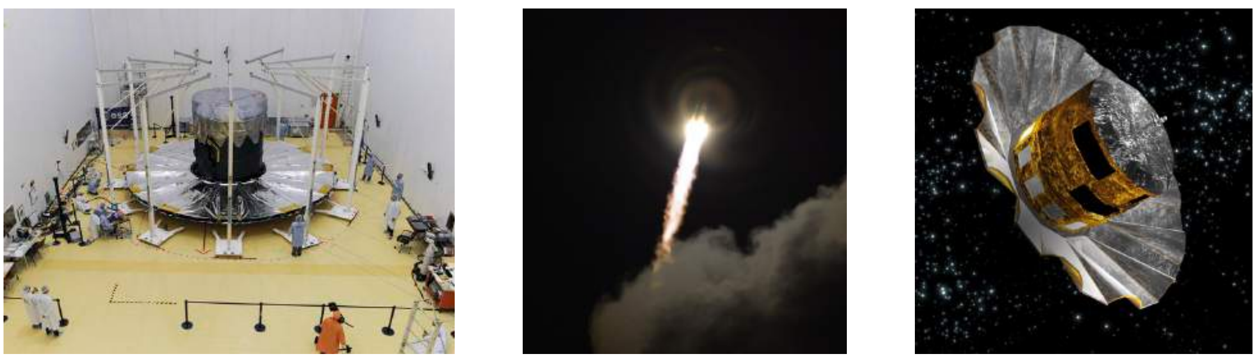

Figure 3. The European Space Agency's Gaia astrometric satellite.

Amateurs and Students Carry On with Wide Visual Binaries

With professional astronomers concentrating on speckle interferometry observations of close visual binary stars, continuing the observations of wide visual binaries (and other double stars) fell on the shoulders of amateur and student astronomers (Argyle 2012). Many amateurs and students have used an astrometric eyepiece with a ruler and protractor etched into a reticle to observe wide, bright double stars (Genet et al. 2010), while others have used CCD cameras to reach fainter magnitudes and somewhat closer separations.

An astrometric eyepiece is a self-contained, easy-to-use astronomical instrument that costs less than $200 USD (Figure 4). These eyepieces have been used by well over 100 students in an Astronomy Research Seminar offered by Cuesta College every fall for the past eight years and a summer-camp version of the seminar at the University of Oregon's Pine Mountain Observatory. The student teams' observations ended up as published papers, including over two dozen papers published in the *Journal of Double Star Observations*.

Recently, Cuesta College's Astronomy Research Seminar was expanded as a hybrid online/in-person course that included 38 students from 10 different schools. The overall seminar instructor, Genet, was aided by 14 assistant instructors (primarily local high school science teachers) and a number of advanced amateur astronomers and other professional astronomers. Most of the students were high school students, taking the seminar as their first college course. One team observed double stars with an astrometric eyepiece, while most of the others used CCD cameras—some in person and others remotely at robotic observatories (Figure 5). Although most of the teams observed wider double stars, two teams were involved with speckle interferometry observations of close double stars.

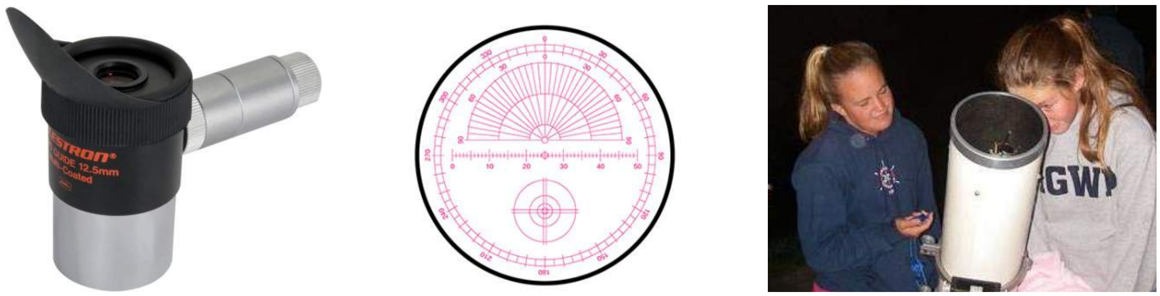

Figure 4. Astrometric eyepieces with a laser-etched reticle were used by Arroyo Grande High School students taking Cuesta College's Astronomy Research Seminar.

Figure 5. Cadet teams at the Army and Navy Academy in Carlsbad, California, made remote observations using iTelescope's network of robotic telescopes (left). A student team in Pearl City, Hawaii, used a CCD camera on the 0.5-meter telescope at Leeward Community College for their observations (right).

Speckle Interferometry Moves to Smaller Telescopes

Florent Losse, an amateur astronomer in France, was a key pioneer of small-telescope speckle interferometry (Figure 6, left). Because he did not have access to an intensified CCD (ICCD) camera or an electron multiplying CCD (EMCCD) camera, the read noise on regular CCD cameras would have been very high at fast readout speeds. Thus Florent patiently took the time for slow readouts, one frame at a time for hundreds of frames on each double star.

Losse's speckle observations of close visual binaries began appearing in the 6th Orbit Catalog, and were right in line with speckle observations made by professional astronomers with larger telescopes. Florent also extended his user-friendly, well-documented double star reduction software, REDUC, to include speckle interferometry, paving the way for other amateur astronomers to also make speckle interferometry observations of close binaries on their telescopes.

