Double Star Research, Instrumentation, & Education

Summer Seminar Projects

Edited by Jacob Hass

Double Star Research, Instrumentation, & Education: Summer Seminar Projects

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Cal Poly Summer 2015 Astronomy Research and Development Seminar

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Small Telescope Research and Development

Scientific research conducted with small telescopes is noted for the many professional and amateur astronomers who work together on research projects. They use small telescopes equipped with affordable instrumentation, and their research results are in published papers that significantly advance scientific knowledge. Examples of research areas of professional-amateur cooperation within astronomy include double star astrometry, variable star photometry, exoplanet transit photometry, and asteroid light curve photometry.

Small telescopes make their valuable contributions to astronomical research through time series, networked, and other observations that only large numbers of small telescopes with their amateur operators can provide. Small telescopes also continue to play a vital role in recruiting and training the next generation of astronomers and instrumentalists, and serve as test beds for the development of novel instruments and experimental methods. Advances in technology are favoring small-telescope science with increasingly effective and low-cost cameras, more numerous and efficient remote robotic telescopes, and more capable yet affordable computers.

It is widely agreed that small telescopes contribute significantly to astronomical research, both through direct research contribution and through their use in education. Weaver (2003) points out that

> Both quantitative and qualitative arguments demonstrate the continuing importance of small telescopes to the astronomical endeavor. The quantitative arguments show that it is significantly less expensive per citation to use the smallest telescope that will accomplish the research. Both the quantitative and qualitative arguments show that the research accomplished by small telescopes is of continuing and lasting significance to the discipline, as witnessed by their non-diminishing contribution to astronomy over the last century and the persistence of their citation histories.

Ringwald et al. (2003) point out that

> Small telescopes can hold their own with larger instruments since more time is available on them. This makes possible monitoring campaigns, aerial surveys, and time-resolved campaigns, particularly if the telescopes are networked or automated—all difficult to carry out with larger telescopes, for which even small amounts of telescope time are in great demand.

An Experiment in Undergraduate Astronomical Research

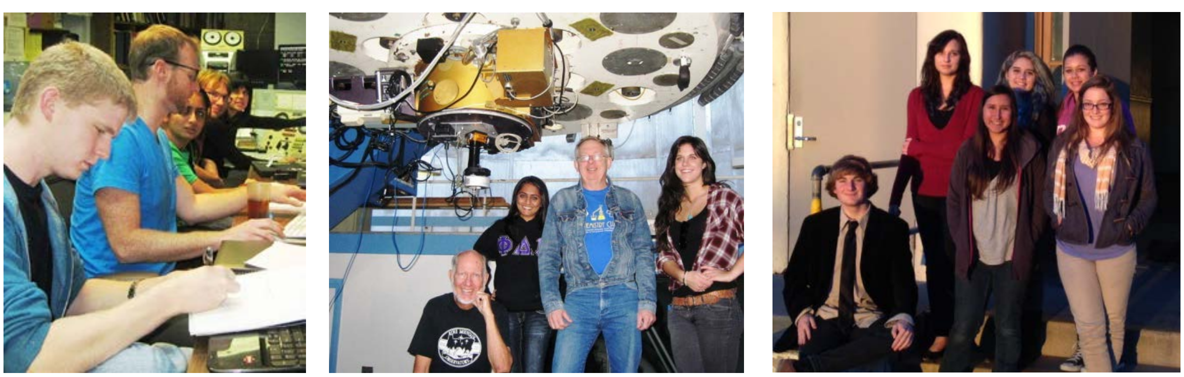
Shortly after my retirement from a quarter-century as a research and development supervisor at federal laboratories, I was teaching astronomy and mathematics part-time as an adjunct at the small, remote Superstation Mountain campus of Central Arizona College east of Phoenix. With free time on my hands, I decided to try an educational experiment. I was curious whether or not students could successfully conduct scientific research in a manner similar to the research scientists that had worked for me, but on more modest projects? Specifically, could the students:

- Learn science by doing science
- Plan and manage their own research as student teams
- Join a community of professional and amateur researchers
- Publish externally-reviewed papers in a specific research area
- Present their research results at a conference

Three student teams were formed, and they used a robotic telescope at my Fairborn Observatory to observe Delta Cepheid type variable stars over several pulsation cycles. All the experimental goals were met, except the "papers" were just abstracts in the Bulletin of the American Astronomical Society because the students ran out of time at the end of the semester to write full papers. The students stood by their posters at the Albuquerque AAS meeting in 2001. One of the students, Clay Lapa, a home-school student just starting community college, was only 16 years old.

Students pose in front of an amateur's half-meter telescope during an observing session.

Declaring the first round of my experiment a "qualified" success, the experiment was continued, starting in 2006, at Cuesta College. By 2008, the seminar had focused on the astrometry of visual double stars, measuring their position angles and separations with increasingly sophisticated methods. The seminar was held on Cuesta College's south "campus" which, during the day, was Arroyo Grande High School. The students were, primarily, high school juniors and seniors taking the Cuesta seminar after hours as their first college course. The students were supported by a growing community of professional and amateur astronomers, as well as a growing number of seminar graduates who continued their research after graduation and enjoyed helping new students learn the research "ropes." What began as student observations of wide, somewhat bright observations with astrometric eyepieces, evolved into CCD observations of fainter doubles and, eventually, into highly sophisticated speckle interferometry observations below the seeing limit with high-speed electron-multiplying CCD cameras.



Left: students control the 2.1-m telescope at Kitt Peak National Observatory, and (center) pose under the telescope. The speckle interferometry observations they made were cutting-edge astronomical research using a state-of-the-art EMCCD camera the team brought to Kitt Peak. Right: Cuesta College analysis team leader/high school student Bobby Johnson (seated on left) landed a four-year scholarship at Brown University, while Merle Adam (far right), was first author of their paper (Adam et al. 2015) and received a four year scholarship to Yale University.

Collaboration with others led to replication of the successful Cuesta College astronomy research seminar in additional venues. In conjunction with the University of Oregon's Pine Mountain Observatory, a series of highly concentrated summer seminars was initiated that resulted in a number of published papers by both high school and undergraduate students (e.g. Schrader 2010, Baxter 2011, & Brashear 2012). Soon the seminars' most seasoned and active graduates co-edited books (Genet et al. 2010, Weise et al. 2015) and co-chaired conferences, culminating in the Maui International Double Star Conference (Weise et al. 2015).

These seminars have, over the past eight years, yielded some three dozen published papers (with over a dozen more in the pipeline) coauthored by more than 100 students (e.g. Marble et al. 2008, Dowdy et al. 2009, & Estrada et al. 2010). The students' measurements have added many published double-star measurements to the permanent archive of the Washington Double Star Catalog maintained by the U.S. Naval Observatory.

Seminar students have co-edited four books: *Small Telescopes and Astronomical Research* (Genet et al. 2010), *The Double Star Reader* (Clark et al. 2014), *Speckle Interferometry of Close Visual Binaries* (Genet et al. 2015a), and *Double Star Astrometry: Collaborations, Implementations, and Advanced Techniques* (Weise et al. 2015). The seminars' graduates have co-chaired many workshops as well as three major international conferences: Galileo's Legacy in 2009, Small Telescopes and Astronomical Research in 2010, and the Maui International Double Star Conference in 2013.

Lessons Learned from the Undergraduate Student Research Seminar

The success of the student research projects resulted from, primarily, simply following the normal "rules" of scientific research. These practical rules are often only learned as a graduate student, post-doctoral researcher, or even later. Frustrated that so many doctoral students were graduating without learning the basic "ropes" of being a scientist, Peter Feibelman (2011) developed a course he turned into the classic book, *A PhD is not enough! A Guide to Survival in Science*. Although I made several attempts to "soften" science's rules to make it easier on my seminar students, it was found that this undermined the core strength of the research seminar. Science, a highly successful form of cultural evolution, has developed its many rules for good reasons. Students like to know that they are doing the real thing, not some watered-down version that they are likely to interpret as condescending. The primary lessons learned so far from this long-running student research seminar "experiment" have been:

- Research should be conducted within a supportive community of practice, typically within a narrow specialty. Astronomical research with smaller telescopes works well—especially research such as double star astrometry where the observations can be completed in a single evening or economically by a remote robotic telescope.
- Research must be original and be published as papers in appropriate (specialty) journals reviewed and read by the members of the relevant community of practice.
- Projects need to be of modest scope.
- Publication is mandatory; it places everyone's reputation on the line, including that of the students, instructors, schools, journals, and the seminar itself. Thus papers need to be of high quality. Writing, rewriting, and reviewing such papers takes time—typically half of the semester.
- Publication is not enough. Results should be presented by at least some of the students at conferences attended by researchers from the relevant community of practice.
- Team members should not be expected to contribute equally. Author order provides justice to variations, allowing each member to contribute as their time, talents, and experience dictate.
- Additional team members should be included from the outset or added, as needed or desired, from outside the class. Do whatever it takes to conduct and complete a high-quality research project.

Past Cal Poly Student Engineering Development Projects

Scientific research in astronomy and other sciences often involves both scientists and engineers working together on projects; this was certainly my experience as a research supervisor at federal laboratories. Cal Poly has a large, renowned College of Engineering, and it was natural for me to tap student resources for advancing the development of small telescopes and associated instruments and software. For the past eight years I teamed up with Dr. John Ridgely in Mechanical Engineering to sponsor a series of senior projects and Masters Theses. Many of these projects were completed by student teams majoring in mechanical engineering, but there have also been electrical and architectural (structural) engineering student projects.

Three mechanical engineering students pose with the "Cal Poly 18" alt-az telescope.

Many of the same professional and amateur astronomers who supported the Cuesta College astronomy research students also supported the Cal Poly small-telescope engineering development students. This led to a fairly close, tight-knit community of practice that supported students at both of the two schools (which are only a few miles apart).

Left: low cost, precision positioner for use in a hexapod telescope.
Right: a three-actuator telescope control system test setup.

An early major project was the design and construction of an 18-inch alt-az telescope that pioneered the use of direct drives on smaller telescopes (no gears or pulleys—the telescope itself becomes the motor). The "Cal Poly 18" led directly to the CDK-700 28-inch telescope built by PlaneWave Instruments, now used by a number of major observatories around the world.

A three-student Cal Poly mechanical engineering team designed and built the prototype for an instrument rotator subsequently manufactured by Orion Telescopes. Another three-student team designed a low cost precision positioner for use in a hexapod platform that could contain medium-sized telescopes, while a Masters' student followed this with a control system for a telescope positioned by three screw mechanisms.

A three-student Cal Poly Architectural (structural) Engineering team designed and built a 1.5m light-bucket experimental telescope for high speed photometry and intensity interferometry. This portable telescope is a non-imaging flux collector.

Left: The Cal Poly 1.5-meter experimental light-bucket flux collector telescope (the blue coating on the mirror protected the mirror during assembly). Right: installation of ultra-high-speed photometer for intensity interferometry field tests.

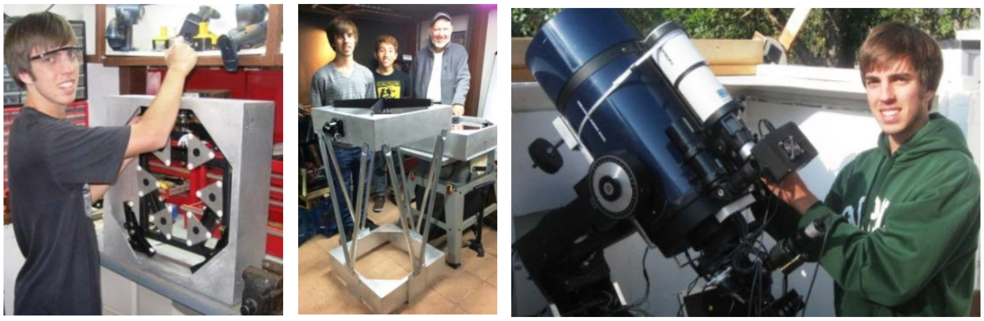
Cal Poly Summer Research Seminar

For the past several years I thought it would be good to involve Cal Poly students in astronomical research and development during their first few years at college, not waiting until the senior year or graduate school to start conducting research. A key difficulty was that, during the school year, Cal Poly physics and engineering students are much too busy to devote time to a research seminar. Also, during the summer, when they do have time, they often need financial assistance if they are not to return home or forego some summer employment.

Thanks to the generosity of a private donor, Cal Poly was able to fund me and six undergraduate students—four physics students and two liberal studies (science teaching) students—for a six-week, in-person summer astronomical research seminar (2015). Another physics major, who lived locally, joined the seminar without funding.

First three on left: Cal Poly students Donald Loveland, Kevin Phung, and Jennie Smit. First three on right (front to back), Zoe Sharp, Tristan Nibbe, and Jacob Hass. The students were presenting their proposed summer seminar research projects. Attending the briefing, left to right starting with yellow blouse, Drs. Lola Berber-Jimenez (Chair Liberal Studies Dept.), Phil Bailey (Dean College of Science and Mathematics), John Ridgely (Mechanical Engineering Department), Russell Genet (Research Scholar in Residence at Cal Poly and Cuesta College Instructor), and Jason Curtis (Dean of Science and Mathematics at Cuesta College). The photo was taken by Emily Hock (Liberal Studies student).

Four of the physics majors were interested in telescope and instrument development. In response to this, two graduate mechanical engineering graduate students opened their engineering development projects to the physics students. This underscores a key point, and that is many scientists are instrumentalists, and there are many skills shared by both scientists and engineers, leading to a great deal of common ground for collaboration.



Left: Jacob Hass installs a 17-point Wiffle-tree mirror suspension. Center: Hass, Keving Phung, and Genet and portions of the 17.5-inch optical tube assembly project. Right: Hass working on the intensified speckle interferometry project.

The seminar students met with me on Tuesday, Wednesday, and Thursday mornings for six weeks. Teams were quickly formed, with most students being a member of more than one team. Each team prepared a written proposal and gave formal presentations on their proposals.

In one of the projects, seminar physics major Donald Loveland led a team that evaluated shaped aperture masks developed by Cal Poly ME graduate student Edward Foley in conjunction with a post-doc, Neil Zimmerman, at Princeton University working on similar masks for space telescopes. Shaped aperture masks preferentially diffract the bright light of the parent star away in specific directions, forming dark discovery zones to image faint exoplanets. We are employing masks for the same purpose to discover faint secondary stars in binary systems.

A number of the seminar participants attended an Orion Observatory potluck dinner and observing session. Ed Foley, seated front and center, displays the shaped aperture mask he designed.

The most ambitious project, completed by Matthew Clause, a Mechanical Engineering graduate student, was a three-mirror laboratory prototype for a sparse aperture speckle interferometry telescope. If a number of small spherical mirrors can be brought into phase via servomechanisms at low cost, they can form the basis of an inexpensive large telescope. Initial cost estimates suggest that a 4 meter sparse aperture telescope could be built for about \$500,000, about 1/100th the cost of a traditional filled aperture telescope of this size.

Matthew Clause, a mechanical engineering graduate student, designed and built the nine high-precision actuators on the left that supported three spherical mirrors, center, all mounted in a test tower, right, with a high brightness LED and astronomical camera at the center of curvature to enable optical alignment through the use of interferometry.

The Seminar's Surprising Outcome

My original plan for the Cal Poly summer six week seminars was to form two teams, each with three students, to undertake a couple of very straight forward double star observational projects that could be completed, including observations, analysis, paper writing, and external review, within six weeks. The last day of the seminar would be set aside for formal briefings on their projects by the two teams. This is not what happened.

Instead of just moving ahead with this plan, I thought it might be interesting to lay out various projects that I was working on or thinking about, and that other (engineering) students were working on at Cal Poly. I was not totally surprised that a number of the physics students were keenly interested in being involved in a hardware project. Students wanted to know if they could work on more than one project. If the projects couldn't be finished in six weeks, they wondered, could they be continued in the second six weeks of the summer—much of it via the internet (which works for writing and polishing papers). Almost always willing to try something new (and seeing the chance for Cal Poly science and engineering students to work directly together on astronomy research and development projects), we went ahead with this highly ambitious approach to the summer research seminar.

With such a solid group of projects all related to double star research and development one way or the other, it seemed appropriate that the papers should be published as a special issue of the *Journal of Double Star Observations* and then reprinted as a hardcover book. However, editing a special issue of a journal and publishing a hardcover book are both major tasks, albeit tasks that can be valuable training for students and significant resume builders.

Anticipating this publishing opportunity, a parallel summer project, conducted with the seminar itself as the "guinea pig", was launched. The project developed a student paper format and instructions that allowed students themselves to bring their own papers into nearly publishable format. This development was spearheaded by a three-person team: Cal Poly Graphic Communication student Meghan Legg; long-time astronomy research seminar supporter, educator, and English expert Dr. Vera Wallen; and the Managing Editor of the Collins Foundation Press, Dr. Cheryl Genet. They developed a format and instructions, held a mini-workshop for the students on how to format their papers, and also provided the students with written instructions. The students, in turn, provided the team valuable feedback. The publication project team also coordinated their format with the Editors of the *Journal of Double Star Observations,* the intended book publisher, and book's printer.

Jacob Hass, the local "volunteer" physics student, not only participated in most of the projects, but, being local, kindly helped to wrap up many of the projects in the second six weeks. He then volunteered to be the Editor of the special issue of the *Journal of Double Star Observations* as well as the hardcover book by the Collins Educational Foundation. Final formatting of the papers and the many activities required to publish a book were taken on by Cal Poly Graphic Communication students and Associate Editors Meghan Legg, Hope Moseley, and Sabrina Smith.

Social Learning within Communities of Practice

Communities of Practice is both the title of the seminal 1998 book by Etienne Wenger and a cornerstone concept in social learning theory. Scientific research, as with most other human endeavors, is carried out within a community of practice.

> Communities of practice are formed by people who engage in a process of collective learning in a shared domain of human endeavor: a tribe learning to survive, a band of artists seeking new forms of expression, a group of engineers working on similar problems, a clique of pupils defining their identity in the school, a network of surgeons exploring novel techniques, a gathering of first-time managers helping each other cope. In a nutshell: Communities of practice are groups of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly (Wenger 1998).

Social learning takes place in the process of becoming a member of a community that defines what competence means in a specific domain of expertise. As Wenger (1998) points out:

> Learning is a matter of engagement: it depends on opportunities to contribute actively to the practices of communities that we value and that value us, to integrate their enterprises into our understanding of the world, and to make creative use of their respective repertoires … Practice is a process of interactive learning [that] enables newcomers to insert themselves into existing communities. It is the learning of mature members and of their communities that invites the learning of newcomers.

The students in our seminar learned by developing actual proficiency in the practices of a community of scientists and engineers, and publishing their work in places where it can be accepted or rejected by experienced members of that community. The process of introducing students to a specific practice of that community (writing a scientific paper) is not simply a matter of teaching them a set of writing conventions that they then apply: it involves expert members of that community acting as gatekeepers to the dynamic practices of the community.

For students, learning R&D practice is not just learning a skill but developing a new identity, which Wenger (1998) describes as a core dimension of learning in a community of practice:

> Learners must be able to invest themselves in communities of practice in the process of approaching a subject matter. Unlike in a classroom, where everyone is learning the same thing, participants in a community of practice contribute in a variety of interdependent ways that become material for building an identity. What they learn is what allows them to contribute to the enterprise of the community and to engage with others around that enterprise … Learning [within a community of practice] transforms our identities: it transforms our ability to participate in the world by changing all at once who we are, our practices, and our communities.

Wenger (1998) identified the solution to a key educational paradox that is represented by my astronomy research seminars:

> If learning is a matter of identity, then identity is itself an educational resource. It can be brought to bear through relations of mutuality to address a paradox of learning: if one needs an identity of participation in order to learn, yet needs to learn in order to acquire an identity of participation, then there seems to be no way to start. Addressing this most fundamental paradox is what, in the last analysis, education is about. In the life-giving power of mutuality lies the miracle of parenthood, the essence of apprenticeship, the secret to the generational encounter, the key to the creation of connections across boundaries of practice: a frail bridge across the abyss, a light breach of the law, a small gift of underserved trust — it is almost a theorem of love that we can open our practices and communities to others (newcomers, outsiders), to invite them in our own identities of participation, let them be what they are not, and thus start what cannot be started.

Acknowledgments

There were many contributors to the astronomy research and development seminar who I am pleased to acknowledge. Funding was provided by a Cal Poly donor. Lola Berber-Jimenez (Chair Liberal Studies Dept.) initiated the seminar with the support of Phil Bailey (Dean College of Science and Mathematics). John Ridgely (Mechanical Engineering Department) supported the seminar with his graduate students, Edward Foley and Matthew Clause.