Several years ago, Genet and one of his Cuesta College students, Jo Johnson, joined Brian Mason for a night during one of Mason's speckle interferometry runs on the 4-meter telescope at Kitt Peak National Observatory (Figure 6, right). Genet wanted to see, in person, how speckle interferometry observations were made by professional astronomers on large telescopes. The U.S. Naval Observatory has two identical, intensified CCD (ICCD)-based speckle cameras. One is permanently mounted on their 26-inch refractor in Washington, while the other is used for "off campus" observing runs at various telescopes such as the 4-meter telescopes at Kitt Peak National Observatory and Cerro Tololo Interamerican Observatory. Although sizeable, the speckle camera system and supporting electronics and computer fit within a check-in bag so they can be flown to observing sessions.

Figure 6. Florent Losse and his 0.4-meter telescope (left). Genet, Mason, and Johnson in the Casseigrain cage of the 4-meter telescope at Kitt Peak National Observatory with USNO's ICCD camera (right).

Some time ago, a number of companies began manufacturing electron-multiplying CCD (EMCCD) cameras using back-illuminated CCD chips made by e2v. These cameras were quite expensive (typically $40,000 USD), large, and heavy, and they required a fairly short cable to connect them to a PC plug-in card. They were not small-telescope-friendly cameras! However, Andor Technologies eventually began making a much smaller, lower cost ($14,000 USD) EMCCD camera based on a front-illuminated chip made by Texas Instruments. These "Luca" cameras were USB-based, and were compact enough to be easily mounted on smaller telescopes. Genet acquired one of these cameras, thanks to a grant from the American Astronomical Society and a sizeable discount from Andor Technologies, and made it the heart of a portable speckle interferometry camera system (Genet 2013).

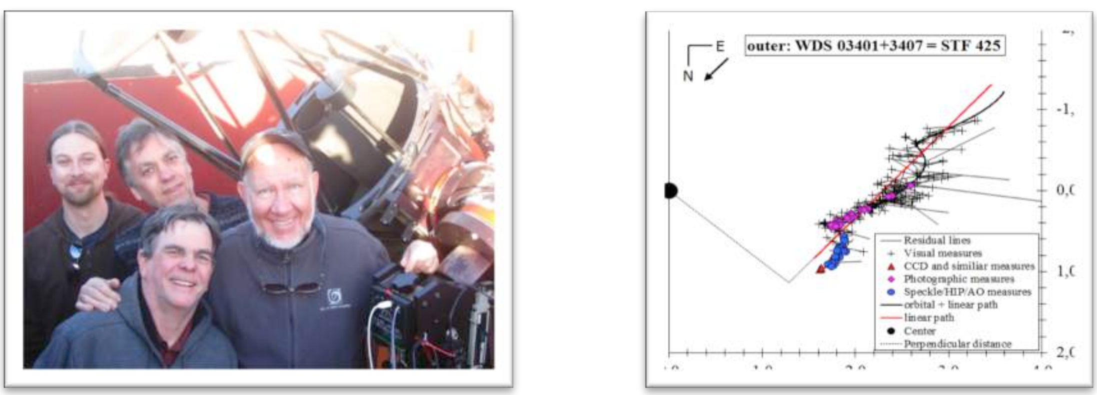

Figure 7. Joe Roberts, Dan Gray, Dave Rowe, and Russ Genet with the PlaneWave Instruments CDK-20 telescope at the Pinto Valley Observatory (left). New triple star discovered during their observing run at the Pinto Valley Observatory (right).

David Rowe (Figure 7) kindly offered the use of his PlaneWave Instruments 0.5-meter Corrected Dall-Kirkham (CDK) telescope at his Pinto Valley Observatory in the Mojave Desert Reserve for the first speckle interferometry run using this portable speckle camera system. Although the first two nights of the run were engineering evaluations of various sorts, speckle interferometry of close double stars began in earnest on the last night. Some 42 doubles (including two new triple stars discovered during subsequent analysis) were observed before solar power for this remote observatory ran out at midnight. This observing run and its results are described in "Two New Triple Star Systems with Detectable Inner Orbital Motions and Speckle Interferometry of 40 Other Double Stars" (Genet et al. 2015a). A few months later, other observers joined in for second and then third speckle observing runs on the 0.5-meter telescope at the Pinto Valley Observatory (Figure 8).

Figure 8. Eric Weise installs speckle interferometry camera on the CDK-20 telescope at the Pinto Valley Observatory (left). The eight observers on the third Pinto Valley Observatory run (right).