David Rowe (CTO of PlaneWave Instruments) provided technical guidance on several projects and, along with John Kenney (Chair, Physics and Astronomy Dept., Concordia University) and Bruce Holenstein (President, Gravic Inc.) funded the three matched spherical mirrors for the sparse aperture telescope experiment. We thank Tong Lui (President, Hubble Optics) for making these mirrors. Reed Estrada (Chief Edwards Test Pilot, Northrop Aviation) and Chris Estrada (Univ. of California, Los Angeles), made the sparse aperture telescope test stand designed by Cal Poly Architectural Engineering student Michael Nidetz.

Benoit Schillings (Director, La Cresta Observatory) loaned us the optical intensifier used in one of our projects. Clif Ashcraft (Director, Perrineville Observatory) made the crucial observations for the paper on the ZWO CMOS camera. Joseph Carro (Cuesta College) provided the telescope (and its operation) for the student observations of Alberio, while Brian Mason (U.S. Naval Observatory) provided the past observations of Alberio. Richard Harshaw (Director, Brilliant Sky Observatory) was instrumental in our analysis of past speckle interferometry observations of close double stars at Kitt Peak National Observatory.

Cheryl Genet (Collins Foundation Press), Vera Wallen (retired Coast Union School District Superintendent), and Meghan Legg, Hope Moseley, and Sabrina Smith (Cal Poly Graphic Communication students) were instrumental in formatting and publishing the collected papers. Finally, and certainly not least, a very special thanks to Jacob Hass (Cal Poly Physics student) for editing this volume.

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Albireo: 260 Years of Astrometric Observations

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Abstract The historical record of Albireo's observations reflects the progress of double star research. Some 294 astrometric observations have been published starting with Bradley's 1755 observation and ending with our 2015 observation. Several observation techniques were used over this 260 year span. Noteworthy are the historic contributions of astronomers such as James Bradley, Christian Mayer, William Herschel, Giuseppe Piazzi, Friedrich Georg Wilhelm von Struve, Sir John Herschel, Sir James South, Edward Skinner King, and Andrei Tokovinin. Overall trend lines of the past observations of Albireo are compared to our current observation, and are generally concurrent. Dividing Albireo's past observations of separation into time segments shows evidence of a known third star in Albireo's system.

Introduction

Albireo, the fifth brightest star in the constellation of Cygnus, is a multiple star system. Its two major components, STFA AB, shown in Figure 1, is, arguably, the most famous and recognizable of all visual double stars. Albireo's primary (the A component) at magnitude 3.18 and spectral type of K2II, gives it a bright gold color. The secondary (B component) at magnitude 5.82 is only slightly fainter, and its spectral type of B8 gives it a bright blue color. With a separation of 34.3″, this wide pair is easily observed with small telescopes. Albireo's AB pair was first observed in 1755. Since then, there have been 292 additional published observations of the position angles and separations of the AB pair. With this paper, our 2015 observation will be the 294th published observation of Albireo.

Figure 1. Albireo's main components: Component A, right, and Component B, left.

Observation Techniques

The different techniques used to observe Albireo have been divided into six main categories, starting with the earliest technique used and ending with the most recent technique used: Micrometers with Refractors, Micrometers with Reflectors, Heliometer, Photographic, and Charge Coupled Device.

Micrometers with Refractors

Micrometers have, over the centuries, been widely used on refractors to measure the separation and position angles of double stars. Most refractors had a long focal length, providing a highly magnified image which is helpful when observing close double stars. Furthermore, because the refractors did not have a secondary mirror central obstruction, the light was not diffracted, giving crisp images. Most of the double star measurements made by Friedrich Struve used a high-precision filar micrometer made for him by Joseph Fraunhofer.

To increase precision, measurements were made with the micrometer in one position, and it was then rotated 180 degrees to take a matching measurement. This allowed some instrumental biases to be removed.

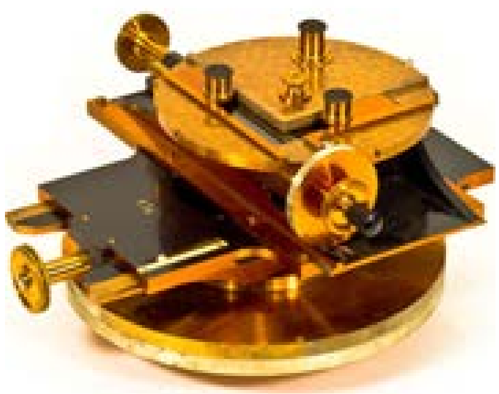

Figure 2. The filar with micrometer used on the 36 inch refractor at the Lick Observatory.

Micrometers with Reflectors

William Herschel used an early micrometer for most of his double star measurements. Reflectors, later on, tended to be used more in photography, but some were still used with filar micrometers. A recent example of a double image micrometer on a large, historic reflector telescope were the double star observations made in 2013 with a Lyot double image micrometer on the 60-inch reflector on Mt. Wilson, once the largest telescope in the world (Weise, et al. 2015).

Heliometer

A heliometer, used to measure the angular distances in the sky, is essentially a telescope with its objective lens cut into two halves, one of which can be moved independently, usually via a precise screw micrometer. Each half of the lens displays a separate image, and the distance the two lenses need to be separated to superimpose the images is used to calculate angular separation. In 1838, using a heliometer, German astronomer Friedrich Bessel, seen in Figure 3, was the first person to successfully measure stellar parallax. By measuring stellar parallax he was able to determine the distance to the star 61 Cygni.

Figure 3. Friedrich Bessel with a typical heliometer

Photographic

Photographic astrometric measurements were made on images recorded on glass plates coated with a silver emulsion. One plate typically contained many double stars. By having a permanent image, it was possible, long after the observations were made, to go back and measure the position angle and separation of a double star. Although photographic measurements were generally more precise than visual measurements with a micrometer, at least on wider double stars, a sharp-eyed observer on a large refractor could observe doubles that were amazingly close.

Charge Coupled Device (CCD)

A CCD is a camera that provides two-dimensional electronic imaging. The first CCD measurement was taken in 1975, but only became prevalent in the early 1990s with the introduction of a very affordable CCD camera kit by Richard Berry, then Editor of *Astronomy Magazine,* and a commercially produced camera by Allan Holmes at the Santa Barbara Instrument Group (SBIG). Charged couple devices use a circuit etched onto a silicon surface that forms small cells called pixels. As photons of light strike the pixels, a charge is generated that is read by the electronics and converted into an image of the light patterns striking the silicon chip.

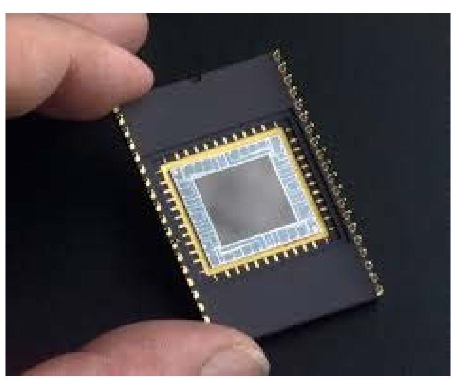

Figure 4. A typical CCD silicon chip.

Historical Observations

Introduction

Nine of the dozens of astronomers to observe Albireo have been singled out due to the significance of their observation or contributions to double star research. These nine are: James Bradley, for making the first observation of Albireo; Christian Mayer, for publishing the first double star catalogue; William Herschel, for identifying nearly a thousand double stars; Giuseppe Piazzi, for publishing a catalogue containing an observation of Albireo along with 6,748 other stars; Friedrich Georg Wilhelm von Struve, for discovering the most doubles stars to date; Sir John Herschel and Sir James South, for continuing William Herschel's research by observing many double stars in the southern hemisphere; Edward Skinner King, for publishing the first observation of Albireo using photographic techniques; and Andrei Tokovinin, for being the first astronomer to observe Albireo with a Charge Coupled Device camera.

James Bradley

The first measured position angle and separation of Albireo was made in 1755 by James Bradley. Shown in Figure 5, Bradley joined a long line of astronomers, including early Greek astronomers and Galileo, who attempted to measure the distance to a bright, nearby star. Bradley observed a star which conveniently passed almost directly overhead throughout most of the year, with the goal of observing its stellar parallax. Starting in 1824, Bradley, along with Samuel Molyneux, observed Gamma Draconis using the Kew zenith telescope seen in Figure 5.

Although Bradley failed to detect any parallax, he made two fundamental discoveries. In 1729, he discovered the aberration of light, an effect that changes the apparent position of stars as observed on Earth by up to 20″ due to the finite speed of light and Earth's varying velocity as it orbits the sun (Bradley 1727). Eighteen years later, Bradley discovered the nutation of the earth, a cyclic-nodding motion of the earth on its rotational axis which is caused by the moon's gravitational pull. In 1742, Bradley succeeded Edmond Halley as England's Astronomer Royal, the Director of the Royal Observatory Greenwich.

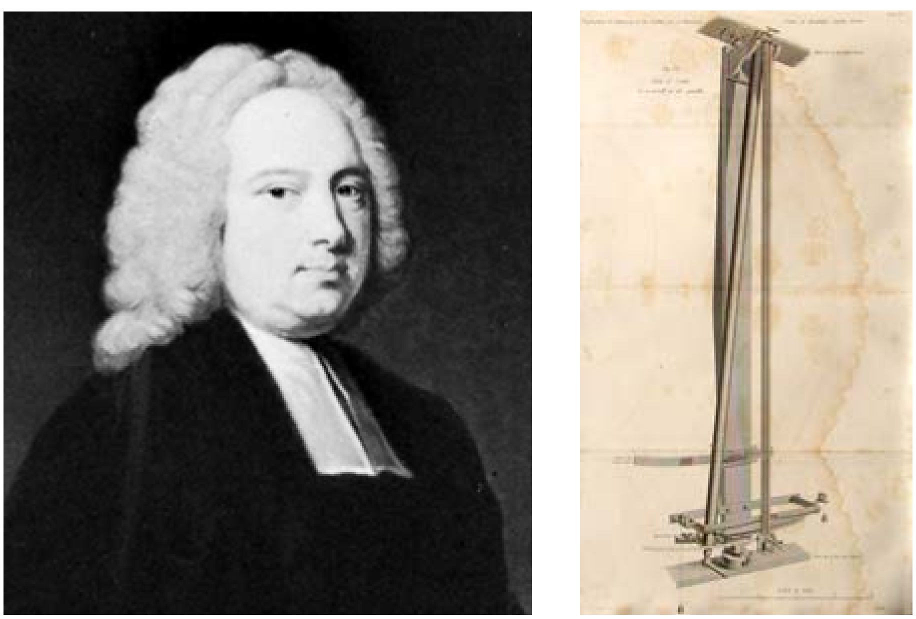

Figure 5. James Bradley, left, along with a drawing of the Kew zenith telescope, right.

Christian Mayer

Christian Mayer (Figure 6), born in 1719 and the second astronomer to observe Albireo, was a Czech astronomer and professor. In 1752, he accepted a teaching position at Heidelberg University as a professor of Mathematics and Physics. However, because of his interest in astronomy, he was appointed Court Astronomer at Mannheim. Mayer gave a lecture in 1777 on double star observations to the Academy of Mannheim and faced criticism that demanded evidence that would prove two stars were gravitationally bound as opposed to the fainter being just a background star. Using the mural quadrant (Figure 6), at the Mannheim Observatory, Mayer listed 72 double star systems in a small book that was published in 1779 as the first catalogue of double stars (Mayer 1779).

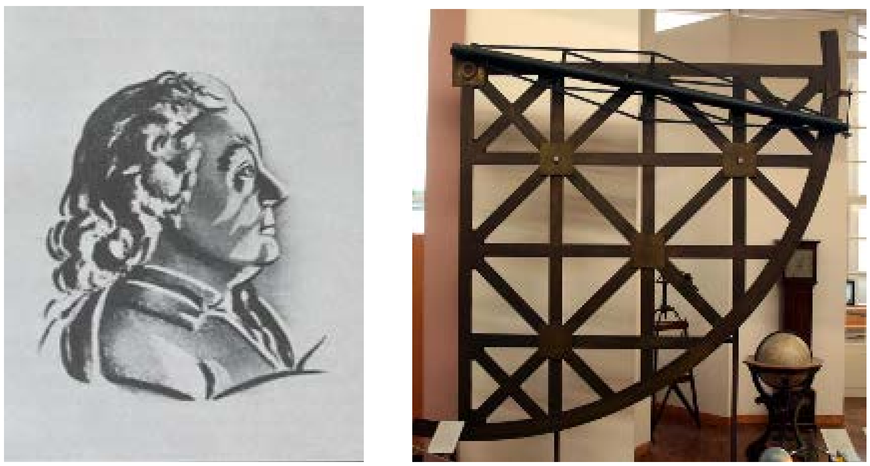

Figure 6. Christian Mayer along with the mural quadrant at Mannheim Observatory.

William Herschel

After immigrating from Hanover to London in 1759, Herschel, seen in Figure 7, continued his career as a musician before becoming interested in astronomy. His sister, Caroline, who later assisted him in his stellar observations, joined him in England. Herschel’s son John described Caroline’s relationship to William as being, “attached during the 50 years [they were together] as a second self to her Brother, merging her whole existence and individuality in her desire to aid him to the entire extent and absolute devotion of her whole time and powers” (Hirshfeld 2001, p176).

After performing and teaching music, Herschel pursued his interest in how math and music were connected. It is during this time he began to move his efforts away from music and math toward astronomy. With his innovative idea of placing the majority of his energy on aperture rather than precision for telescopes, he realized astronomers could see fainter objects due to the “greater light-gathering capacity” of his homemade telescopes (Hirshfeld 2001, p172). Herschel was described as “a parallax hunter practically from the moment he first pointed a telescope to the heavens” (Hirshfeld 2001, p173).

Herschel continued Galileo’s double-star method for measuring parallax by assuming that the brighter star was closer while the fainter star was farther from Earth. Herschel made this assumption because he thought that all stars were about the same brightness. Due to parallax, he predicted that these pairs of bright and faint stars would get closer and farther apart as Earth revolved around the sun.

However, through continued observations over the next quarter century of bright/faint pairs, he found that in many cases one star appeared to be moving around the other star. He realized that these doubles stars might not be separated by huge distances as he first thought, but were revolving around each other (Herschel 1803). This led Herschel to conclude that all stars may not have the same brightness.

With his large telescope he swept the skies for double stars. It was one fateful night in 1781 that Herschel used his own reflecting telescope, seen in Figure 7, to sweep the skies for double stars and discovered the dim and faint planet, Uranus. He was then appointed the “King’s Astronomer,” thanks to his discovery of Uranus. After this discovery Herschel “became the eighteenth century’s Galileo: a telescope maker, explorer of the deep space and friend of the common people” (Hirshfeld 2001, p172). Herschel, in 1782, became the third astronomer to observe Albireo.

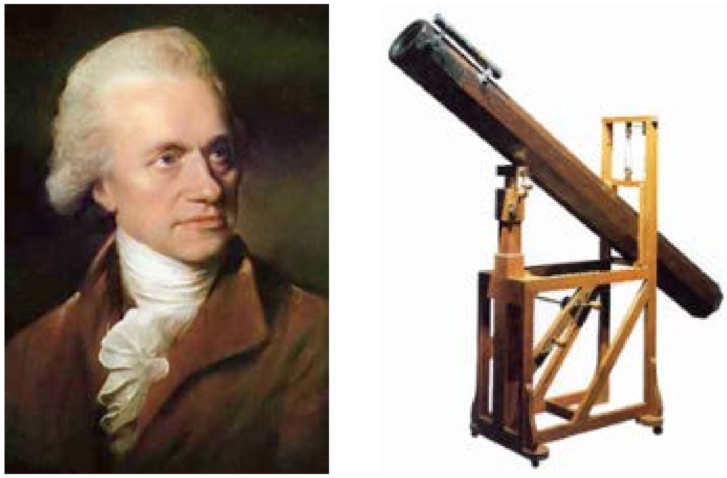

Figure 7. William Herschel and his seven-foot reflecting telescope.

Giuseppe Piazzi

Giuseppe Piazzi, shown in Figure 8, was an Italian Astronomer and Mathematician born in 1746. Piazzi received his Doctorate in Philosophy and Mathematics from the Theatine Order in Milan, and became the Chair of Higher Mathematics at the Academy of Palermo. Piazzi later built an observatory in Palermo. Using this observatory, Piazzi discovered the first asteroid, Ceres. After ten years of observing, Piazzi published a catalog containing 6,748 stars that he had observed with high astrometric accuracy (Piazzi 1803). Among them was Albireo, along with many of the other stars that early astronomers had cataloged.

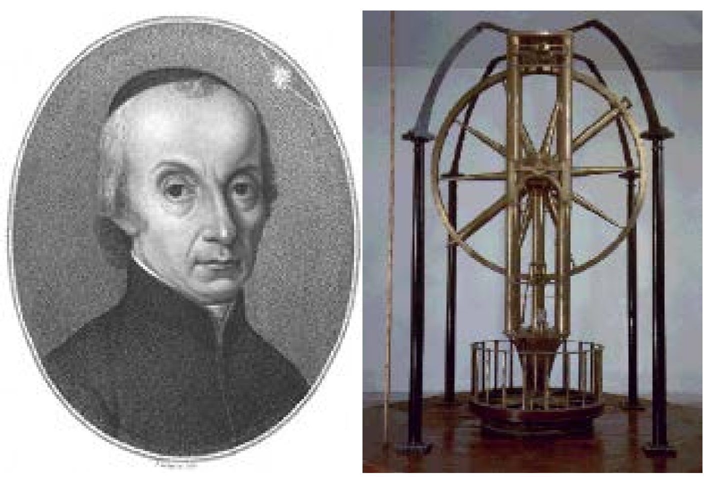

Figure 8. Piazzi and his five foot vertical circle

Friedrich Georg Wilhelm von Struve

Struve's family avoided the French occupation of Germany by moving in to Dorpat in Imperial Russia. In 1808 he began his studies at the Imperial University of Dorpat, where he discovered his passion for astronomy. From 1813 to 1820, he taught at the university as an astronomy professor, while collecting data at the Dorpat Observatory. In 1820, he became a full-time professor and the Director of the Dorpat Observatory.

In 1824, Struve received a nine-inch telescope from Joseph Fraunhofer. Due to the advanced mechanisms of this telescope, it was named the "Great Refractor." This telescope featured the first equatorial mounting drive that eliminated the drift of stars due to Earth's rotation. The telescope weighed roughly 5,000 pounds with a fourteen foot tube (Hirshfeld 2001, p252).

Struve, seen in Figure 9, is best known for his discovery and observations of double stars, as well as his research on the parallax of stars. Although many double stars he observed had been studied earlier by notable scientists such as William Herschel, Struve discovered the most new double stars, published in his 1827 double star catalogue *Catalogus novus stellarum duplicium* (Struve 1827). Struve made micrometer measurements of the position angles and separations of 2,714 double stars. Although Friedrich Bessel had been the first to measure the parallax of a star, Struve was the first to measure the parallax of Vega.

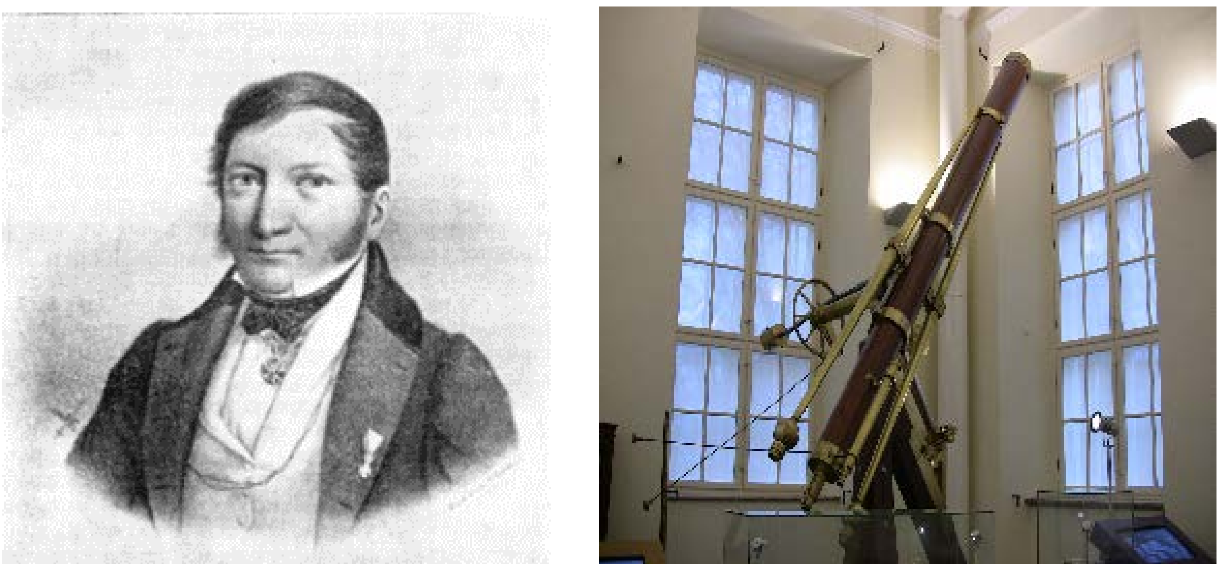

Figure 9. Friedrich Georg Wilhelm von Struve and the famous Fraunhofer nine-inch equatorially mounted refractor.