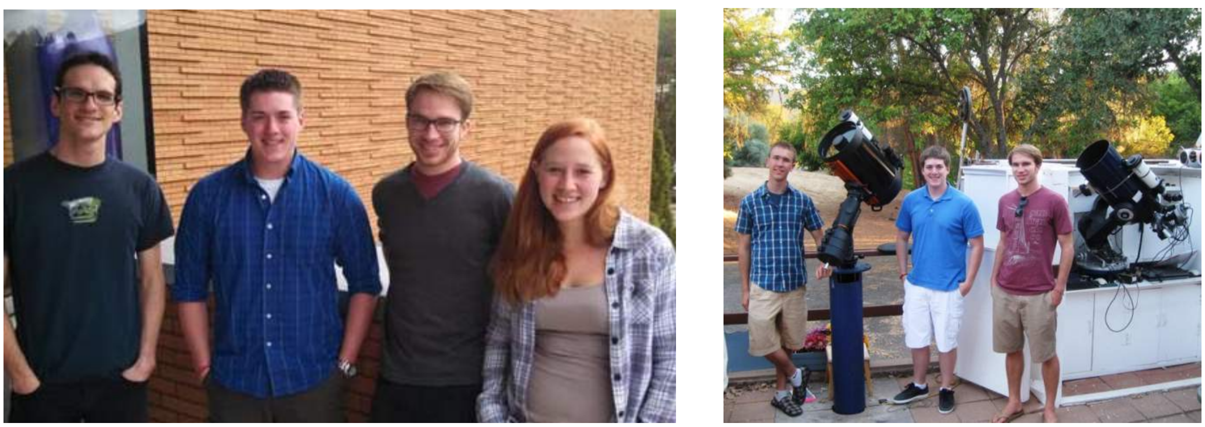

Figure 9. Cal Poly student observers Jason Goad, Cameron Allen, Ryan Morshead, and Katilin McArdle (left). Eric Weise, Cameron Allen, and Ryan Morshead with two of the telescopes at the Orion Observatory (right). The Cal Poly students used the 10-inch telescope on the right for their observations.

Speckle observations were also made at the Orion Observatory, Genet's private observatory near Santa Margarita Lake that is often used by students from California Polytechnic State University, Cuesta College, and local high schools for their research projects (Figure 9). An example of such a project is "Research of Double Stars with Speckle Interferometry" (Allen et al. 2015).

Another example of speckle interferometry at the Orion Observatory was the observations of ten close double stars by two visiting astronomers from Shanghai Astronomical Observatory, Yuanyuan Ding and Chaoyan Wang, along with Weise and Genet (Figure 10). Calibration of the pixel scale was made with a slit mask with uniformly spaced slits. Half of a focus mask was used for these observations, with the other half masked off. This form of calibration is similar to the famous Young "double slit" experiment (Weise et al. 2015).

There are over 2000 binaries with published orbits and accompanying plots. Some of the plots show observations falling almost exactly on the published orbit like a "string of pearls," while others show that recent observations have deviated from the previously published orbit, suggesting the orbit may need revision at some point. Recent observations of some binaries suggest that the published orbits are way off, i.e. "bad orbits." To aid observers in selecting binaries to observe, Weise and Genet (2015) developed a binary orbit classification scheme.

Figure 10. Eric Weise, Chaoyan Wang, Yuanyuan Ding, and Russ Genet (left). They made speckle interferometry observations of double stars with the 0.25-meter telescope at the Orion Observatory. The slit mask used for pixel scale calibration (right).

Speckle Interferometry Observations at Kitt Peak

Elliott Horch, an astronomer at Southern Connecticut State University, kindly invited Genet to join him on a two-night run on the 3.5-meter WIYN telescope at Kitt Peak National Observatory. Elliott's two-channel speckle interferometry camera, shown in Figure 11, is arguably the most advanced of all cameras (Horch 2012). A dichroic splits the beam into R- and I-band wavelengths with the speckles imaged on two high-end Andor EMCCD iXon cameras. Because the special cables to the plug-in PC cards had to be kept short, a PC was fastened to the bottom of the speckle camera. Two instances of the Andor Solis camera control screens can be seen on Genet's PC in Figure 11.

Figure 11. Elliott Horch and his speckle camera on the 3.5-meter WIYN telescope. One of the Andor EMCCD cameras can be seen. The other is out of view on the other side. The black PC can be seen fastened to the bottom of the system (left). Russ Genet operates the two cameras from the warm room while Elliott operates the log (right).

The 3.5-meter WIYN telescope is somewhat complex to operate as it requires controlling the shape of the primary mirror. The many actuators which control the shape of the mirror can be seen in Figure 12 (left). Dave Summers, one of the most experienced telescope operators on the mountain, operated the telescope for Elliott and Genet (Figure 12, right).

During a break, Genet stopped by the 2.1 meter telescope to visit Catherine Pilachowski (Figure 13). Pilachowski and a graduate student were using the Phoenix near-infrared spectrograph, which can be seen on the bottom of the telescope in Figure 13. It was clear that this would be a good telescope to use for speckle interferometry. During the day Genet also visited Matthew Penn at the McMath-Pierce solar telescope facility, as one of these three telescopes might be usable for nighttime speckle observations.

Figure 12. The many actuators on the back of the 3.5-meter WIYN telescope (left). Dave Summers controls the telescope (right).

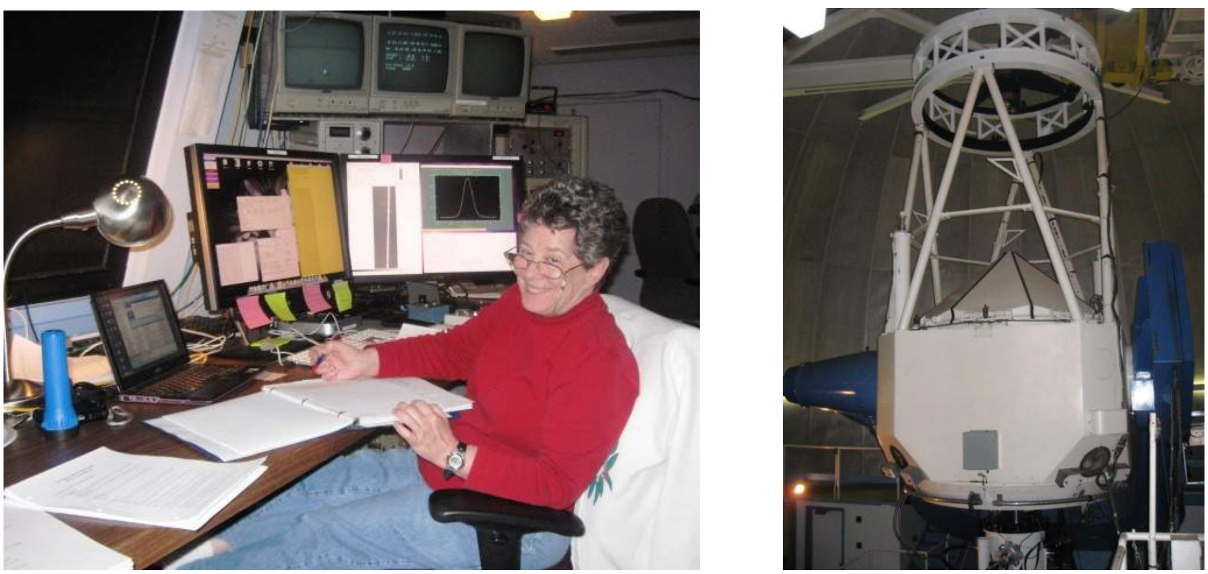

Figure 13. Catherine Pilachowski in the warm room of the 2.1-meter telescope controlling (left) the near-infrared spectrograph on the bottom of the telescope (right).

A spring visit was made to the National Optical Astronomy Observatory's headquarters in Tucson to discuss possible speckle observations on the 2.1-m telescope. Richard Joyce kindly pulled out drawings of the telescope and suggested how a speckle camera might be interfaced to the 2.1-meter telescope in terms of physical mounting, cabling, and software.

It was decided that the telescope's acquisition/guider unit should be left in place and an aluminum interface plate should go between Genet's small, portable speckle camera and the large, almost two-foot diameter opening at the bottom of the acquisition/guider unit. Heather Mathis located, in a remote corner of the 2.1-meter dome, an instrument interface plate that had not been used for many years, and it was adopted as the interface.

To make sure that everything worked properly, a single night of engineering checkout time was made available at the end of July 2013 (Genet et al. 2015c). The engineering checkout team consisted of Genet, Tom Smith, Kent Clark, and Paul Wren. When they arrived, Mathis had already removed the massive Phoenix spectrograph and was adding the lead counterweights needed to compensate for the lightweight speckle camera. Smith mounted the EMCCD camera to the interface plate, and the team connected up the cables (Figure 14).

Figure 14. Mathis installed counterweights (left), Smith fastened the EMCCD camera to the interface plate (center), and Mathis and Genet fastened down the cables (right).

Dave Summers trained the team on opening and closing the observatory, operating the telescope, loading up the telescope computer's cache with a target list, etc. (Figure 15). The 2.1-meter is a complex system, with a thick manual that describes its operation.

Figure 15. Genet at the telescope operator's station (left). Crew in the warm room: (left to right) Dave Summers, Kent Clark, Tom Smith, and Paul Wren.

Knowing that the speckle interferometry camera would work on the telescope, a proposal was prepared and submitted which requested seven nights for observations preceded by one night of engineering checkout. Obtaining time on the telescopes at Kitt Peak National Observatory is very competitive, and the team was fortunate to be awarded the eight nights.

As it would have been difficult for students and others to stay for the entire eight-night run, the run was split into "A" and "B" teams, with a smaller "weekend" team sandwiched in between. Genet stayed for the entire run, as did Smith. Joining Genet and Smith from the A Team were: Mark Trueblood, Winer Observatory; Eric Weise, Univ. of Calif., San Diego; Alex Teiche, California Polytechnic State University; Dan Wallace, Univ. of North Dakota; Josh Plummer, Univ. of South Alabama; and Kent Clark, Univ. of South Alabama.

The Weekend Team consisted of John Kenny, Kayla Chaney, and Rikita Patel, all from Concordia University, Irvine. The B Team consisted of Paul Wren (in addition to Genet and Smith).