Sir John Herschel and Sir James South

Sir John Herschel, only son of William Herschel, began his independent astronomical career by further measuring many of the double stars that his father had previously observed, including Albireo. By investigating their movements since his father had cataloged them, Herschel hoped to discover something about the nature of gravitational force. He compiled a catalog with the help of the British astronomer Sir James South. Together South and Herschel published their observations in the *Philosophical Transactions* and were awarded the Gold Medal of the Royal Astronomical Society, a society John Herschel had helped found (Herschel and South 1824).

After working with the Royal Astronomical society for three years, Herschel traveled to South Africa, to extend his father's work to the southern hemisphere. He settled with his wife in Cape Town, and lived there for five years. During this time he recorded the position of nearly seventy thousand stars. These observations were published in his book *Results of Astronomical Observations, Made During the Years 1834 —38 at the Cape of Good Hope* (Herschel 1847).

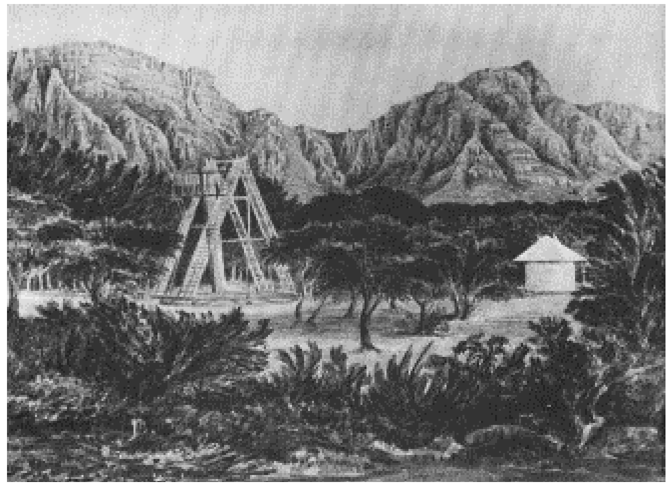

Figure 10. Sir John Herschel and his twenty foot telescope in Cape Town, South Africa.

Edward Skinner King

The first published photographic astrometric observation of Albireo was made by Edward Skinner King, an American astronomer in the late 1800s and early 1900s (King 1928). King's work at the Harvard Observatory, Figure 11, gave him access to state-of-the-art equipment to advance his research. The photographic technique allowed more precise determinations of Albireo's position angles and separations.

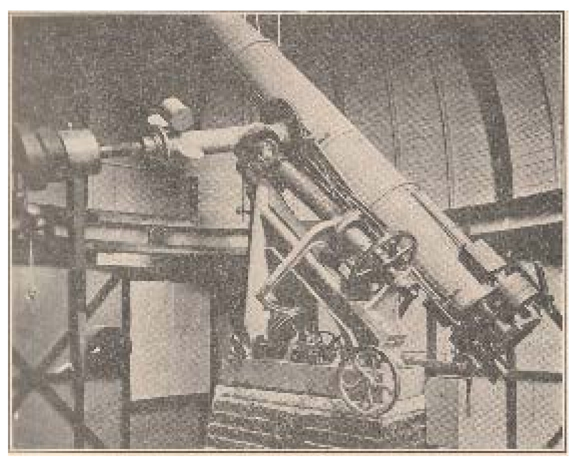

Figure 11. Harvard College Observatory along with the 11-inch refractor telescope used during the time period.

Andrei Tokovinin

Andrei Tokovinin, Figure 12, graduated from Moscow State University with a PhD in physics. He worked for the Sternberg Institute in Moscow for 20 years, where he spent his time building instruments and observing. He travelled to various countries and finally settled in Chile at the Cerro Tololo Inter-American Observatory, seen in Figure 12. He works with the National Optical Astronomy Observatory to improve the image quality of ground-based observations. Tokovinin was the first astronomer to observe Albireo with a CCD camera (Tokavinin and Shatskii 1995).

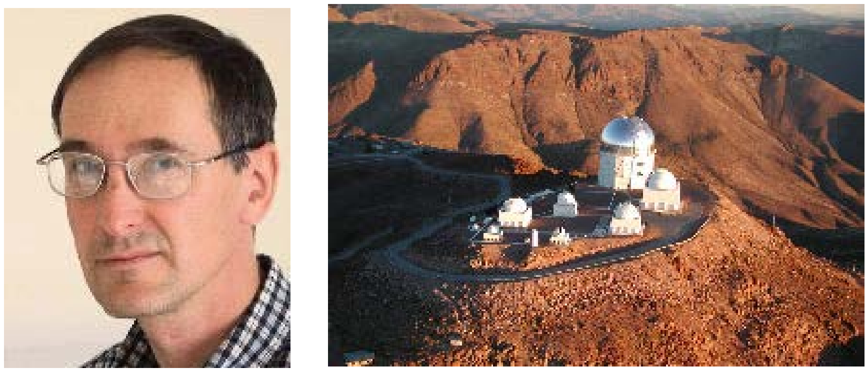

Figure 12. Andrei Tokovinin and the Cerro Tololo Inter-American Observatory.

Current Observation

The current observation of Albireo, reported in this paper, was made at the Orion Observatory on June 21, 2015 using a C-11 telescope equipped with a Celestron astrometric eyepiece. Ten measurements of the position angle of Albireo were made. To record the position angle, the primary star was placed at the 30th (middle) "tick" on the linear scale of the eyepiece and the tracking was then turned off, which caused the primary star drifted to the outer circular scale. When the star reached the outer scale, the tracking was turned back on and the angle that it stopped at was recorded. Unfortunately, during the observing session, the values were recorded to the wrong graduation. To correct this, ten degrees had to be added to each of the measurements.

Ten measurements of the separation of Albireo were made. This was done by placing the primary and secondary star a little below the linear scale of the eyepiece and estimating the "ticks" between them. Figure 13 shows one of the ten observations made of the separation of Albireo. In order to reduce observer bias, the eyepiece was rotated 180 degrees after each measurement and two observers were alternated.

To calibrate the linear scale, the primary star’s drift path was aligned with the linear scale and placed at the 0 mark. The telescope’s drive was then turned off and the time it took the primary star to move from the 0 to the 60 mark was recorded with a stopwatch to the hundredth decimal place. The average time was calculated and, using the formula below, the linear scale factor was determined.

$$Z = \frac{15.0411 * cos(\delta) * t}{d}$$

where δ is the declination of the star, t is the drift time in seconds, and d is the number of “ticks” on the linear scale. For the Celestron astrometric eyepiece, d was 60 ticks. Using these constants, the linear scale factor was determined to be 7.03″/tick.

Figure 13. A Celestron astrometric eyepiece, along with a photo of Albireo in the astrometric eyepiece showing a measurement of the separation.

Table 1 shows both the average separation and position angle, as well as their corresponding standard deviations and standard errors.

	Separation (Arcseconds)	Position Angle (Degrees)
Average Value	36.0	52.8
Std. Dev.	2.4	1.0
Standard Error	0.8	0.3

Table 1. The average, standard deviation, and standard error of the mean for the measured separation and position angle.

Discussion

Overall Plots

To test how the current observations compare to past observations, the previous observations reported in the WDS catalog were plotted on the graphs shown in Figures 14 and 15. Several outliers were omitted to increase the scale of the plots. The linear trend lines of these graphs were then found. The predicted values of Albireo's position angle and separation are the points on the trend line at the time of the current observation. These predicted values are then compared to the current observation.

To calculate the time of the current observation, we took the current year, 2015, and calculated the fractional year by taking the Julian number for June 21 (172) and dividing it by 365 which resulted in 2015.471 as the time of the current observation.

By plugging in this value of x in the two linear regression equations, the predicted values for position angle and separation based on the trend line from past observations were determined. The theoretical separation was 34.6″ and the theoretical position angle was 54.1 degrees. From these values it was determined that the percent difference in separation was 4.0% and the difference in position angle was 1.3 degrees.

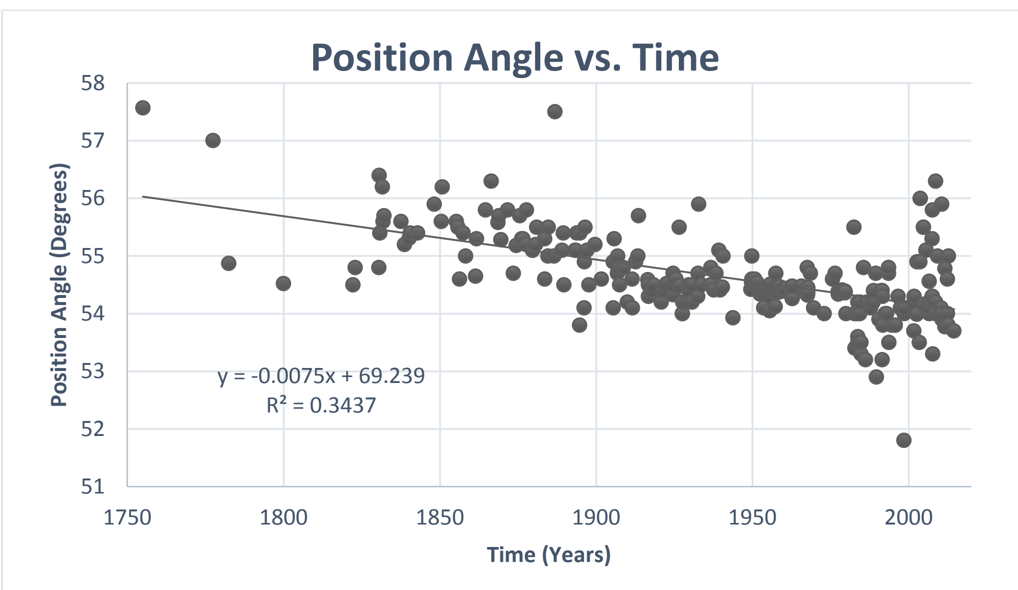

Figure 14. Previous observations of the position angle over time. Both the trend line and least squares regression formula are included.

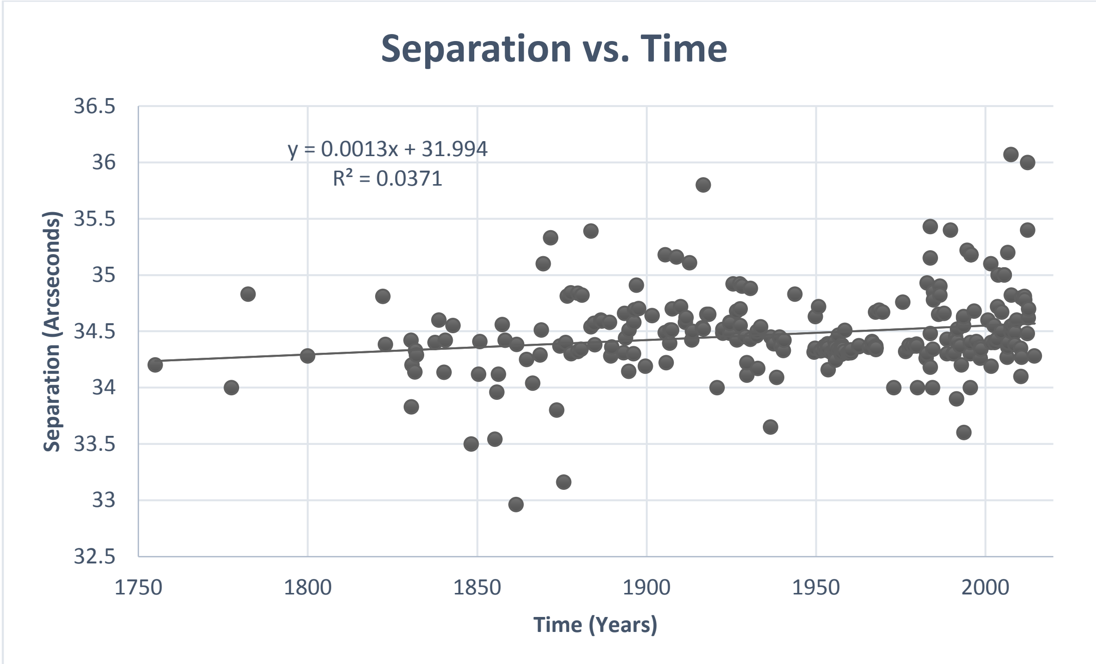

Figure 15. Previous observations of the separation over time. Both the trend line and least squares regression formula are included.

Trends in Various Techniques

Observation Technique	Category	Symbol	Color
Micrometer with Refractor	Ma	Triangle	Grey
Micrometer with Reflector	Mb	X	Yellow
Heliometer	D	Square	Orange
Photographic	Po	Star	Blue
Charge Coupled Device	C	Diamond	Blue
Others	Others	Circle	Green

Table 2. Several observation techniques with corresponding categories and symbols.

Figures 16 and 17 show the past observations of position angle and separation of Albireo using symbols for the different major observation techniques. Table 2 shows an expanded legend, matching that on the graph, which shows the various observation techniques and their corresponding categories and symbols. These observation techniques fell into five distinct categories along with an “other” category which contains lesser used techniques such as speckle interferometry, microguide eyepiece, and transit circle/ meridian circle. One feature of Figures 16 and 17 is how scattered both the micrometer with refractor and reflector are. Also, these were the two techniques that seemed to have been used from the beginning of Albireo’s observations to the present. Another feature is the precision of photographic techniques.

Besides one distinct outlier in Figure 16, photographic observations are grouped so closely that they form a distinct line. Lastly, these graphs show when various observation techniques were first prevalent and when they became less frequent. For example, the heliometer's observations lasted from 1825 until 1900, the photographic from 1900 until 1975, and the CCD from the late 1900's until the present.

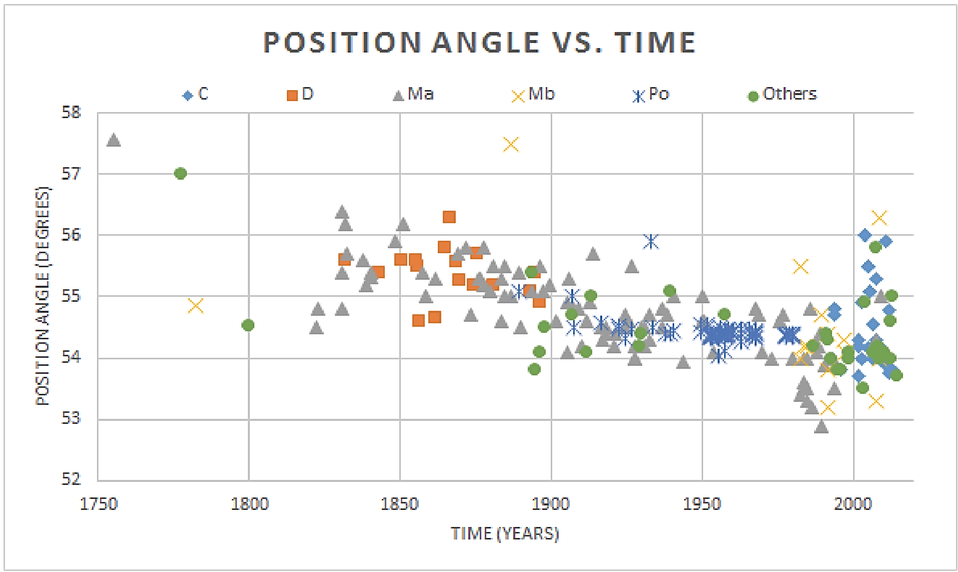

Figure 16. Position angle over time. Each different symbol represents a different type of observation technique corresponding to the legend at the top of the graph.

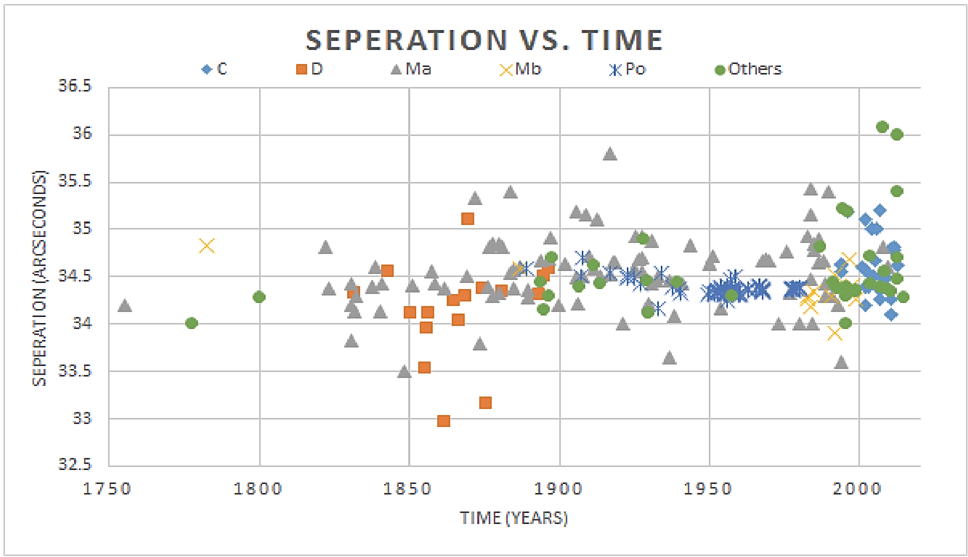

Figure 17. Various observation techniques of separation over time. Each different symbol represents a different type of observation technique corresponding to the legend at the top of the graph.

Interestingly, the trend line for photographic techniques has a negative slope compared to the overall trend line, which is positive. After breaking up the overall graph, without outliers, into sections of time, a distinct "bump" can be seen from the late 1800's to 1950. This "bump" is shown in Figure 18, along with various trend lines plotted over sections of time. It looks as if more of a curve would fit the graph compared to a straight line. This curve in the separation may be caused by a third star in Albireo's system. In fact, Albireo does contain a third star, the C component, which is 0.4″ from the A component. Looking at Figure 18, there appears to be a subtle period of displacement from this star starting in 1750 and lasting until 1950. After this, the cycle appears to start to repeat by beginning to increase again. Albireo's A and C component do have a period of 213 years, which is consistent with the observed value in Figure 18 of at least 200 years.

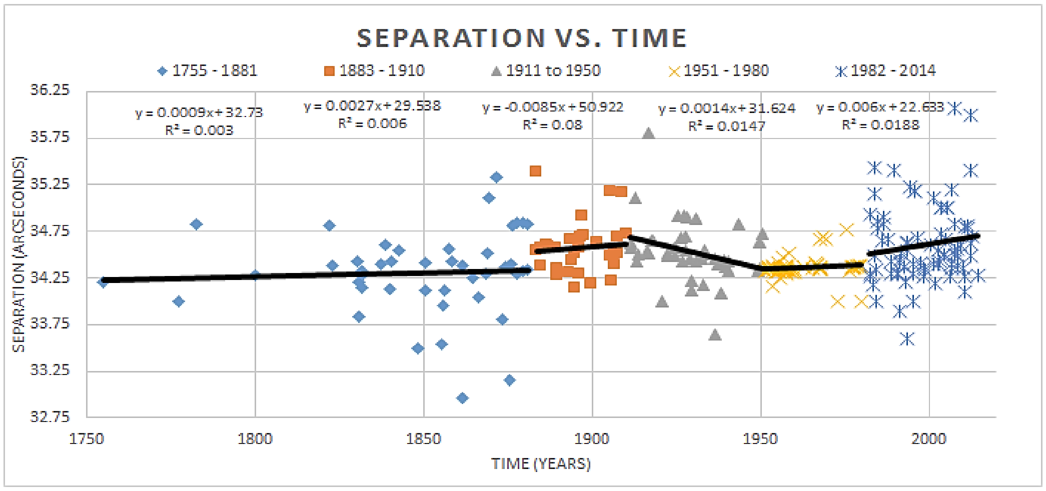

Figure 18. The separation over time of Albireo cut into distinct segments of time represented by various symbols. The trend line equations are added just above or below each trend line.

Conclusion

The history of Albireo and the observation techniques used to observe it parallel the overall development of double star astrometric research. By making observations with an 11 inch telescope and astrometric eyepiece, we were able to measure the current separation and position angle of Albireo. Plots of past observations implied the existence of Albireo's known third star.

Acknowledgements

We thank Brian Mason at the U.S. Naval Observatory for providing a list of past observations of Albireo.

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Detecting Faint Secondary Stars with Shaped Aperture Masks

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Abstract Two shaped aperture masks were evaluated to test for useful ranges when examining double stars with large differential magnitudes and separation. Through observations of multiple double stars, the Gaussian Donut mask showed no conclusive evidence that it was more successful than an unmasked telescope. Due to the detection ability of speckle interferometry alone, and a relatively large diffraction pattern from the mask, the Gaussian Donut mask was unable to make a significant difference. Comparatively, the Bow Tie mask showed promise with a small diffraction pattern allowing for close inner working angles of near 1″. Given the current boundaries, further investigation of the mask's abilities will allow for better detection and the resolving of close double stars.