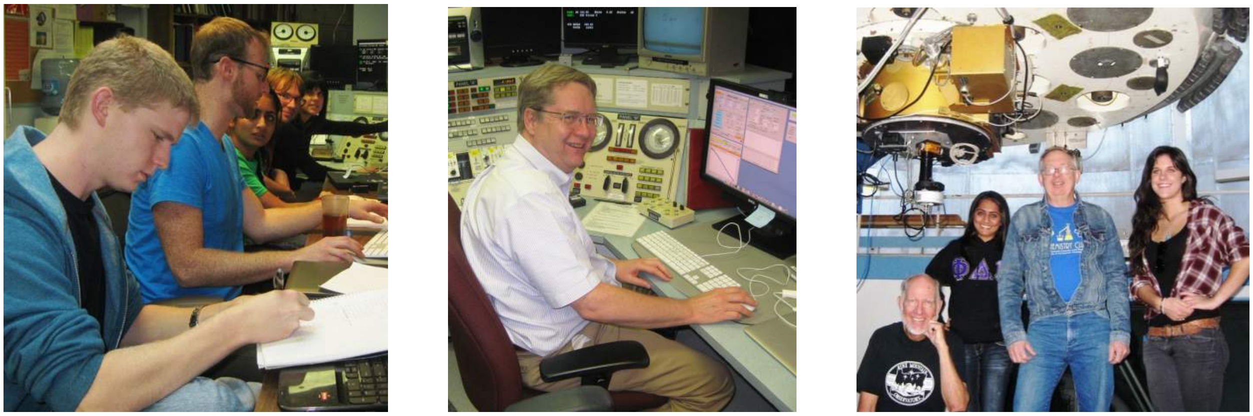

Figure 16. Students in the warm room: Josh Plumer, Dan Wallace, Rikita Patel, Alex Teiche, and Kayla Chaney (left). JDSO Editor Kent Clark at the controls (center). Russell M. Genet, Rjikita Patel, John Kenney, and Kayla Chaney under the telescope (right).

As luck would have it, the first seven nights were totally clear without even a hint of clouds. The eighth night was cloudy for the last half of the night. Speckle observations were made of over 1000 close double stars, many of them binaries, as well as several hundred single stars for use in deconvolution. Over a terabyte of data was gathered. The run is described in some detail in "Kitt Peak Speckle Interferometry of Close Visual Binary Stars" (Genet et al. 2015d).

Just a couple of weeks after the run, two high school teams taking Genet's Astronomy Research Seminar (Figure 17) used data from the Kitt Peak run as the basis for their research seminar papers. See "First Speckle Interferometry Observations of Binary BU 1292" (Adam et al. 2015a), and "Speckle Interferometry Observation of Binary WDS 01528-0447" (Adam et al. 2015b).

While reducing the data for just a few close binary stars observed on the 2.1-meter telescope at Kitt Peak using Florent Losse's REDUC was not a problem, doing this for over a thousand double stars, matching up single deconvolution stars to the doubles, and including deconvolution in the reduction was problematic. Not being an approach anyone would want to repeat on another run, three major efforts were launched to solve this problem.

First, the results from the first Kitt Peak run were not well organized. Not only was there a problem matching single deconvolution stars to double stars, but identifiers had been entered by hand by the various camera operators, and over 100 of them had entry errors. It took a Cal Poly student, Alex Teiche, several months to square away the data base. He developed a spreadsheet that pointed to both the double stars and their matching single deconvolution stars in a uniform manner. See "Kitt Peak Speckle Interferometry Program Database Generation" (Teiche 2015).

Second, Dave Rowe and Russ Genet decided that to reduce the large Kitt Peak data set and to prepare for future runs of this size, a new reduction program was needed. To this end, Rowe wrote the software, while Genet tested it out on the Kitt Peak data organized by Teiche. Over 30 versions of the program were written by Rowe and tested by Genet during January and February of 2014. A user's guide was developed in parallel with programming and testing. See "User's Guide to PS3 Speckle Interferometry Reduction Program" (Rowe & Genet 2015).

Rowe's speckle interferometry program, an addition to his Plate Solve 3 program, has many advanced features. All the observations can be preprocessed automatically (making all the Fourier transforms). This reduces the file size and subsequent reduction times by about a factor of one thousand.

The program, PS3, can run in either of two modes. The first is a manual mode where one selects a double, one at a time, from a data base, and, optionally, a matching single deconvolution star. The second mode is semi-automatic, using the Teiche spreadsheet as a pointer to both the double and single stars.

In the semi-automatic mode, PS3 automatically generates solutions and displays autocorrelograms, although the user can override an automatic solution and provide a manual solution.

PS3 has many other features, including adjustable Gaussian high and low pass filters, an axes interference filter, display of both the autocorellogram and the power spectral density, and automatic recording of all the reduction parameters and any user's comments.

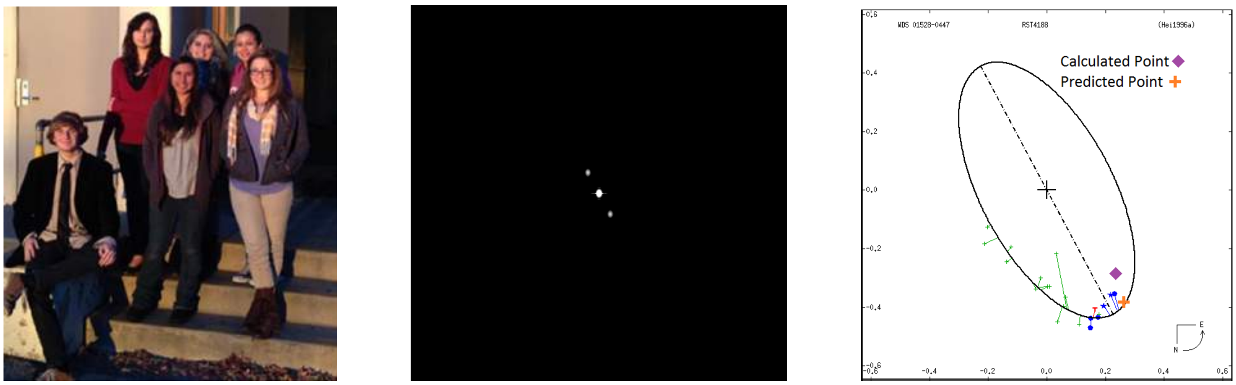

Figure 17. One of the high school research teams (left), their autocorellogram (center), and their observational plot (right) that compared the point predicted from the ephemeris and the observed (calculated) point from Kitt Peak.

Third, to avoid difficult-to-use observational results in the future, an observational/data-flow process was defined. Standard formats were established to match the observational results to the PS3 reduction program, thus allowing observations to be reduced in a semi-automatic fashion. The specifications included instructions and formats for pre-run preparation, choosing targets and recording observations during runs, and post-run reduction. See "The Double Star Speckle Interferometry Observation and Reduction Process" (Genet 2015).

With a well-defined observational process, data formats, and a semiautomatic, well-documented reduction program in hand, the group was ready for another major speckle interferometry run. They applied for and were granted another week of observing at Kitt Peak in April of 2014 to observe doubles on the other half of the sky (Figure 18).

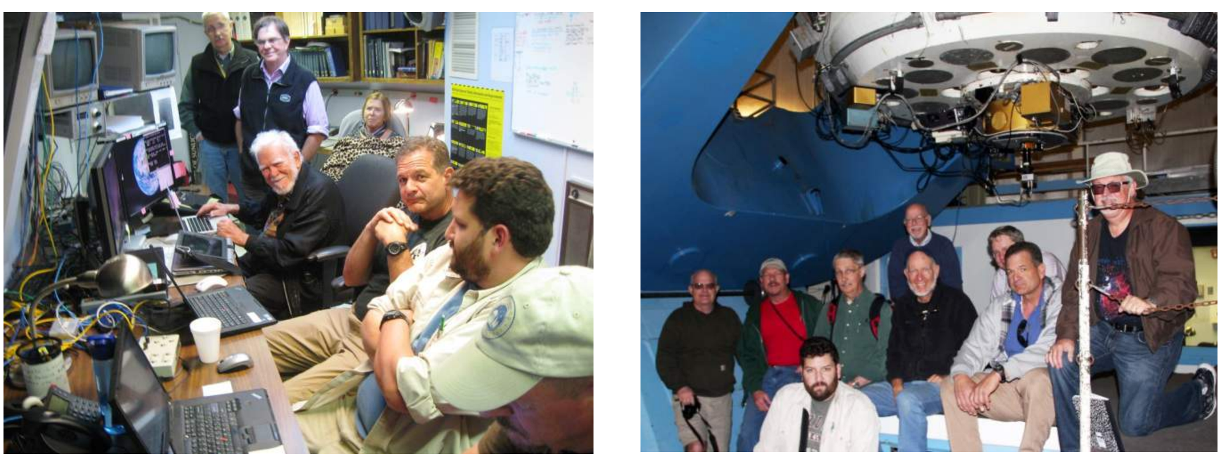

Figure 18. Observers in the warm room (left): Wayne Green, Dave Rowe, special guest Keith Hege (and his wife under the books), Reed Estrada, and Chris Estrada. Observers under the telescope at the second Kitt Peak run (right): Greg Jones, Tom Smith, Chris Estrada (front), Wayne Green, Ed Wiley (rear), Russ Genet (front), Kent Clark (rear), Reed Estrada (front), and Richard Harshaw.

Figure 19. Detrick Branston makes a measurement on the north port of the 1.6-meter Main telescope of the McMath-Pierce Telescope Facility, while Pat Boyce, Richard Harshaw, and Ed Wiley provide advice (left). Pat Boyce and Richard Harshaw assemble the speckle camera system for observations on the 0.8-meter East Auxiliary Telescope (right).

As in the first Kitt Peak run, the observers were split into two teams, one for the first half of the run, and the other for the last half. Genet and Smith, again, stayed for the entire run. The observers on the 2.1-meter telescope included Kent Clark, Reed Estrada, Chris Estrada, Tom Frey, John Ridgely, Dave Rowe, Alex Teiche, Nathalie Haurberg, Cassie Hollman, Izak McGieson, Rafel Ramos, Don Westergen, Grady Boyce, Tom Smith, and Russ Genet.

Simultaneous with the speckle interferometry observations on the 2.1-meter telescope, another team of observers evaluated the suitability of the Main 1.6-meter and Auxiliary East 0.8-meter telescopes at the McMath-Pierce solar telescope facility for nighttime speckle interferometry observations of close double stars (Figure 19). The McMath team included Richard Harshaw, Greg Jones, Ed Wiley, Pat Boyce, Jimmy Ray, David Douglass, Lri Prause, Detrick Branston, and Russ Genet (who split his time between telescopes).