Introduction

Diffraction

Diffraction occurs when an opening is placed in the path of a beam of light causing the light to bend around the edge. Smaller openings cause the light to bend extensively, while a larger opening will cause a much less noticeable phenomenon. Famous experiments such as the double and single slit experiment exhibit this, as well as demonstrating the wave-particle duality principle of light. The light bends around the edges as waves, which allows for destructive and constructive interference. This causes an overall diffraction pattern of bright and dark regions where there is constructive interference and destructive interference respectively. Figure 1 shows the diffracted waves and how they come to fruition on the screen. There are clear bands created where the waves end with constructive interference. With this in mind, other diffraction patterns can be created depending on the shape of the obstruction and how the light is diffracted. Figure 1 demonstrates the famous Airy Disk pattern which is created by a circular opening. The light diffracts in such a way to create concentric rings around the central fringe outward. The rings demonstrate an area of constructive interference of the light going through the circular opening.

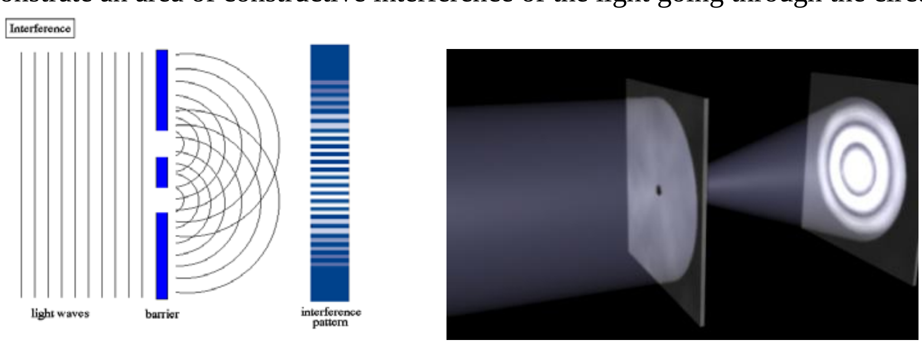

Figure 1. The left image shows the double slit experiment. The right image shows the circular aperture diffraction pattern.

The diffraction from the circular opening works similar to how a telescope diffracts light from a star. Fraunhofer diffraction simplifies diffraction by assuming a star is far enough away to treat it as an infinitely far away object. With this condition, the telescope aperture can be treated as a single point circular opening, causing the same diffraction pattern. Figure 2 shows this diffraction on a simulated single star with an Airy Disk pattern around it.

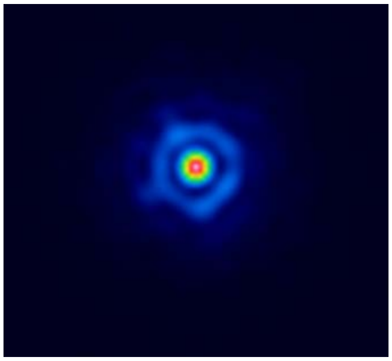

Figure 2. Simulated Star with Airy Pattern.

Importance for Binary Stars

The Airy Disk pattern occurs with any star that is observed through a circular aperture, which is the phenomenon that occurs through all telescopes. As seen in Figure 3, this feature can be very prominent when observing a double star, as the ring can potentially block a secondary star.

The primary focus of the project was to promote the discovery of binary star systems that have large differential apparent magnitudes as well as close separations. These normally would be heavily disrupted by the Airy Disk pattern. With a large differential apparent magnitude, the brighter star's diffraction pattern will easily engulf the much fainter star. In addition to this, having the stars in close proximity causes the secondary star to be within the range of the diffraction. Figure 3 shows a simulation of a binary star system with about 1″ of separation and only two differential orders of magnitude between them. This shows the damaging effects of a bright main star with close separation to its companion star in how difficult it is to resolve them.

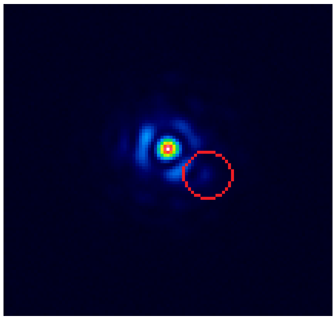

Figure 3. A Simulated Binary Star System with 1″ separation and two differential orders of magnitude in Atmospheric Seeing Distortion simulator. The red circle demonstrates the placement of the secondary star.

Why do these specific binary stars matter?

Spectral classification assigns a letter based on the surface temperature of a star. The scale goes through the letters O, B, A, F, G, K, and M, where O stars are relatively hot and M stars are relatively cool. With this temperature gradient in mind, and knowing the Stefan-Boltzmann law $E = \sigma T^4$, it becomes evident that cooler stars will have a much lower energy output (Peterson and Ryden 2010). This energy output directly correlates to the luminosity of the star. In a binary star system with a hotter star and a cool M star, the M star will be easily drowned out based on luminosity. This does not take into account atmospheric distortion and the Airy Disk diffraction that exacerbates the situation. M class stars are difficult to find, leading to an underrepresentation on the HR diagram critical in pinpointing the composition of our universe.

Similar to the spectral classification, being able to determine if the system is a binary or optical double is crucial. One way to do this is to determine the motion of the star; if they are gravitationally bound they will rotate around one another, and if not they will simply move apart. With widely separated stars, the movements will be difficult to detect because the periods can move up to hundreds of years or longer. Knowing Keplar's Law of Periods, $P^2 = a^3$, it becomes evident the period grows very quickly as the separation increases (Peterson and Ryden 2010). Being able to find very close binary and double stars makes the process much easier, as the period will be much shorter and actually noticeable as compared to wider binaries.

Origin of Aperture Masks

The idea for diffraction masks started out as a technique to discover exoplanets and is now being applied to double star research. Exoplanets will behave just as the double star systems being observed, as it will be revolving around a much brighter stellar body. Both issues found in binary star discovery lie in the nature of exoplanet research. For the large delta magnitude problem, this will be heavily magnified because the exoplanets will not be emitting any sort of light. The only light that will be seen will be what is reflected by it. This can cause these planets to become quite dim in relation to a secondary star component of a binary system, making them even more difficult to find.

As for the second problem, the habitable zone is an area where exoplanets will be most useful as that is where they could harbor life. This distance ranges anywhere from a quarter of an astronomical unit to 15 astronomical units, causing the resulting small separation to also be a difficult factor. Aperture masks for this problem would need to allow for enough light gathering power while also allowing for smaller inner working angles. These two combat one another due to larger obstructions causing smaller diffraction patterns. Conversely, as the mask is made larger, light gathering power is forfeited, causing a tradeoff.

For the moment, the transit method is used by NASA with great accuracy, but aperture masks would be well suited to allow for direct observing of these exoplanets. Using the transit method, an actual transit must occur, limiting when data can be taken. Furthermore, the exoplanet must be edge-on with the star, further limiting the ability to view. The aperture mask can fix this problem, allowing for the ability to view the planet at any position and allowing for the ability to find new exoplanets not previously discovered. Aperture masks can aid in the determination of the location of an exoplanet versus only using the transit method, allowing for more information to be discovered and logged.

Designing and Creating the Diffraction Masks

In determining whether a diffraction mask will be useful, the first step involves creating a simulated version of the mask in MATLAB. MATLAB is a computation environment capable of handling development as well as analysis of data. More importantly, MATLAB excels in handling matrix computation, which is relied on in mask design. A matrix the size of the mask is created and assigned either zeroes or ones. The numbers represent the brightness of the pixel it is assigned to. The number one tells MATLAB to turn the pixel white, while a zero tells it to turn the pixel black. The aperture mask itself is comprised of all the black pixels.

Taking the Fourier transform of this decomposes the mask's frequency into the most basic sinusoidal waves it's comprised of, which demonstrates where the diffraction will occur. When creating the original outline for the mask, there are two basic principles that need to be followed in the design. First, as the size of the obstruction gets bigger, there are more sinusoidal waves that can fit in the original frequency, causing a stronger, more inward diffraction pattern. Secondly, as the obstruction gets smaller, fewer waves can fit, causing a weaker, more outward diffraction pattern.

Once a mask has been proposed and determined to be efficient in terms of allowing for a close inner working angle and large discovery zones, it can be physically created. Sturdy but light materials such as acrylic and foam core have worked well as aperture masks. Next, the material needs to be laser cut using the outline from the MATLAB processes. It is important to be aware of widths and sizes to obtain a clean cut. Once cut, the mask is best sprayed with a dull black color in order to not interact with any light waves.

Diffraction Masks

With the airy pattern disrupting the viewing of a secondary star, it becomes important to attempt to push this light in a different direction with the intent to form "discovery zones." These zones are where the secondary star can be observed. These discovery zones are places of destructive interference of light from the primary star due to the wave nature of light that allow for easier viewing. Understanding that the telescope aperture acts no different than pinhole diffraction, the shape of the aperture can be changed to achieve different forms of diffraction patterns.

Changing the aperture can be done by using diffraction masks which are disks that go in front of the telescope. The masks effectively change how the light will bend. The first mask proposed was the Gaussian Donut mask, designed by Ed Foley, which can be seen in Figure 4. This design was based off of a Gaussian curve mask developed by Kasdin and his group (Kasdin et al. 2003). On the left of Figure 4 is the actual shape of the mask and what will be obstructing the front of the telescope. On the right of the image is the theoretical diffraction pattern that occurs when the telescope is obstructed by the mask. The darker triangular areas on the left and right side of the pattern are the areas where the secondary star would want to be placed, as that is where the light is destructively interfering.

The primary goals of the masks are to achieve a strong contrast ratio between the darker and lighter regions, and achieve a small working angle to resolve closely separated binary stars. The working angle is where the secondary star can be placed to allow us to see it. The darker regions will allow the ability to resolve fainter stars, and the smaller working angle will allow for resolution of closer stars. The Gaussian mask itself is theorized to best be used at wider working angles, 4" to 7" for the Celestron C-11 that is being used for this project.

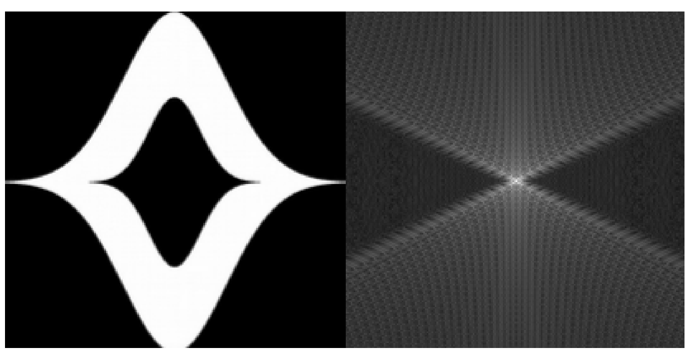

Figure 4. Gaussian Donut Mask shape with diffraction simulation to the right.

The second mask evaluated was the Bow Tie mask, which was designed by Neil Zimmerman at Princeton. This mask, seen in Figure 5, does not have as clearly defined discovery zones as the Gaussian mask, but instead gives closer working angles. The brighter area in the center of the diffraction pattern on the right shows where most of the light will be diffracted, while the darker is where the light from the primary will destructively interfere. The inner dark circle is theorized to work at 1″, which is much closer than the Gaussian Donut's 4″ to 7″. On the other hand, the area of discovery is quite small and will be much harder to position.

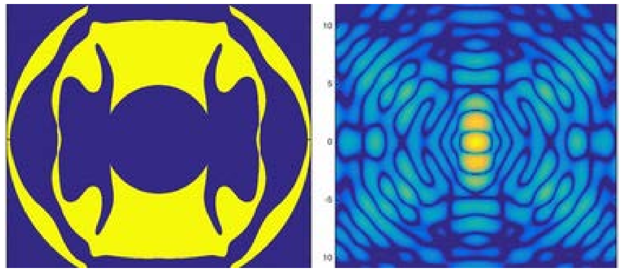

Figure 5. The Bow Tie mask designed by Neil Zimmerman. The mask shape is on the left and the diffraction pattern is on the right.

Equipment

All of the data was taken on the Celestron C-11 Schmidt-Cassegrain telescope at the Orion Observatory. The C-11 optical tube assembly sits on a German equatorial mount with full range of motion. The setup used involved back end instrumentation for easier imaging. The instrumentation revolves around a flip mirror that directs light into a Canon DSLR acquisition camera. Once centered, it can be flipped to an Andor Luca EMCCD for imaging. The set up can be seen in Figure 6. The EMCCD camera used a TeleVue 2.5x Barlow lens on targets above 2″ and was set to 20ms exposures, taking 1000 images to create a data cube. Each image was taken at 128 by 128 pixels. The camera was controlled through a Windows 8 laptop with Andor Solis Imaging software and the data was reduced with Dave Rowe's Plate Solve 3 (Rowe & Genet 2015). The masks used were cut out of acrylic and placed on the front end of the telescope; one of the masks, the "Gaussian Donut," can be seen on the front end of the C-11 in Figure 6.

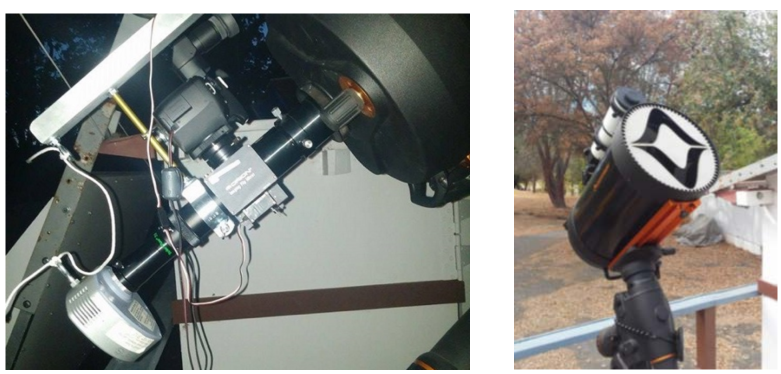

Figure 6. The left image shows the back end imaging components, the right image shows the Gaussian Donut mask on the C-11 telescope.

Data

Images taken through the Andor Luca EMCCD camera were taken as .sif files and translated into fits cubes. The fits cubes are then able to be speckle reduced in Plate Solve 3. When acquiring the actual data, three to five sets of data were taken for each binary pair. The first set of data was images with no aperture mask in front of the telescope. This was done to provide a control to compare further images. If the stars were greater than 6″ in separation, only the Gaussian Donut mask was used to take data. If the stars were under 4″ only the Bow Tie mask will be used. If the star is between 4″ and 6″, both masks will be used due an ambiguity in masks' limits. When using a mask, a data set was taken from a neutral position in 30° intervals up to 90° position to find the best spot for the closest inner working angle. The masks have symmetrical diffraction patterns; therefore going through the whole rotation will not be necessary, although multiple spots are needed due to the small angle of the discovery zones.

A list was compiled from the WDS catalog of 119,400 stars to find appropriate targets for imaging. Due to being in the Northern Hemisphere, any stars with negative declination were taken out, leaving 70,696 stars. Next, stars with separations between 1″ and 15″ were chosen to give a wide range of targets. Anything above 15″ was unnecessary and anything below 1 would be under the theoretical limit of the telescope itself. This constraint dropped the list of stars to 35,378. In addition, any secondary star lower than 12th magnitude was taken out due to the limit of the EMCCD camera coupled with the telescope's aperture. Anything that faint would be undetectable and thus unnecessary, bringing the star list down to 14,105. Filtering the primary stars to only 7th magnitude and brighter to achieve easy finding pushed the list much farther down to 601 candidates. Lastly, an RA filter of 13hours to 20hours left 163 final candidates that filled all of the requirements.

The data section below has two components, discussing each mask on its own. The first section discusses the Gaussian Donut mask, exploring limits and usefulness. The second section discusses the Bow Tie mask, investigating the same information. The left image is the double star without a mask, and on the right with a mask.

Star List

Star Name	Separation	Mag. 1	Mag. 2	Delta Magnitude	Mask Used
BU 287	7.2	2.96	12	9.04	GD
STF 2140	4.7	3.48	5.4	1.92	GD/BT
STF 2579	2.5	2.89	6.27	3.38	BT
BU 627	1.8	4.84	8.45	3.61	BT

Table 1. Star list that was used to obtain data.

Gaussian Donut Mask

BU 287 was imaged without a deconvolution star. The secondary component of the binary system was near the limit of the equipment's detecting ability, which was around 12th magnitude, and difficult to get desirable results. The primary star is 2.9th magnitude, causing the secondary star to be drowned out and hard to resolve. The image on the left in Figure 7 with no mask demonstrates detection of the faint secondary star. Although difficult to see, it can be seen near the top right of the image. The image on the right in Figure 7 shows the double star with the Gaussian Donut mask, where the secondary star is a faint smudge. Placing an aperture mask on the telescope ultimately blocks portions where light can be gathered, potentially causing a star at the limit of the unmasked set up undetectable.

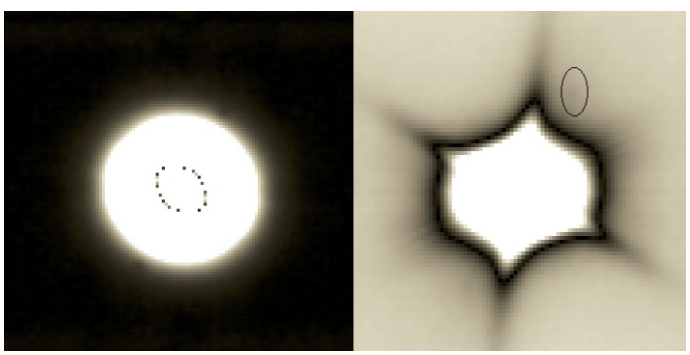

Figure 7. Images of binary star BU 287. The left shows the unmasked image while the right shows the masked image.

STF 2140 was imaged without a deconvolution star. The secondary star was only two orders of magnitude lower than the primary star at 5.4th magnitude, making it very bright. The main focus of this image was to determine an inner working angle for the mask. With no mask, the airy null pattern doesn't seem to be as clear. This could be an overexposure issue that is weakened once a mask is able to block out light. As for working angles, the star still has some room to move inward. This demonstrates the spot necessary to achieve the closest inner working angle, in the smallest triangular regions.

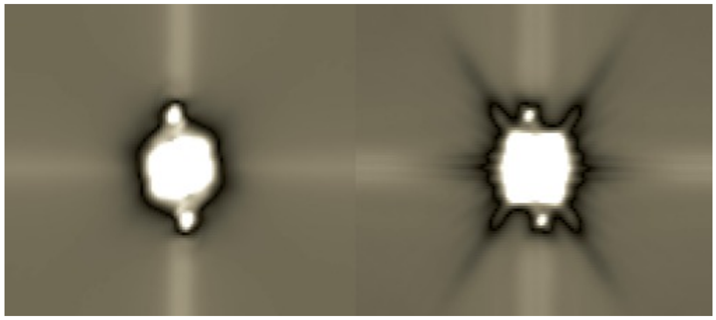

Figure 8. Images of binary star STF 2140. Main focus is on the large diffraction spikes from the aperture mask.

Bow Tie Mask

STF 2140 had a deconvolution star used on both images. Considering the same magnitudes, this image was primarily used to test inner working angles. The left image in Figure 9 shows the pair with no mask, and the right image shows the pair with the mask. The secondary star has a clear airy disk pattern with clear room to continue to move in further. When using the astrometry tool in Plate Solve 3 the inner working angle shows to be approximately 1.8″, which can be closer under better conditions.

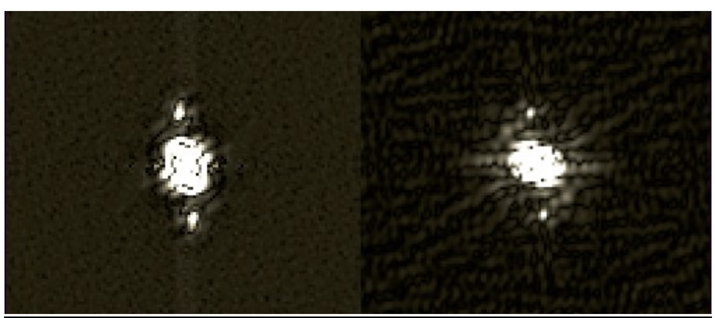

Figure 9. Images of binary star STF 2140. The secondary component of the system is much clearer and circular in the masked image in comparison to the unmasked image.

STF 2579 used a deconvolution star for both of the images due to what was found in the STT 328 images. By being separated by 2.5″ the binary star system falls under the 4″ limit where a deconvolution would not be required. The bright primary star of 2.9th magnitude and the secondary star of 6.7th magnitude don't produce a large differential magnitude, but it works well in determining an inner working angle for the mask. In the image with no mask, it is clear the diffraction pattern of the primary star is beginning to interfere with the detection of the secondary star. The airy null pattern is neither complete nor is it as dark in comparison to the image with a mask. The image with the mask clearly demonstrates the Bow Tie mask's theoretical diffraction pattern, and when analyzed with the astrometry tool, it shows an approximate 1.5″.

Figure 10. Images of binary star STF 2579. There is clear demonstration of the Bow Tie diffraction pattern with a much more defined outline of the secondary component.

BU 627 used a deconvolution star for both of the images. With the primary component of the system being 4.8th magnitude and the secondary component being 8.5th magnitude, the main purpose of this image was to further refine the inner working angle of the mask. BU 627 is separated by 1.8″ which is clear when compared to STF 2579 and how close the secondary star sits near the primary star. The secondary star also starts to become less noticeable in comparison, due to the drops in magnitude. With the mask, the secondary component has a clear airy null pattern surrounding it, making it much easier to pinpoint. Using the astrometry tool just as in STF 2579, a limit of 1.2″ is shown, which is better than in the previous image.

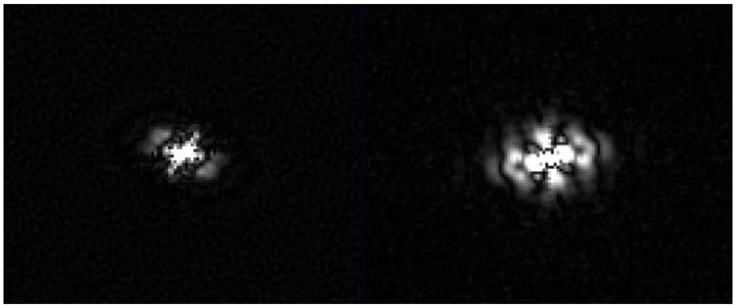

Figure 11. Images of binary star BU 627.

Conclusion

Through the analysis of numerous double stars with both the Gaussian Donut and Bow Tie mask, rough estimates can be made of where they work their best, based on an 11 inch aperture telescope. The Gaussian Donut appears to be useful, but unnecessary due to the independent ability of speckle reduction. The diffraction pattern diffuses out approximately 4″, while speckle reduction is shown to easily reach 2″ and lower. When observing large differential magnitudes, the mask also had difficulty detecting much fainter components. This may have been an issue in the 11 inch aperture, losing light gathering power as the mask obstructed the opening.

The Bow Tie mask showed promising results by demonstrating very close working angles that were able to surpass the ability of speckle reduction without any mask. In STF 2579 and BU 627 the diffraction of the primary component could be seen interfering with the airy null of the secondary component without a mask. With the Bow Tie mask, the diffraction was diffused outward, allowing better contrast inward and thus better detection. With the theoretical discovery zone of the Bow Tie mask residing around 1″, this was able to be further supported with multiple images of the double stars, giving room for continual observations.

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Intensifiers: A Low Cost Solution for Observing Faint Double Stars?

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Abstract Intensifier tubes have commonly been used for night vision, but could have potential to be a low cost solution to telescopes observing faint stars. Four total generations of intensifiers have been produced, but only Generations 2 and 3 show promise for Astrometric research due to the development of the microchannel plate and more efficient photocathodes. Although these intensifier tubes have potential to improve the performance of telescopes using speckle imaging, a new low cost CMOS camera is able to perform as well as we had hoped the intensifier could.

Introduction

Since the invention of speckle interferometry by David L. Fried in 1965, film cameras limited the capability of double star observations (Fried 1965). Speckle imaging became frequent in the 1970's, but the low quantum efficiency of these film cameras could only capture a small portion of light, making only bright double stars suitable for observations. The 1970's introduced the Charge Coupled Device (CCD) camera, shown in Figure 1, which is far more sensitive to light but has issues with high speed read noise when converting data from analog to digital. This is the same issue that most CMOS cameras are prone to. The high speed read noise limits small telescopes to seventh magnitude stars when using CCD or CMOS cameras at high speed for speckle interferometry. Shown in Figure 1, the Electron Multiplying CCD (EMCCD) camera, invented in 2001, does not face the same issues as its predecessors as it amplifies the signal with an on-chip gain register prior to the noisy analog-to-digital converter on the output, thus reducing the amount of read noise relative to the signal. However, EMCCD cameras cost $14,000 to $40,000, making them an expensive option for both amateur and professional astronomers.

Figure 1. A CCD camera, left, along with an EMCCD camera, right.

A potential alternative to an EMCCD camera is an intensifier tube, which is commonly used in night vision devices. Intensifier tubes amplify the light the telescope receives from distant stars. Photons over a range of the electromagnetic spectrum enter the telescope and are converted to electrons by a photocathode. Early generations of intensifier tubes convert the electrons back into photons, but later generations were able to amplify the quantity of electrons. The resulting photons are focused by an eyepiece lens, making an image much brighter than the original. Intensifier tubes cost approximately $200 to $3,000, making them a potentially cost efficient alternative to EMCCD cameras. This may make collecting speckle data from close, faint binary stars with a mere CCD actually plausible.

However, after this project was well along, it was found that a new, very low cost, CMOS camera was able to do what we had hoped for the intensifier tubes, on a smaller budget and with better performance (Genet, et al. 2015). Due to the quality of the new camera, we found it unnecessary to test and observe with the intensifier.

Intensifier Description

The concept of an intensifier tube was first proposed in 1757 by Mikhail Lomonosov. He proposed and later proved that tubes could be built which would allow the naked eye to view objects in the dark (Ponomarenko & Filachev 2007, p1). Although he originally proposed this idea, it was far ahead of its time and would not become a relevant idea until Broglie proposed that electrons, and matter, had wavelike properties (Broglie 1923). Ten years after Broglie's PhD thesis, scientists working for Philips developed the first infrared converter. Since then, there have been four generations of intensifier tubes invented throughout the past century.

Generation 0

The Generation 0 intensifier tube uses an objective lens to collect and focuses incoming photons onto a photocathode which emits an electron due to the photoelectric effect (Einstein 1905). The photoelectric effect states that when a photon hits a metal, a photoelectron can be "knocked" loose. The maximum kinetic energy of one of these photoelectrons is governed by the equation below.

$$KE_{Max} = hf - \emptyset$$

where h is Planck's constant, f is the frequency of the incoming photon and ϕ is the work function of the material. This means that for the photoelectric effect to occur, the energy of the incoming photon, hf, must be greater than the work function of the metal. Each photocathode is composed of different materials which causes the work function to change; therefore, the threshold frequency of incoming photons required to knock an electron loose varies by material.

In the Generation 0 intensifier, a S-1 photocathode consisting of silver, oxygen, and caesium (Ag, O, and Cs) is used. Due to the composition of the photocathode, it responds best to near-infrared electromagnetic radiation (Skatrud & Kruse 1997). This photocathode has a spectral range from 400nm to 1200nm and a peak quantum efficiency of .4% at 740nm (Hamamatsu Photonics 2006, p35). The quantum efficiency of a photocathode is the percent of incident photons that are converted to electrons by the photocathode. This percent can be calculated for a specific wavelength of light as seen in the equation below (Hamamatsu Photonics 2006, p38).

$$QE_{\lambda} = R_{\lambda}(hc/p\lambda)$$

where c is the speed of light, h is Planck's constant, λ is the wavelength of the incident photon, q is the charge of a photon, and R is defined as the photocurrent, or electric current, of the photocathode divided by the radiant flux, or the radiant energy transmitted over time.

After the photons are converted to electrons, they are then accelerated in an electrostatic field and inevitably hit a phosphor screen. The phosphor screen then releases 20 to 200 photons for every electron hitting the screen, multiplying the image even further. The phosphor screen is also what gives many intensified images their green color.

Generation 1

The difference between the Generation 0 and Generation 1 intensifier tubes was the discovery of more effective photocathode materials. The Generation 1 contains a S-20 photocathode consisting of sodium, potassium, antimony, and caesium (Na, K, Sb, and Cs). The S-20 photocathode peaks in quantum efficiency at a wavelength of 375 nm, which is on the border of ultraviolet and the visible spectrum (Hamamatsu Photonics 2006, p35).

Although, like the Generation 0 intensifier, it does not peak in the visible spectrum, the quantum efficiency of the S-20 photocathode peaks at 20% (Hamamatsu Photonics 2006, p35). Compared to the Generation 0 intensifier, the Generation 1 intensifier's quantum efficiency is fifty times larger, due to the improved photocathode, making it superior in converting incident photons to electrons.

Generation 2

The Generation 2 intensifier tube, whose optical layout can be seen in Figure 2, differs from the Generation 1 in two specific ways. It uses a S-25 photocathode instead of the S-20, and a newly developed microchannel plate. The S-25 cathode consists of sodium, potassium, antimony, and caesium (Na, K, Sb, and Cs). The same materials are used in the S-20 photocathode, but the S-25 uses thicker layers of this material. As a result, the S-25 has a reduced quantum efficiency of 8% but causes the photocathode to peak in quantum efficiency at 580nm (Hamamatsu Photonics 2006, p35). Another property of the intensifier tube is that compared to the Generation 1, it is more sensitive to the infrared portion of the spectrum and less toward the blue end of the spectrum. Although there is a significant loss in the photocathode's quantum efficiency, the electron multiplication of the microchannel plate makes up for this.

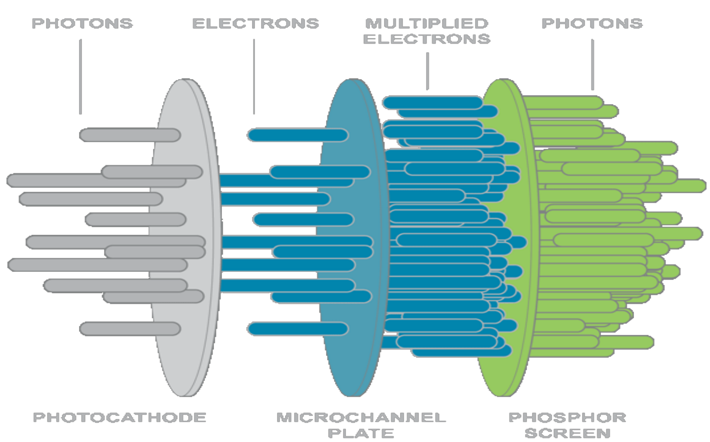

Figure 2. The optical layout of the Generation 2 microchannel plate. From left to right, the photocathode, microchannel plate, and phosphor screen.

In addition to the improved cathode, the Generation 2 intensifier uses the newly developed microchannel plate seen in Figure 2 to amplify the signal. This microplate is a thin glass wafer manufactured from thousands of individual, hollow glass fibers, or microchannels. A large potential difference is applied across the microplate. Electrons enter the microchannels within the high voltage plate and collide into the channel walls. Each individual electron elicits hundreds of additional electrons, as seen in Figure 3. This process greatly multiplies the number of electrons that entered the tube. These multiplied electrons hit the phosphor screen, resulting in a magnified image.

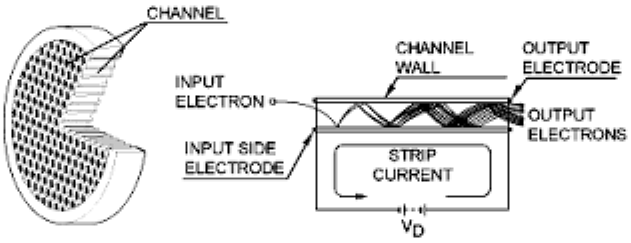

Figure 3. A Microchannel Plate, left, along with an individual microchannel, right.

Generation 3

Advancements in photocathode technology induced the development of the 3rd generation intensifier tube which used gallium arsenide (GaAs) for the photocathode. This gallium arsenide photocathode has a spectral range of 380 to 890nm and has a peak QE of 14% at 760nm (Hamamatsu Photonics 2006, p35). Although this QE is not as high as previous photocathodes, the photocathode "demonstrates a nearly flat, high-sensitivity spectral response curve from 300 to 850 nanometers" (Hamamatsu Photonics 2006 p31). This makes the photocathode sensitive to infrared and visible light where other photocathodes might drop off in the visible or infrared. The Generation 3 photocathode also includes a microchannel plate, but due to damaging chemical and electrostatic effects inside the tube, a metal-oxide coating, known as an ion barrier film, was added on the input side of the MCP to protect the photocathode. The film greatly increases the lifespan of the Generation 3 tubes to 15,000 hours in comparison to the Generation 2 tubes which have a lifespan of 2000 hours.

Discussion

Intensifier tubes show promise in aiding telescopes in seeing fainter and closer double stars due to their ability to convert a broad spectrum of a star's spectrum into visible light. By converting a broad wavelength of a star's spectrum along with many internal mechanisms, these intensifier tubes are able to multiply the light received from a star. Pairing an intensifier tube along with a typical CCD camera may be able to produce results equivalent to an expensive EMCCD camera.

Although intensifiers may be an adequate alternative to an EMCCD camera, a new low cost CMOS camera has produced results that are similar to what we had hoped for from the intensifier tubes (Genet, et al. 2015). This caused the testing of intensifier tubes in aiding speckle imaging to be overcome by the CMOS camera. Intensifier tubes may still prove useful for observing certain astronomical objects. Due to an intensifier's ability to convert light, particularly from the infrared end of the spectrum, intensifiers could be beneficial when observing objects whose spectrum lies in infrared light. Further investigation into this subject may prove to have valuable results.

Acknowledgements

We would like to thank Benoit Schillings, from La Cresta Observatory, for allowing us to use his intensifier.

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Newtonian 17.5-inch Optical Tube Assembly

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Abstract The optical tube assembly design is composed of three aluminum boxes connected by steel conduits. After modeling the design, an equation was derived to determine where the center of mass of the telescope was. This determined where the center box would be placed and how long the trusses would be. Collimation was achieved using a laser collimating tool. For testing, the telescope was tilted toward Polaris because of the convenience of the star being fixated on the celestial sphere. Stars were observed and were able to be brought to focus during the field testing of the telescope.

Introduction

Before the invention of the Newtonian reflector in 1668 by Isaac Newton, astronomers worked with refractor telescopes (Wilson 2004, p.9). Refractor telescopes utilize an objective lens located in the front of the aperture in order to direct and focus light into an eyepiece. Unfortunately, refractor telescopes run into the issue of chromatic aberration. Chromatic aberration is the phenomena in which different wavelengths of light diffract at different angles when traversing through a medium, in this case, the telescope's lens. This causes images produced to be blurry when viewed because the different wavelengths are focused at different points.

To contrast, the Newtonian reflector, seen in Figure 1, relies on mirrors to direct incoming light instead of lenses, causing chromatic aberration to cease to be a problem. Parallel light rays enter through the aperture and are reflected off of a primary concave mirror located at the very end of the optical tube assembly. The light is reflected back to a secondary diagonal located a focal length away along the centerline of the primary. The secondary then directs the light to the eyepiece and the focuser to the observer.

Figure 1. A replica of Newton's reflector telescope.

Design

Optical Layout

The optical layout determines the parameters in the optical tube assembly's construction. From the optical layout seen in Figure 2, the distance between the secondary and primary mirror is 62.5" and the distance between the secondary to the eyepiece is 16.125". The secondary mirror has to be offset by 0.25" from the centerline in order to direct all of the light into the eyepiece.

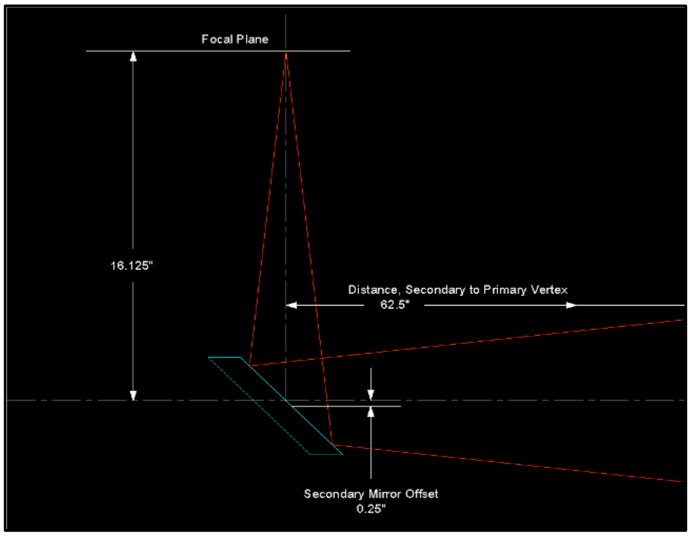

Figure 2. Optical layout of the OTA.

Structure

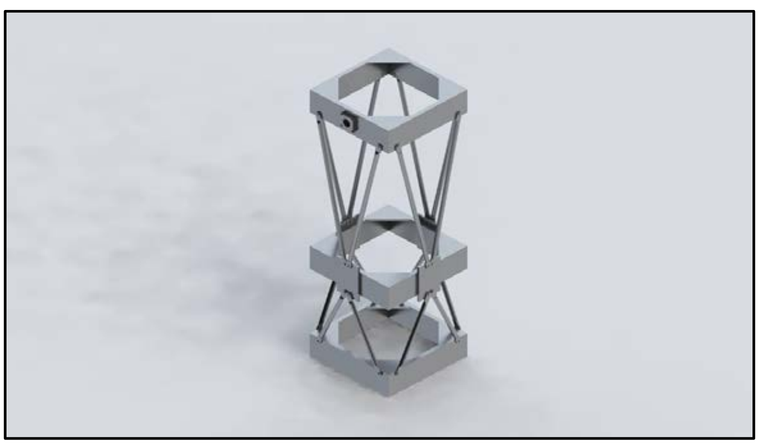

Figure 3. SolidWorks diagram of OTA.

The optical tube assembly, seen in Figure 3, consists primarily of three aluminum boxes of size 22" x 22" x 6". The bottom box contains the 17.5" primary mirror and the mirror cell. The top box contains the secondary mirror that is held in place by a spider manufactured by Astrosystems. Steel conduits connect the middle box to both the top and bottom boxes. Covers on the top and the bottom of the box protect the mirror from the environment. The covers are made of aluminum composite sheets consisting of a polyethylene core in between 0.3mm aluminum outer layers. The bottom cover is 20.5” x 22” and slides right in between two z-bars that act like rails screwed underneath the bottom box. The top cover is 21” x 21” and slides into place with between two z-bars.

Mirror Cell

The mirror cell was custom-made by Aurora Precision. The frame of the cell is composed of welded 1” x 1” square steel tubing that is .09” thick and coated in black. The cell is fixated in the aluminum box by two aluminum cradles, called a whippletree, on one end and a hinge that allows detachment on the other end (Aurora Precision). Two brass knobs located on the bottom of the mirror cell allow tilting for collimation, seen from the side view in Figure 4. The mirror is held down by four clips and is supported by six .14” thick stainless steel triangular supports creating 18 points of floatation seen in the top view of Figure 4.

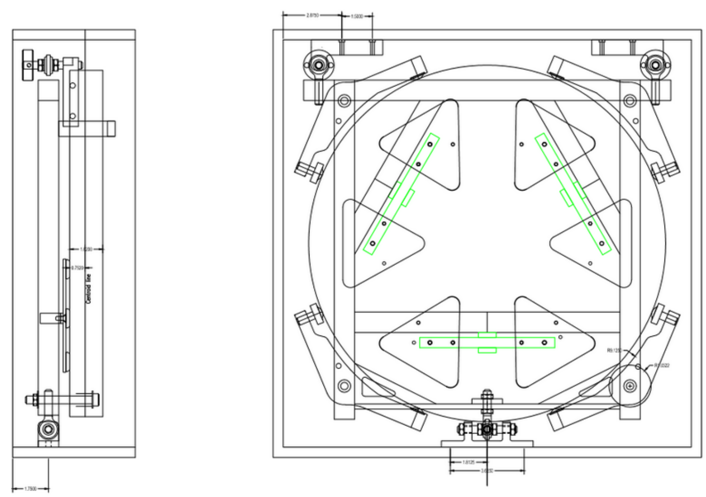

Figure 4. Side view, left, and top view, right, of mirror cell.

Secondary Mirror

The secondary mirror and spider support system were manufactured by AstroSystems. The secondary mirror, whose dimensions are in Table 1, is held in place by the spider. The spider is 2.5” wide at its center body, having a maximum length of 26” with four 0.029” thick vanes (AstroSystems). At the end of each vane protrudes two fasteners that are threaded into aluminum angles, which are bolted down onto the gussets on the top side of the top aluminum box. A side view of the spider can be seen in Figure 5 along with its dimensions shown in Table 1.

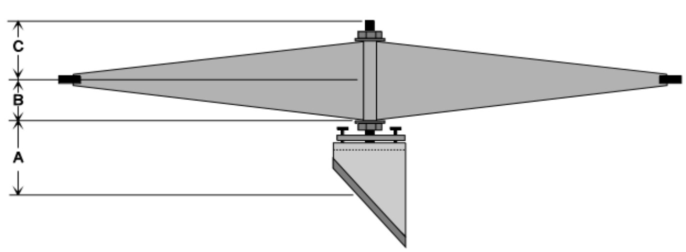

Figure 5. Diagram of the spider and secondary support system.