Pointing tests on the 1.6-meter telescope suggested that it could make useful speckle observations. See "Potential of the McMath-Pierce 1.6-Meter Solar Telescope for Speckle Interferometry" (Hashaw et al. 2015a). However, efforts were concentrated on the 0.8-meter East Auxiliary telescope. Several optical. configurations were evaluated, and one was used to make useful speckle operations of several close double stars. For the papers on the McMath-Pierce research, see "Testing of the McMath-Pierce 0.8-Meter East Auxiliary Telescope's Acquisition and Slewing Accuracy" (Harshaw et al. 2015b), "Close Binary Star Speckle Interferometry on the McMath-Pierce 0.8-Meter Solar Telescope" (Wiley et al. 2015), and "Speckle Interferometry with the McMath-Pierce East Auxiliary Telescope" (Harshaw et al. 2015c).

The 2.1-meter telescope facility at Kitt Peak includes a separate and independently-controlled 1.0-meter telescope that feeds the large spectrographs in the basement below the 2.1-meter telescope. During our observing run at Kitt Peak, Wayne Green and John Kenney observed a number of short-arc, very long-period binaries with the high-resolution Echelle spectrograph to obtain radial velocities (Figure 20).

After the Kitt Peak second run, Greg Jones compared the performance of a number of low cost, high speed CCD and CMOS cameras. Richard Harshaw purchased one of these cameras (the Celestron Skris CCD camera) and began making speckle interferometry observations of brighter, close double stars. Harshaw compared a number of calibration procedures for these low cost cameras and concluded that drifts were best for camera angle, and slit masks were best for pixel scale. See "Calibrating a CCD Camera for Speckle Interferometry" (Harshaw 2015d).

Figure 20. Wayne Green and John Kenney at the top, slit end of the spectrograph (left). The light from the slit then enters the basement room which contains several spectrographs including a high resolution Echelle (right).

Advanced Technology Developments

Although stellar masses in the middle of the main sequence have been accurately established through the combination of astrometric and spectroscopic observations of binaries, the masses of stars on both ends of the main sequence, as well as those evolved off of the main sequence, are not well known. Only recently, the masses of late-M dwarfs were found to be off by a factor or two (Dupuy et al. 2012). Astrometric observations of short-period binary stars, with one of these needed stars as a component, are required to establish their masses in a fundamental manner. Once individual masses are determined, stellar evolutionary models can be refined.

Three technologies, discussed below, have the potential to extend the reach of binary-star speckle interferometry. A program of potential observations and advanced hardware and software engineering developments has been suggested. See “Speckle Interferometry of Short-Period Binary Stars” (Genet et al. 2015b).

Hipparcos, the European Space Agency’s astrometric space telescope, discovered thousands of potential short-period binary stars—many of which, over two decades later, have not yet been confirmed, while others have not been sufficiently followed to establish good orbits. The short periods of some of these close visual binaries allow the establishment of high quality orbits within a reasonable time frame. Furthermore, their components have sufficient orbital velocities to allow radial velocity curves to be obtained. The combination of accurate astrometric orbits and radial velocity curves can provide individual component stellar masses in a very fundamental manner.

In the future, we expect that the number of potential close binaries discovered by the European Space Agency’s recently launched Gaia astrometric telescope, the Large Synoptic Survey Telescope (LSST), and other survey telescopes will, literally, suggest millions of short-period binary candidates worth pursuing. The first challenge will be to determine, through astrometric observations, which of these many potential candidates actually are short-period binaries. The second challenge, by way of differential, multi-band photometry, will be to determine, in turn, which of the actual binaries have at least one component that is a star that is not in the middle of the main sequence, and hence have poorly known masses.

Although the survey telescopes, such as Gaia and LSST, will provide a virtual flood of binary star possibilities, the number of observers and the telescope observational time required to follow up on them is well beyond our current capabilities. One approach to solving this dilemma is automation. A workshop on the automation of speckle interferometry was held at the U.S. Naval Observatory in June of 2014 (Figure 21).

Figure 21. Attendees at the U.S. Naval Observatory Workshop on the Automation of Speckle Interferometry gather under the historic 26-inch refractor. Reed Riddle, Merlene Clark, Bill Hartkopf, Jerry Hubbell, Kent Clark, Brian Mason, and Russ Genet (left). Brian Mason and Bill Hartkopf at the 26-inch refractor's control station (right).

Following the USNO workshop, an undergraduate Electrical Engineering student at California Polytechnic State University, Alex Teiche, spent the summer writing over 10,000 lines of code to fully automate speckle interferometry observations on the 10-inch telescope at the Orion Observatory. See Figure 22 and "Automated Speckle Interferometry of Double Stars" (Teiche et al. 2015).

Figure 22. Alex Teiche checks the equipment automation setup at the Orion Observatory (left). Alex watches the telescope run automatically from the observatory's warm room (right).

For his Master's thesis in Mechanical Engineering at California Polytechnic State University, Ed Foley is developing masks with various geometric shapes to disperse the light of bright primary stars away from "discovery zones." This will allow fainter secondary stars to be observed than would be possible without the masks. Shaped aperture masks for space telescopes have been under development at Princeton University for quite some time. Neil Zimmerman, a post-doc at Princeton, designed a mask specifically for Celestron C-11 telescopes such as the one at the Orion Observatory and also at Jimmy Ray's observatory in Arizona. See "Observations of Large Delta-Magnitude Close Binaries with Shaped Aperture Masks" (Foley et al. 2015) and Figure 23.