Mirror Minor Axis	Mirror Major Axis	A	B	C
4.25”	6.01”	5.65”	1.50”	2.75”

Table 1. Dimensions corresponding to parts of Figure 5. Each dimension is represented in inches.

Construction

To determine the overall height of the OTA, the primary mirror was placed 3” from the bottom of the bottom box in order to allow room for collimation by tilting the mirror cell using the brass knobs. The secondary mirror was placed a focal length, approximately 62.5”, away from the primary mirror. This caused the overall height of the OTA to be 70.125”.

Determining the position of the center of mass of the structure determined where the middle box is placed in relation to the top and bottom boxes. Placing the middle box at the center of mass would balance the telescope. The center of mass was found using Equation 1.

$$W_1 X_{in} + W_{T1}\left(\frac{X_{in}}{2}\right) = W_2(D - X_{in}) + W_{T2}\left(\frac{D - X_{in}}{2}\right) \qquad \textit{Eq. 1}$$

D is the distance between the center of the bottom box to the center of the top box in centimeters. W_1 is the weight of the bottom box and its interior components; likewise, W_2 is the weight of the top box with the weight of potential instrumentation accounted for. W_{T1} and W_{T2} are the weights of the steel conduits that are connected to the bottom and top boxes, respectively. X_{in} is the distance between the bottom box and the middle box; therefore, it is effectively the center of mass of the telescope. Using D = 64.125” and the values from Table 2, the value of X_{in} was determined to be 23”. Therefore the middle box was placed 23” from the center of the bottom box.

Variable	Weight (Pounds)
W_1	62.15
W_2	28.85
W_{T1}	8.95
W_{T2}	16.78

Table 2. Weights of different components of the OTA.

Once the positions of the boxes were found, the length of the steel conduits were determined to be 19.05” and 36.30” by using simple trigonometry. The steel conduits were then cut to the required lengths using a bandsaw. Originally circular, the ends of the conduits were flattened with a vice and ground down with a grinder. Holes were drilled on the flattened ends of the conduits using a drill press so the conduits could be bolted to the aluminum boxes.

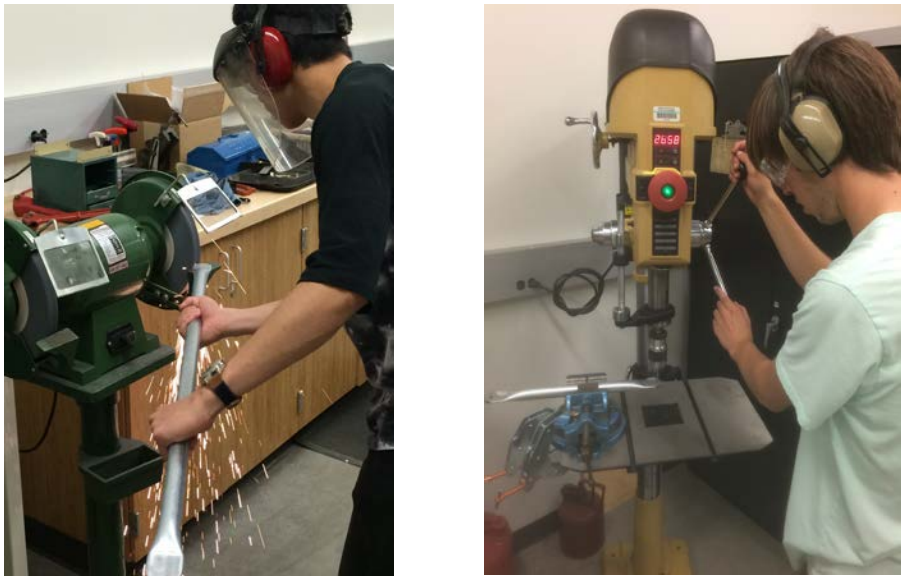

Figure 6. Kevin Phung, left, and Jacob Hass, right, work on grinding and drilling the steel conduits.

Alignment

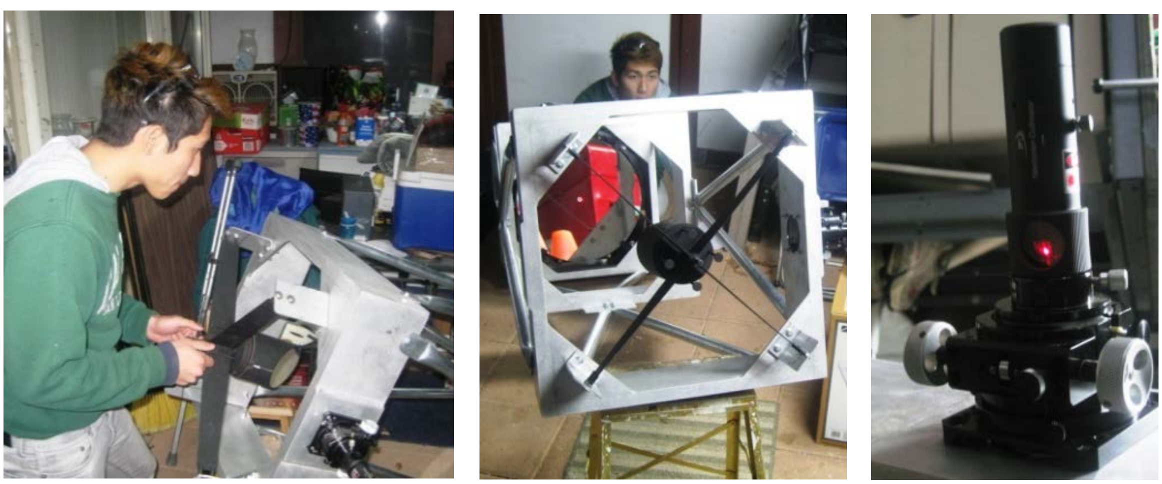

Figure 7. Collimation of primary and secondary mirrors, left and center, using the laser collimating tool, right.

The first step to collimate the telescope was to direct the laser into the center of the primary mirror by adjusting the actuators on the back of the spider. Next, the actuators on the back of the mirror cell were adjusted so that the laser was reflected back up the diagonal and into the eyepiece. A screen with crosshairs located on the collimating tool gave a reading on how centered the laser beam was. The ideal was to center it on the crosshairs for perfect alignment.

Testing

Figure 8. Installment of CCD camera, left, and image of drift captured, right.

To test the optical tube assembly, stars were observed at the zenith and were focused with an eyepiece with a focal length of 25mm. After installing an SBIG ST-402 CCD camera into the focuser, stars drifting across the zenith were captured as seen in Figure 8.

Conclusion

By deriving a solution to the center of mass of the OTA with the constraint of the focal length of the primary mirror, the length of the trusses that connect the pieces of the telescope were determined. The OTA was constructed in the machine shops located at California Polytechnic University and brought back to the Orion Observatory. During the field test, stars drifting past zenith were observed with an eyepiece and captured using a CCD camera. This deemed the construction a success.

Acknowledgements

We thank David Ardnt for permitting us to use the physics machine shop. We thank Matt Moelter for allowing us to use a lab room. We thank Dave Rowe for providing the optical layout for our telescope and Nathan Currier of Aurora Precision for the custom-made mirror cell. Finally, we would like to thank the Aero Hangar and its technicians for instructing and permitting use of the machinery located at the machine shop on campus.

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

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

Introduction

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

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

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

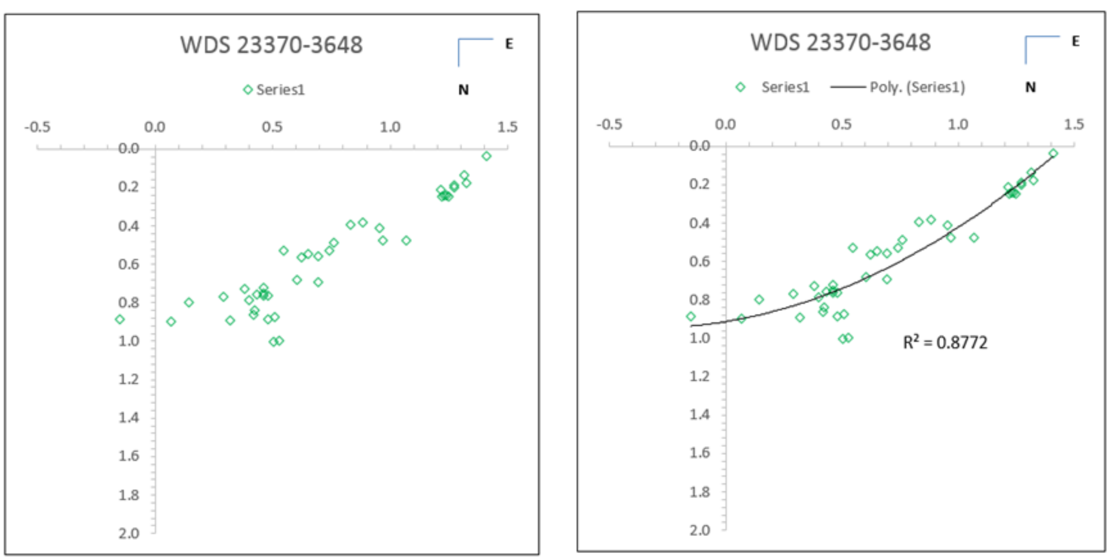

Figure 1. A sample of raw data left, along with raw data with a trendline superimposed on it, right.

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

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

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

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

The Work Done at Pulkovo Observatory

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

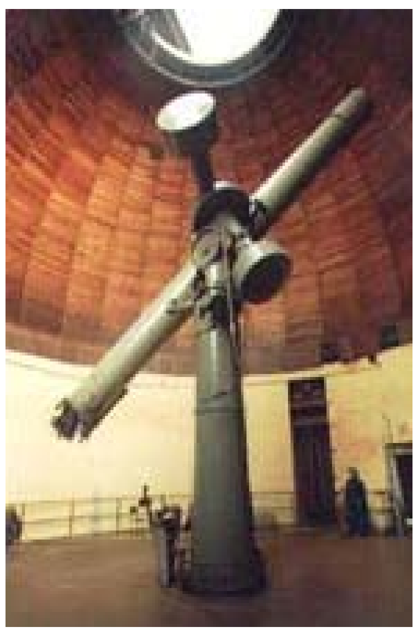

Figure 2. The 26-inch refractor at Pulkolov Observatory. It has been used by Alexey Kiselev, Olga Kiyaeva, and their colleagues to make extensive observations of wide double stars for over a half century.

Survey of 5,500 Double Stars

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

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

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

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

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

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

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

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

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

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

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

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

Close Short Arc Binaries and Speckle Interferometry

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

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

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

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

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

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

Goal of this Project

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

Selection of the Stars for Observation

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

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

Table 2. Target List for Kitt Peak 2013

Equipment and Procedures

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

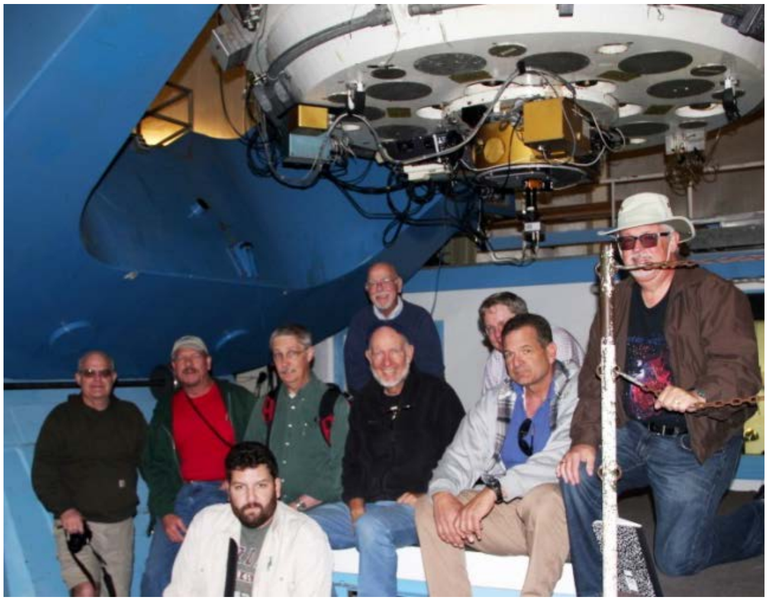

Figure 3: Observational team poses under the 2.1-meter telescope at Kitt Peak.

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

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

Reduction of the Data with Plate Solve 3.33

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

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

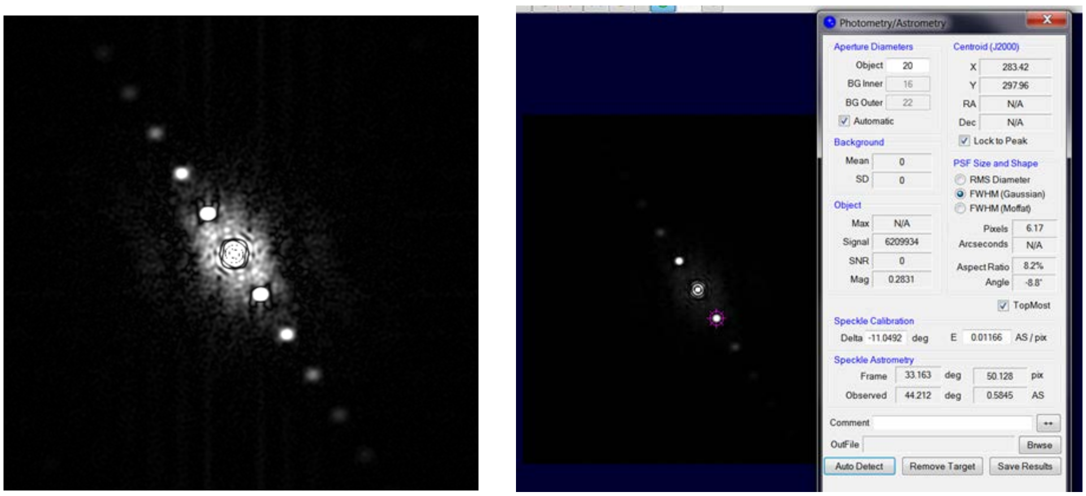

Figure 5. A raw autocorellogram of WDS00287+3718, left, and the star after processing.

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

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

Camera Angle and Pixel Scale Calibration

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

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

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

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

Table 3. Calibration Data

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

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

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

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

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

Table 3. Calibration Results

Results

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

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

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

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

Discussion

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

WDS 00287+3718 (A 1504 AB)

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

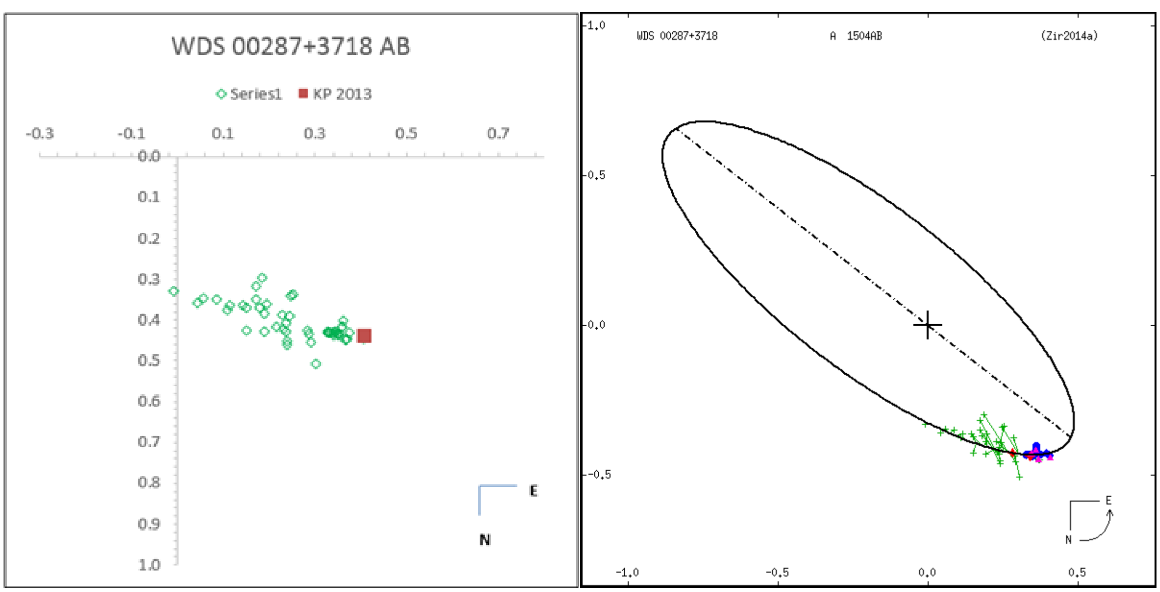

Figure 6. A plot of WDS00287+3718 AB left, along with the orbital plot from the 6th Orbital Catalog.

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

WDS 00373+5801 (BU 1097)

The data plot is shown in Figure 7.

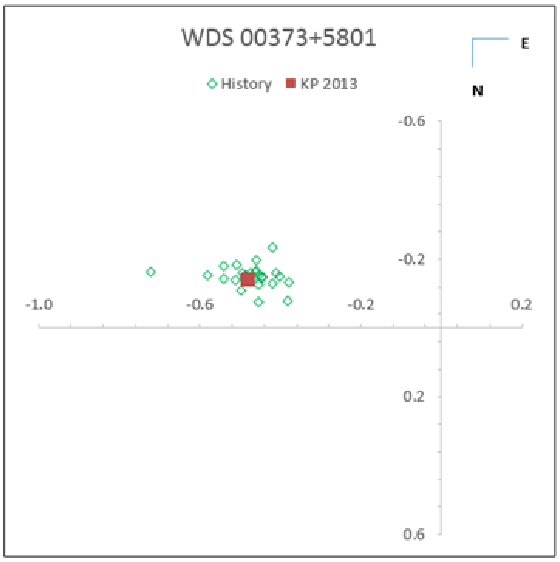

Figure 7. Plot of WDS 00373+5801

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

WDS 00405+3627 (COU 1051)

The data plot is shown in Figure 8.

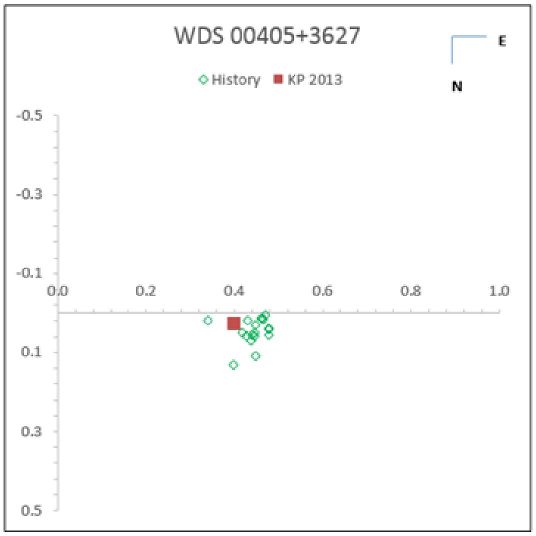

Figure 8. Plot of WDS 00405+3627

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

WDS 02250+2519 (COU 357)

The data plot is shown in Figure 9.

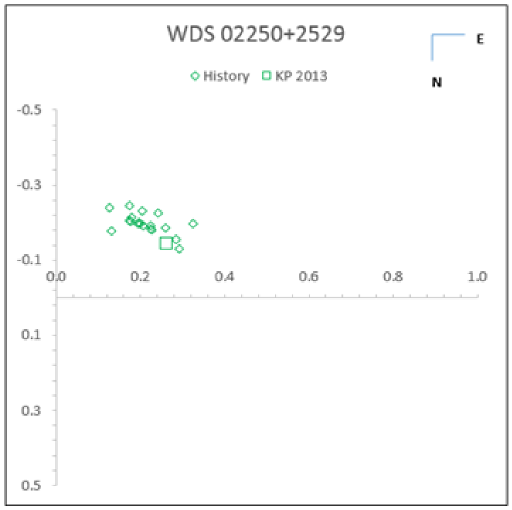

Figure 9. Plot of WDS 02250+2529

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

WDS 02270+3117 (HO 216)

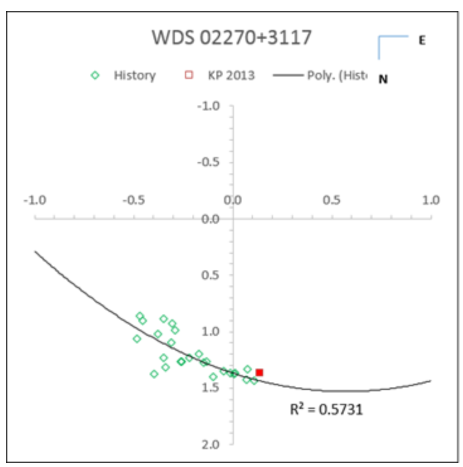

Figure 10. Plot of WDS 02270+3117

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

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

WDS 03356+3141 (BU 533 AB)

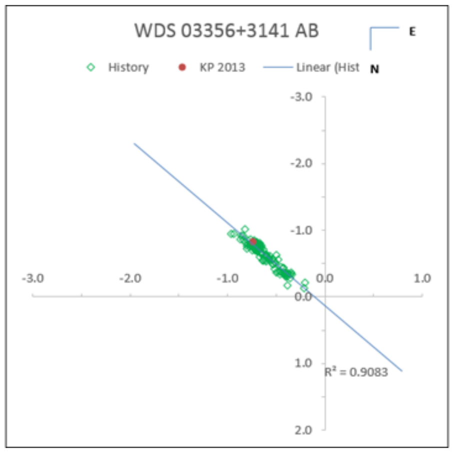

Figure 11. Plot of WDS 03356+3141 AB

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

WDS 03401+3407 (STF 425)

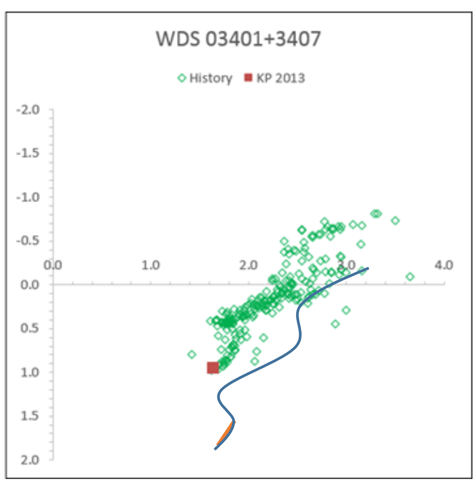

Figure 12. Plot of WDS 03401+3407

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

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

WDS 20177+2025 (COU 219 AaAb)

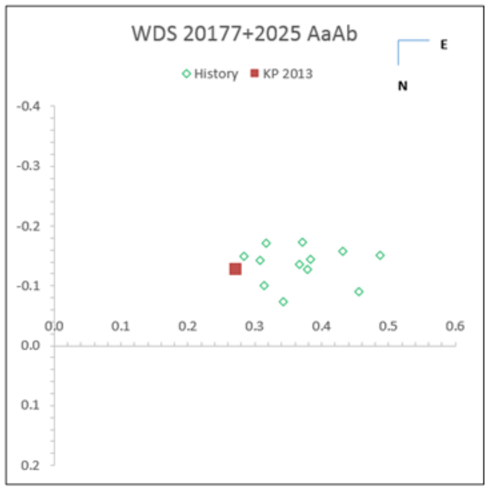

Figure 13. Plot of WDS 20177+2025 AaAb

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

WDS 20419+1931 (COU 226 AB)

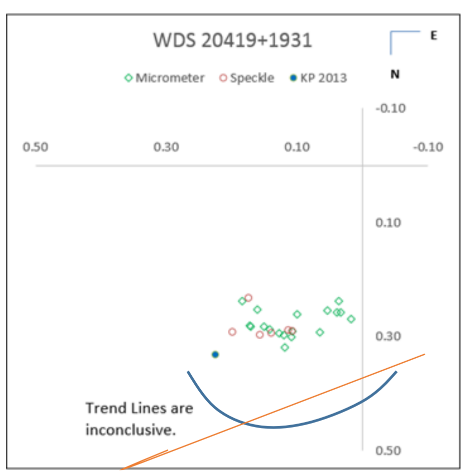

Figure 14. Plot of WDS 20419+1931

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

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

WDS 21352+2124 (BU 74)

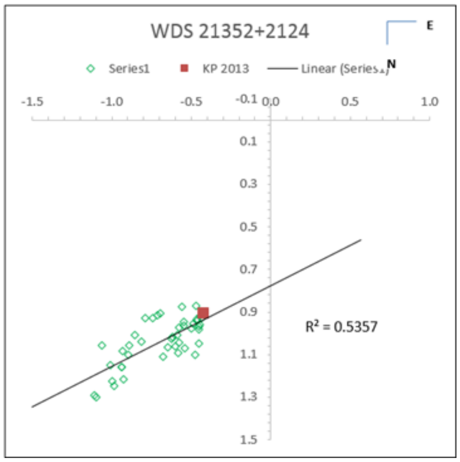

Figure 15. Plot of WDS 21352+2124

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

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

WDS 22214+4148 (A 411)

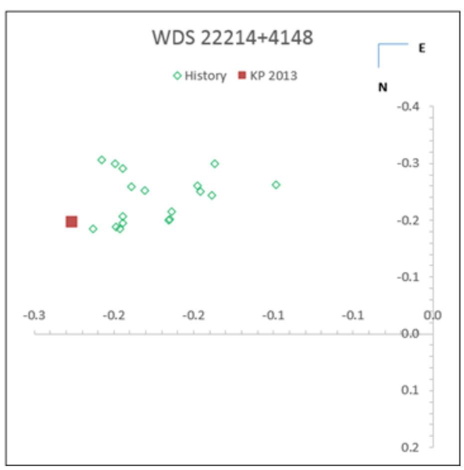

Figure 16. Plot of WDS 22214+4148

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

WDS 22395+4123 (BU 227 AB)

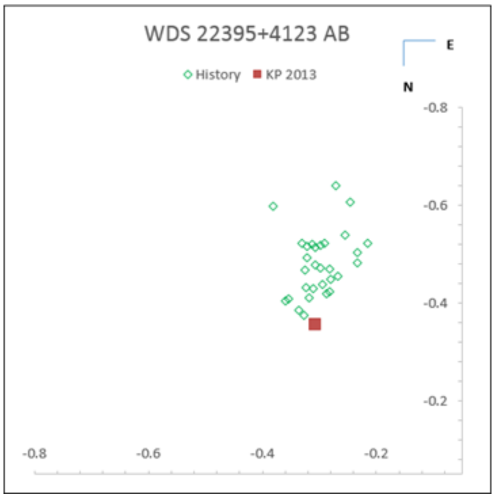

Figure 17. Plot of WDS 22395+4123 AB

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

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

WDS 23267+4103 (COU 1845)

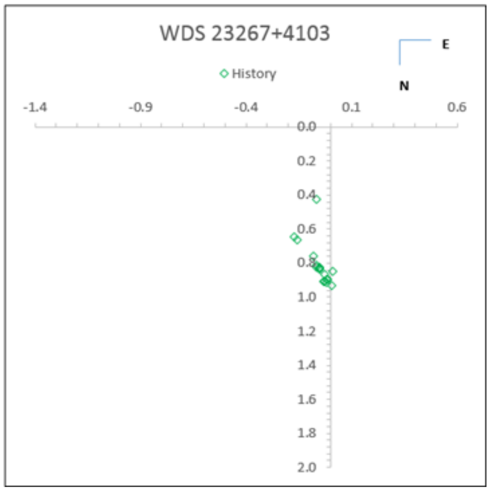

Figure 18. Plot of WDS 23267+4103.

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

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

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

Conclusion

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

Acknowledgements

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

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Being a Scientist While Teaching Science
Implementing Undergraduate Research Opportunities for Elementary Educators

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Abstract Aspiring teachers and current teachers can gain insight about the scientific community through hands-on experience. As America's standards for elementary school and middle school become more advanced, future and current teachers must gain hands-on experience in the scientific community. For a teacher to be fully capable of teaching all subjects, they must be comfortable in the content areas, equipped to answer questions, and able to pass on their knowledge. Hands-on research experiences, like the Summer Astronomy Research Experience at California Polytechnic University, pair liberal studies students with a cooperative group of science students and instructors with the goal of doing research that benefits the scientific community and deepens the team members' perception of the scientific community. Teachers are then able to apply the basic research process in their classrooms, inspire students to do real life science, and understand the processes scientists' undergo in their workplace.

Introduction

The content of elementary school and middle school requires a teacher to be able to teach several subjects within the same day, calling for a broad undergraduate education that dips into several content areas for the major. For teachers to feel fully capable of teaching all subjects, they must be comfortable in the content areas. Undergraduates in Elementary Education, or Liberal Studies, learn content associated with STEM education and discover the best teaching practices; however, until recently, there has not been an opportunity for students to perform research alongside a team of scientists.

Being on a diverse cooperative research team with students from various science-related majors allows Liberal Studies students to contribute to the scientific community that they will inspire future students to be a part of as well. At Cal Poly, two liberal studies majors teamed with five physics majors to gain experience as members of an astronomy research team and analyze the experience from an educational point of view.

At first, this opportunity seemed academically beyond the liberal studies majors because the internship focused on key themes studied in many physics classes but not focused on liberal studies classes. Because of this, many liberal studies majors had reservations before pursuing the research experience. Through the experience, the liberal studies majors realized that an interest in astronomy and basic physics skills could carry them through the experience and they did not need to doubt their abilities. The Astronomy Summer Research Seminar at California Polytechnic University proved to be an enriching experience where the liberal studies majors made useful contributions to the scientific community while being on a cooperative team of mixed majors.

Building Confidence

As America increases emphasis on science and math, it is important that teachers are confident teaching the more intensive curriculum. America has remodeled its science standards to adapt to the rapidly expanding technology industry and a society with jobs focused on science, math, and engineering concepts (Conceptual Shifts in the Next Generation Science Standards 2013*).* With this new, intensive curriculum, teachers must reframe what it means to be an effective teacher (Sheehy 2012). Teachers now have resources and the opportunity for professional development by researching the same concepts that will be taught in the classroom. An online resource for teachers' professional development explains the paradigm shift in educational philosophy, by saying "Education is no longer defined in terms of what a teacher will teach but rather in terms of what a student will be able to demonstrate. Thus, it is from here that instruction must work backward" (Paradigm Shift in Education). The best way to build a teacher's confidence with math and science concepts is to have hands-on experience and work alongside peers that study these concepts in greater depth. This creates memorable experiences rather than forgettable facts. The Next Generation Science Standards shift from learning the basics of science individually to learning the interconnected nature of science (Conceptual Shifts in the Next Generation Science Standards 2013*).* This requires teachers to know how to draw connections between different aspects of the sciences. These science standards incorporate engineering concepts into the classroom, and it is therefore invaluable for future teachers to have hands-on experience with these concepts they will be expected to teach. As the head of the Teaching Track Working Group at the University of Ohio, Brian Bardine states in his article "Research to Practice: 'Teacher Research: Getting Started'" (2015) that teachers not only benefit themselves by doing research programs, but they also benefit their colleagues by bringing renovative ideas to the grade level or school site.

Learning the Process and Making Connections

In the Astronomy Summer Research Seminar the undergraduates helped mechanical engineering students with various projects. For example, one of the projects focused on fitting a Gaussian mask on a telescope to better see a binary star system (Loveland, et al. 2015). A mechanical engineer at California Polytechnic University, Ed Foley, created a Gaussian mask as part of his Masters project, for the research seminar team to use for research alongside him. He then showed the researchers how he made it, and explained the steps for using the equipment. Figure 1 shows part of the team posing with the masks that fit on the telescope. Three of the members on the team then obtained certification to use machining equipment, so they could apply these same engineering skills to projects of their own.

The liberal studies majors were a part of a process involving math, physics, astronomy, and engineering concepts, an inspiring example of higher level thinking that can be applied to elementary school and middle school classrooms. The process developed in the seminar could easily transfer over to a K-8 classroom: forming an idea, researching previous models, constructing a model, and using it for future developments.

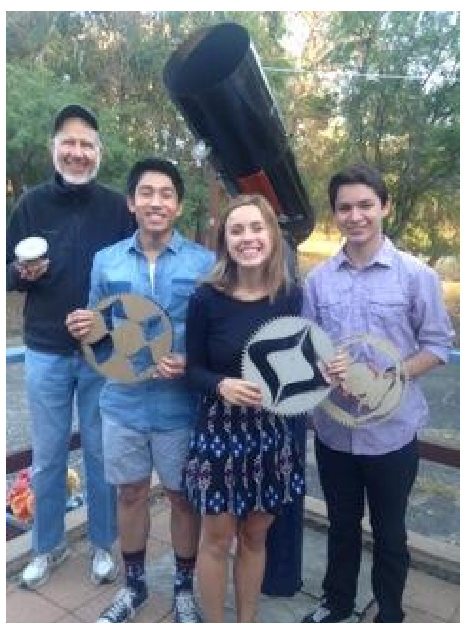

Figure 1: From left to right, Russ Genet, Kevin Phung, Emily Hock, and Donald Loveland show the Gaussian masks developed by Ed Foley.

Advice from a Teacher Scientist

When considering the importance of being a scientist in the teaching profession, it is important to interview current teacher researchers that have ample experience applying their studies to their classes. Author Emily Hock interviewed Dr. David Mitchell, a full-time professor at California Polytechnic University, as well as an astronomer that discovers and researches exoplanets around giant stars, to better understand his dual role as both teacher and astronomer. During the interview, Dr. Mitchell spoke as if he was simultaneously a teacher and astronomer rather than two separate professions. In his teaching profession, he references his research throughout lectures and gives the students real world context, and while doing research, he thinks about how he can improve his classes. David Mitchell received his PhD in Physics, but has always been fascinated by astronomy and has been conducting astronomy research since he was an undergraduate, including documenting and discovering a number of exoplanets. When asked why he thinks liberal studies majors should be a part of a hands-on research experience, Dr. Mitchell made an analogy to his own teaching experience. He said “You have a lot more insight to teaching something when you have done it and gone through the process. It’s one thing to understand the basic ideas... I teach Geology 103 [Introduction to Geology], but I am not a geologist, whereas when I teach astronomy, I have done it, so I have a much deeper understanding.” This affirms that teachers relate more to their lesson when they have personal experience, portraying to the students that they are passionate and experienced.

Dr. Mitchell also said “It is important to know what a scientist actually does. If your student wants to be a scientist and you are unsure what a scientist does on a day to day basis, [it will be discouraging]. What is an example of what they actually do?” This seems menial, but carries significant weight. It does not make sense to encourage students to be scientists, or anything for that matter, if we do not have a concept of what we are encouraging them to do. Experiencing a research seminar as a teacher gives the instructor a deeper understanding of the career field that they are encouraging their students to be a part of.

In an interview with Natalie LaRosa, current second grade teacher, Cal Poly alumni, and STEM Teacher and Researcher (STAR) program alumni, she emphasized the importance of understanding as a teacher what scientific research actually is. Natalie was a part of the STAR program that gives inservice teachers and future teachers the opportunity to do research with the guidance of a professional researcher. Natalie believes that “You have no merit if you do not understand real world science.” This statement suggests that science is not just about memorizing facts, but a process that takes experience to understand. Natalie is preparing to teach second graders in Mountain View, California and says “I will give them [her students] early exposure to real science, and teach them to ask questions.” Through asking questions, Natalie’s students will have the opportunity to investigate their own questions. She says “If students have a question or curiosity, research gives them a chance to explore and investigate it.” Through her experience with research, she will be able to guide her curious students.

An Abundance of Programs

Dr. Mitchell also brought up that there are programs that give in-service teachers opportunities over the summer to do research, so this is not just for undergraduate students. Programs like STEM Teacher and Researcher (STAR), American Association of Immunologists (AAI) Summer Research Program for Teachers, and programs through college campuses across the nation, including Stanford and Columbia Universities, give science research instruction to teachers, enriching their classrooms and keeping them current in science and math concepts. The STAR program helps undergraduates on a teaching path who want to excel in teaching STEM teachers by doing the most real-world science, technology, engineering, and math experience (STAR Program—About STAR 2014). The AAI Summer Research Program for Teachers gives teachers the opportunity to conduct research with Immunologists and familiarize teachers with modern research tools and form relationships with scientific professionals in the community (AAI Summer Research Program for Teachers 2015). The program at Stanford University offers paid research experiences, in addition to class credits (Storm). The unique aspect of the Cal Poly Astronomy Summer Research Experience is that by the end of the summer seminar, the students have the opportunity to publish papers, work through the editing process, as well as enrich their résumés.

Learn by Doing

In comparison to traditional, standard-based curriculum focused on content recall for tests, research shows that the most effective way of learning is by actually creating interactive experiences for students. Educational resources on the internet, such as Astronomical Society of the Pacific online and Cal Berkeley's online lesson database SEGway, have guided lessons for students to follow, with visual aids and interactive components. SEGway has links to follow based on grade level, so the lessons will be appropriate to the science standards of each grade (Complete SEGway Catalog by Grade). The links on the Astronomical Society of the Pacific have lessons organized by topic, making it convenient if a teacher needs a resource to support a specific topic (Fraknoi). These types of lessons typically have aspects of real-world situations, present multilayered problems, guide students to solutions through problem-based activities, and require imagination to do role-playing exercises (Lombardi 2007).

Richard Noss, from the Institute of Education at the University of London, states that the Millenials have "impressive speed understanding technology's potential" which makes in-class use of technology a valuable, and almost necessary addition to interactive lessons (Noss 2012). In application to astronomy, these online tools are very helpful because they are simulators of experiments that would take years to complete, giving students insight into major, big-picture ideas that otherwise would not be accessible. The teacher can take the process they learned through a research experience and online lessons, to build a complete, memorable lesson for their students. When the teacher's experience is paired with learn-by-doing lessons, the students benefit greatly because they are undergoing a smaller-scale version of authentic learning similar to that of the scientific community (Lombardi 2007).

Broad Connections

It is important to acknowledge that without any research experience, the teacher will not have a perfect overall understanding of the research conducted; however, it is likely that with any research, the teacher will be able to relate the seminar to a classroom. Learning the process of having papers edited and published, working with scientists outside of the group, and having to work through glitches—the Summer Astronomy Research Seminar, at the core, has broader concepts that can be linked to any classroom. With this experience, a teacher can now encourage students to work through mistakes, and not fear starting over, because that is what happens constantly in the "real world" (Stremmel 2007).

Acknowledgements

We thank California Polytechnic University, San Luis Obispo for funding and planning the Astronomy Research Summer Program, and providing meeting facilities for the students and instructor. The authors are appreciative of Dr. Dave Mitchell and Natalie LaRosa for sharing their insight about hands-on research. Thank you to Lola Berber-Jimenez for connecting our students with helpful resources and asking questions about how to change the program for next year. Thank you to Phil Bailey for showing so much interest in this program and for approving the funding to give the students this experience.

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Incorporating Remote Robotic Telescopes into an Elementary Classroom Setting

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Abstract As Next Generation Science Standards (NGSS) are implemented across the nation, engaging and content-specific lessons are becoming an important addition to elementary classrooms. This paper demonstrate how effective hands-on teaching tactics, authentic learning, scientifically significant data, and research in the elementary realm can aid students in self-discovery about astronomy and uncover what it is to be a researcher and scientist. It also outlines an effective, engaging, and integrated classroom unit that is usable in both the scientific community and elementary schools. The lesson unit consists of NGSS science and engineering practices and performance expectations as well as California Common Core Standards (CCSS).

Introduction

Within the undergraduate major, Liberal Studies, at Cal Poly, San Luis Obispo, approximately 6% of the students are concentrating in physical science, 15% in biology, and 17% in mathematics. These three subjects, all STEM disciplines, make up less than half of the total Liberal Studies students' concentrations, while approximately 50% are concentrating in child development. Based on these statistics it is clear that there is a huge gap in physical science content compared to other concentration paths. A concern is that teachers will not be equipped to develop their students' knowledge in the field of physical science. Therefore, this lesson is geared to aid teachers who are less strong in the STEM fields and to illustrate to undergraduate preservice teachers how simple it is to integrate physical science into the classroom.

During fifth grade, students are expected to go into depth about astronomy as they learn about the universe, stars, and Earth's place in the solar system. Astronomy is a relatively unknown but fascinating topic for many fifth grade students. It is a natural science that quickly captures their attention. However, science in general seems to be a scary topic for elementary educators; therefore, it may not be effectively taught in elementary classrooms.

The unit outlined in this paper incorporates diverse California standards and activities that are engaging, content specific, and allow for student discovery. By implementing remote robotic telescope observations into fifth grade classrooms, teachers can expose their students to a hands-on understanding of scientific research. The final assessment to the unit will provide students with the experience of publishing a research paper in a developing research topic: binary star systems. This offers students exposure and insight into careers related to science, like research. Although this process for incorporating research, science, engineering, and basic elementary knowledge is directed toward astronomy content, the process is what is truly important in an elementary classroom. Teachers have the opportunity to use an outline similar to this to apply across all grade levels and science disciplines.

Pedagogy

Hands on Learning

In order to engage students in the Next Generation Science Standards, teachers must introduce hands-on activities and research into their classroom. Traditionally, science was taught straight out of textbooks. It was not experimental and lacked excitement. However, with STEM careers becoming more important in our society, it is apparent that teachers need to bring the content out in other ways. Lara Triona and David Klahr, authors of Hands on Science: Does it matter what students' hands are on? (2007) state that, "In hands on science, students' concrete, kinesthetic actions are related to abstract concepts and these activities tend to increase student motivation and engagement" (Triona and Klahr 2007). Therefore, by giving students the opportunity to discover the science themselves, students strengthen their possibilities of understanding abstract concepts, scientific inquiry, and observation.