The time available on 4-meter and larger telescopes for speckle interferometry of close binary stars is insufficient to follow up on currently known close binaries, let alone sort through new short-period binary candidates to determine which ones actually are binaries, and then follow these long enough to establish high-quality orbits. The solution to this difficulty is the development of low cost, large aperture telescopes that could be devoted, in a fully-automated fashion, entirely to close binary star speckle interferometry.

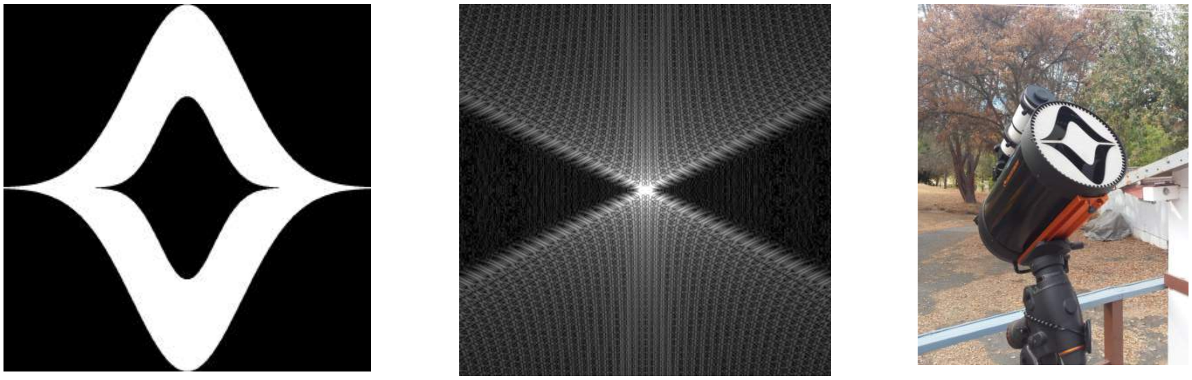

Figure 23. A mask designed by Ed Foley. The central portion of the mask covers the telescope's secondary mirror (left). The Fourier transform of the mask reveals the two discovery zones on the left and right (center). The mask on the Celestron C-11 telescope at the Orion Observatory (right).

A number of workshops and meetings have been held to explore various possibilities. In September 2014 at the Mt. Wilson workshop, participants decided to concentrate on the development of sparse-aperture speckle interferometry telescopes (Figure 24). As envisioned at this workshop, such telescopes will have multiple spherical mirrors (with closely matched focal lengths) arranged to conform to the (sparse) surface of a larger (virtual) spherical mirror. Spherical aberration will be reduced by way of an aspheric secondary (such as Pressman-Carmichael) for a Cassegrain configuration, or refractive optics for a prime focus configuration.

Figure 24. Attendees at Mt. Wilson Workshop on the Speckle Interferometry of Double Stars. John Kenney, Brian Mason, Nils Turner, Russ Genet, Dave Rowe, Alex Teiche, and Reed Estrada. Chris Estrada was behind the camera (left). Dave Rowe explains the basics of bispectrum analysis (right).

At the Mt. Wilson Workshop, Dave Rowe presented simulation results for a 2-meter sparse-aperture telescope with seven 0.5-meter mirrors (Figure 25). The results looked promising. Since then, a rough cost estimate suggests that a 4.0-meter sparse aperture telescope might only cost about $500,000 to build, about 1/100th of the cost of a 4.0-meter filled-aperture such as the recently built Discovery Channel Telescope at Lowell Observatory.

Matthew Clause, a Master's student in Mechanical Engineering, designed a servomechanism to position the multiple mirrors with the high precision required for phasing. Michael Niditz, a Senior majoring in Architectural Engineering, designed a stiff test stand to evaluate a three-mirror sparse-aperture system. The three spherical mirrors were made by Tong Liu at Hubble Optics.

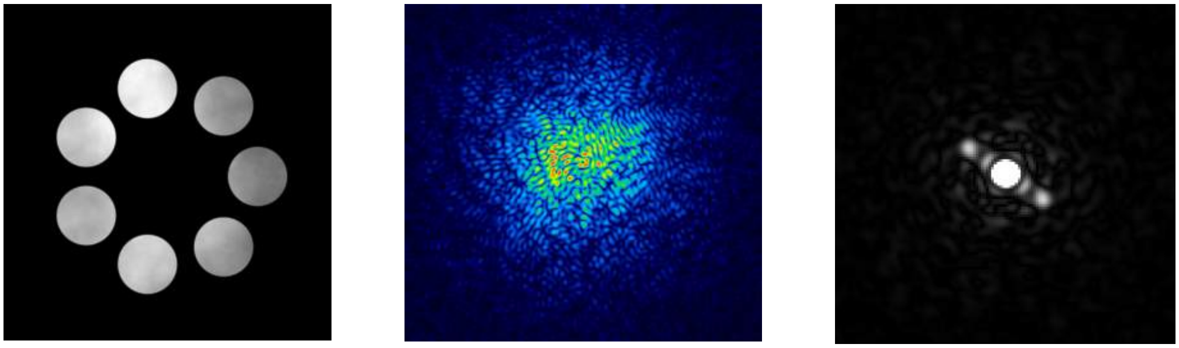

Figure 25. Simulation of two-meter sparse-aperture speckle interferometry telescope.

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