Authentic Learning

Authentic learning is an effective and newly studied pedagogy that can be successfully used in elementary classroom lessons. It "typically focuses on real-world, complex problems and their solutions, using role-playing exercises, problem-based activities, case studies, and participation in virtual communities of practice" (Lombardi 2007). Therefore, the use of authentic learning in an elementary classroom is beneficial for students as they can make connections which offer long term knowledge and higher order learning. It also gives students the opportunity and experience to adapt and apply their learning toward real-world situations, helping them see why the topic is important.

Authentic learning also emphasizes using remote instruments in the classroom to address the approaches in learning. "For students without immediate access to expensive specialized equipment or extremely rare scientific instruments, this approach can open the door to active learning experiences that would otherwise be beyond their reach" (Lombardi 2007). Likewise research in the classroom is effective within this style of teacher because, "...students use data collected by researchers... to conduct their own investigations. They are practicing higher-order analysis on real data sets while contributing to the common knowledge base" (Lombardi 2007). Therefore, introducing the idea of researching a topic, collecting evidence, and publishing a paper is a way for fifth grade students to strengthen their knowledge in the content and prepare them for future research practices. By offering these skills in the classroom, educators are developing students for successful careers once they are out of the K-12 realm.

Lesson Outline

By aligning Next Generation Science Standards and several diverse pedagogies, a unit has been created to teach students about two fifth grade standards, "The sun is a star that appears larger and brighter than other stars because it is closer. Stars range greatly in their distance from Earth"; and "The orbits of Earth around the sun and of the moon around Earth, together with the rotation of Earth about an axis between its North and South poles, cause observable patterns. These include day and night; daily changes in the length and direction of shadows; and different positions of the sun, moon, and stars at different times of the day, month, and year" (National Research Council 2007, p174, p176). Students will begin the unit with the encouragement to ask questions to create self-discovery and discussion. They will be given Post-it notes and asked to hang them on a "Question Board" on the wall. As the unit progresses, students will answer their own peers' questions to assist in group learning and, along with the introduction of stars and the universe, students will discuss these to determine their prior knowledge with one another. The unit will go into depth about the Earth's Sun, the stars, and binary systems in the universe.

Earth's Sun

The first sub-unit is about the Earth's Sun. Most students will not consider it to be a star, and therefore, the apparent brightness and observable patterns will need to be discovered. They will observe that it is incredibly bright and gives the Earth heat and light due to the close proximity and rotation of our planet. Along with this unit, students will be introduced to an engineering design lesson that incorporates the engineer practices about defining problems and designing solutions.

Figure 1. Solar Oven Engineering Activity

In this lesson, students will be instructed to design a solar oven, Figure 1, out of cardboard, aluminum foil, tape, and other objects found easily around the home or in a grocery store to heat s'mores. Students in groups will design, create, and implement their oven during a classroom activity. They will determine the best angle for the sunlight to hit their oven, take data on the best time of day, the highest heat their oven will meet, and other data analysis collections. Once this lesson has been taught and implemented, students will have learned that the Sun is apparently bright because of its closeness to the Earth and the Sun changes its position daily and shows observable patterns due to the orbit of the Earth.

The Stars

Once the students have gone into depth about our star, they will be introduced to a better understanding of the stars in the universe. The lesson will begin with students observing the night sky. They will observe the same spot every night for one week and journal about the changes they see. They will be given a map of the sky and asked to hypothesize why they think some of the stars are dim while others are incredibly bright. Furthermore, students will be led to discover that constellation stars are not all in the same part of the sky and their star brightness is due to their distance. Students will participate in an activity called, "Constellation Heroes." The class will create their own constellations by making a logo or image in the sky with a star map. They will integrate their art standards into this unit by "Us[ing] perspective in an original work of art to create a real or imaginary scene" by creating their constellations into an art piece (Grade Five/Visual and Performing Arts 2015).

Common Core State Standards in mathematics will also be incorporated as students will determine the angles of the constellations they have been introduced to in class in "Constellation Math" (Figure 2). This activity will align with the California CCSS, "Students identify, describe, and classify the properties of, and the relationships between, plane and solid geometric figures" which includes learning to, "Measure, identify, and draw angles, perpendicular and parallel lines, rectangles, and triangles by using appropriate tools" and "know[ing] that the sum of the angles of any triangle is 180° and the sum of the angles of any quadrilateral is 360° and use this information to solve problems" (CCSS, 5.2.0).

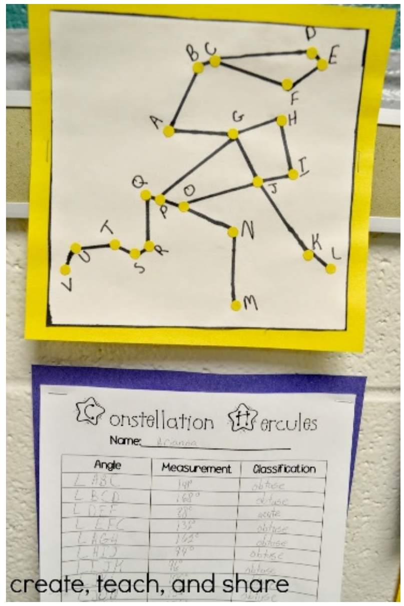

Figure 2. An example of Common Core State Standards' "Constellation Math."

At the end of the subunit on stars, students will be able to determine that stars in the sky have different apparent brightness due to their distance from the Earth. Constellations are not in the same position in the sky and this is apparent due to their brightness. They will also further their knowledge in CCSS mathematics concepts and California State Standards for art.

Binary Stars

Students will learn how to find coordinates for a binary star and will ask for a "star map" of that part of the sky from a remote robotic telescope in the Canary Islands. Students will also research what a remote robotic telescope is and, in groups, present their findings to the class. This will excite the students' curiosity as they will neither know what a binary star is nor the fact that you can send in coordinates and receive back information. By connecting with an outside astronomer, students will see that in the scientific and research community people often must compare results and work together to find information.

After receiving several photos of the sky, the class will hypothesize what a binary star actually is. As they get deeper and deeper into space with their photos from the Canary Islands, it will become apparent that there are two stars gravitationally bound to one another. Students will research further into how many stars they think they see in their sky maps and will continue to research binary systems. After researching what binary stars are, the fifth grade students will understand the diversity of the universe and will have both observational data and science knowledge to create a research paper about their findings.

Research Paper Publication

Students will write a brief research paper about their observations throughout the unit including the Sun, stars, and binary stars. They will write an abstract, discuss their findings, use evidence, and finalize a conclusion on the unit. This end assessment will help students to see the importance of research. It will bring a better understanding of what scientists, mathematicians, engineers, and researchers do every day and will also show how research can relate to both the scientific and educational world. Students will learn that when they are curious, they can simply research a topic and collect evidence and data to find answers for themselves, which encourages problem solving in the classroom. The research papers the students write will be published in a classroom text for teachers, administrators, and parents. This activity will align with the Common Core State Standard for writing 5.2, "Write informative/explanatory texts to examine a topic and convey ideas and information clearly." The activity will help to develop fifth grade researchers who not only know how to collect and analyze data but also how to observe their surroundings and write an information text about them.

Broad Connections

By incorporating math, art, science, and engineering standards, fifth grade students will strengthen their knowledge in astronomy and make connections to the universe in their lives. Their curiosity of space will open their eyes up to using research in their everyday lives to answer questions, expand observation skills, and explore the world around them. This will bring the idea of research to higher importance in their lives so they can answer their own questions. Furthermore, the class will have a better understanding of how research relates to the educational world through their knowledge in science. Finally, the fifth grade students will connect their new understanding to the Next Generation Science Standards by incorporating their knowledge and findings to see that the universe is a unique and diverse aspect of our lives and Earth is a small planet in the vast universe.

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Mt. Wilson 100-inch Speckle Interferometry Engineering Checkout

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Abstract The historic 100-inch Hooker telescope at Mt. Wilson Observatory has been brought back to operational status. Its use for speckle interferometry at its new relayed optical focus was evaluated with an Andor Luca emCCD camera. While useable speckle images were obtained, there was some electromagnetic interference from powerful nearby transmitters that shielding and other EMI reduction measures should handle.

Introduction

Speckle interferometry allows close visual double stars to be observed with separations well below the time-averaged seeing limit. While smaller telescopes, equipped with high-speed, low-noise cameras, have worked well for separations down to about 0.5″, it takes larger telescopes to observe short-period binary stars which have smaller separations.

Our group has observed close visual double stars with separations down to 0.1″ during two week-long runs on the 2.1-meter telescope at Kitt Peak National Observatory. Prior to our first run, we brought our instrumentation for an in-person checkout on the telescope. The 2.1-meter telescope, no longer available for general use, is now being used full time by the California Technical Institute for automated adaptive optics observations. Thus we needed to locate another large telescope to continue our observations of double stars too close for our smaller telescopes to handle.

Since our group is primarily located in Southern California, it was only natural that we should consider the newly revived 100-inch (2.5-meter) Hooker telescope at Mt. Wilson Observatory. This historic telescope, used by Edwin Hubble to discover both the size and expansion of the universe, is back in operation with the focal plane relayed to a convenient location below the primary mirror.

The Hooker telescope has been used in the past for speckle interferometry observations of close double stars by Brian Mason and Bill Hartkopf from the US Naval Observatory, along with Hal McAlister from the Center for High Angular Resolution Astronomy. They used a double slit—similar to Young's famous double-slit experiment —placed at the top of the telescope to provide calibration of their pixel (plate) scale. In a visit to Mt. Wilson by Genet, Nils Turner kindly looked around the dome to see if the slits were still available. They were. Made of lightweight aluminum tubing, the two slits are precisely located on the top of the telescope with pins. A piece of dark cloth, also still available, is stretched between the two slits and fastened to the slits with Velcro, while two other pieces of cloth are installed between the slits and the outer edges of the telescope.

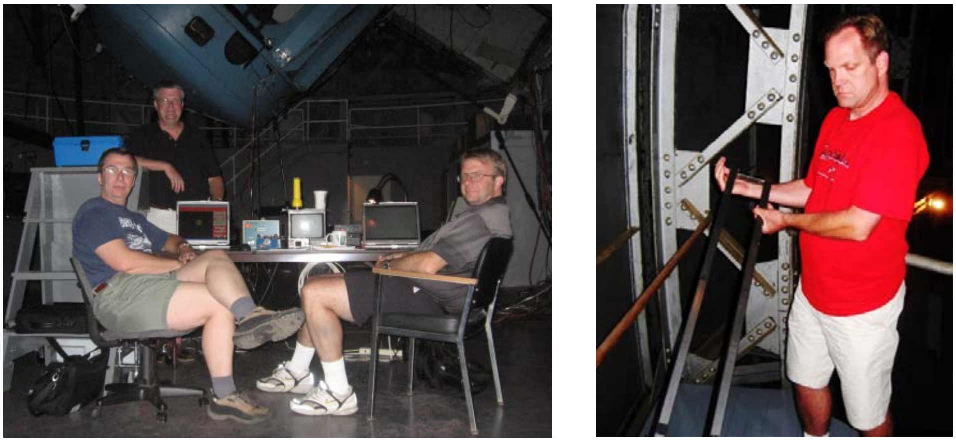

Figure 1. Left: Bill Hartkopf, Hal McAlister, and Brian Mason pose during a close double star observing run on the 100-inch telescope a number of years ago. Right: Nils Turner holds one of the two slits used by Hartkopf et al. for speckle interferometry calibration.

Instrumentation

At earlier observing runs on a 0.5-meter telescope at Dave Rowe's Pinto Valley Observatory, as well as the runs on the 2.1-meter telescope at Kitt Peak National Observatory, our operation of the telescope was from a nearby warm room. The installation at Pinto Valley observatory (Figure 1, left), consisted of a Van Slyke slider which switched the optical path between an SBIG ST-402 wide-field acquisition camera and the optical path through a Barlow lens and motorized filter wheel to the narrow-field Andor Luca S emCCD camera.

The installation on the 2.1-meter telescope at Kitt Peak was somewhat different, as it did not require an acquisition camera since we were able to use the acquisition-guider unit already installed on the telescope with its intensified CCD camera for both target acquisition and centering.

For our Engineering checkout run at Mt. Wilson, our optical system consisted of a 25 mm eyepiece, the Andor Luca EMCCD camera, and a manual flip mirror by which the incoming light could be directed to either the eyepiece or to the camera. We inserted the flip mirror into the eyepiece holder of the optical extension used for visual observing through the 100-inch telescope. For the checkout we did not include a Barlow lens or filter wheel, in order to keep things as simple as possible. The telescope was pointed by the telescope operator, using the standard systems of the 100-inch telescope. The targets were relayed to the operator by their SAO or GSC identities; the telescope operator then used TheSky to determine the current-epoch celestial coordinates, and directed the telescope to the indicated position.

The visual-optics system swing pretty dramatically as the telescope is pointed. When the telescope is aimed at the zenith, the eyepiece holder is about 5 feet above the observing floor; as the telescope is aimed lower in the sky, the eyepiece holder (holding our camera assembly) swings up and out in a large arc.

Our control computer was set up on the observing floor, roughly beneath the camera; and power and USB cables dangled from the camera location down to the computer table. The limited length of the cables meant that whenever the telescope was re-aimed, we also had to move the table.

After the telescope was pointed (based on celestial coordinates of the target), the observer would climb a ladder so that he could look into our eyepiece, and center the target in the field of view. It turned out that the pointing accuracy of the telescope was not good enough to put the target reliably into the field of the eyepiece, so a manual search was done with the observer's slow-motion control to find the target, and bring it to the center of the field. The flip mirror was then flipped, to aim the light into the Andor camera. This was a meticulous but successful method—the target always appeared near the center of the Andor image and could be easily maneuvered using the observer's slow-motion control.

Figure 2. Left: close-up of the speckle camera for the 100-inch checkout with its Andor EMCCD camera, Orion flip mirror, and eyepiece. Light from the telescope entered from the right. Right: the camera installed on the 100-inch telescope at the end of the white optical extension.

For runs on the 100-inch telescope in the future, we plan to improve the effectiveness by:

- replacing the finder-eyepiece with a wide-field-of-view camera (probably a DSLR), to eliminate the need for repetitively climbing the ladder in the dark;
- replacing the manual flip mirror with a motorized (remotely-actuated) mechanism;
- inserting a Barlow lens in the path to the Andor camera, to improve the image scale (at the expense of reduced field-of-view but improved speckle interferometry performance);
- including a remotely-controlled filter wheel in the optical path to the EMCCD camera;
- changing the camera-to-computer link to Ethernet (to be compatible with long cable runs), dressing the cables along the Dec and RA axes, and placing the computer table near the south bearing of the telescope mount, where it can stay regardless of the direction the telescope is aimed.

Observations

Engineering checkout observations with our speckle interferometry camera were made on the evening of December 4, 2015. Mt. Wilson's Director, Tom Meneghini, operated the telescope from the control console on the second level.

Figure 3. The control station in a photo taken by Genet much earlier.

The control console, physically, is little changed from Hubble's days, although precision encoders have been added to the telescope's axes. Given the target's coordinates, the operator uses push buttons to slew the telescope to the approximate target coordinates, and then uses fine-motion controls to move the telescope until the desired coordinates are displayed. The telescope operator, as in Hubble's days, is part of the feedback loop.

Fine motion in Declination is via a tangent arm. For fine Dec motion, the telescope must be unclutched from the Dec worm gear, and then re-clutched to the tangent arm. The very loud clutches help keep everyone awake when they pop.

Figure 4. Left: Dave Rowe centers a double (binary) star using slow motion controls. Right: Russ Genet operates the EMCCD camera from a laptop using Andor's Solis software.

Results

Two double stars and two single stars were observed. A cold front had just passed through, clearing in late afternoon. Thus the seeing was very poor—not at all typical of Mt. Wilson where 0.5″ seeing is not unusual—so we observed somewhat wide (for speckle interferometry on a large telescope) doubles.

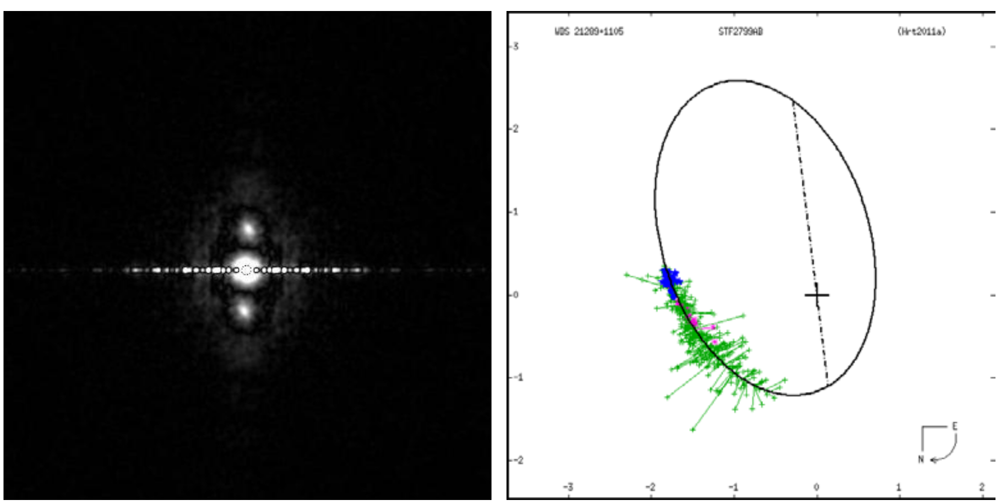

Figure 6. Left: Autocorrelogram of WDS 21289+1105. Right: Orbital plot of past observations.

Shown in Figure 6 (left) is the autocorellogram we obtained from our observation of WDS 21289+1105 (STF 2799 AB) using Dave Rowe's PS3 reduction program. The last reported separation (2014) of this binary pair was 1.93″. We did not determine the current separation (or position angle), as calibration—which can be quite time consuming—was not intended to be part of our short, single-evening engineering checkout. A nearby single star was used for deconvolution.

The horizontal artifact in the image may be due to electromagnetic interference (EMI) from the nearby high-power television transmitters on Mt. Wilson. The interference filter on PS3 was used to reduce these effects, but they could not be eliminated entirely. The dome was pointed toward the south. We expect that the interference would have been worse had the dome been pointed west toward the transmitters, but would have been less had it been pointed toward the east away from the transmitters, although we did not check this assumption. Targets could be observed on the meridian or before they reach the meridian, thus avoiding moving the dome to the west.

Discussion

Prior to the engineering checkout we had formulated eight questions we wanted to answer:

- What would be the physical interface between our camera system and the telescope?
- Would there be sufficient backfocus for our instrument?
- Would we be able to acquire targets with our acquisition camera?
- Would EMI from the nearby high-power TV transmitters cause undue interference with our sensitive EMCCD camera?
- How should we configure our speckle camera for operation on the 100-inch telescope?
- What would be the best way to set up our equipment?
- Would semiautomatic operation of our camera be possible?
- Could a semiautomatic camera system be interfaced with the telescope's control system?

Physical Interface

The 100-inch telescope is equipped with a very solid focuser that accepts 2.75-inch OD male eyepieces or instruments. This can be easily reduced with inserts to 2.0- or 1.25 inches

Backfocus

There are, in essence, no (reasonable) backfocus limits, as the telescope's motorized secondary mirror can move the focus of this f/11.X telescope to any desired position. The manual focuser near the instruments (or eyepiece) can also be used for focus adjustments.

Target Acquisition

We were not able to directly acquire targets with a 25 mm eyepiece. However, searching the nearby field with the fine motion controls, while looking through the eyepiece, we did (perhaps luckily) locate targets fairly expeditiously. The telescope's mathematical mount model is being refined. It is expected that these refinements will result in the displayed RA and Dec coordinates being considerably closer to the telescope's actual position. This may take care of this potential problem. We have not yet compared the field-of-view of the 25-mm eyepiece used in the engineering checkout with the expected field-of-view of our acquisition camera—perhaps a DSLR or large format CCD camera.

Electromagnetic Interference (EMI)

We were very concerned that EMI from the powerful, nearby TV station transmitters would induce irreparable pattern noise. At its heart, speckle interferometry sensitively looks for any patterns, and is thus unusually sensitive to repetitious noise, even if at a very low level. We were relieved that EMI (if that is what the horizontal pattern noise was) was at a tolerably low level. However, we plan on further investigations with respect to noise and remedial actions such as adding shielding, ferrite coils, etc. It might be noted that if we run a much longer cable between the emCCD camera and its control PC (including conversion from USB to Ethernet and back to USB), this could introduce additional problems, although we are currently planning on using a fiber-optic cable.

Eventual Camera Configuration

While we were able to acquire the targets visually with an eyepiece (with some searching), and manually changed the optical path between the eyepiece and the EMCCD camera, the eventual camera system would include an acquisition camera and remote (computer) control of the optical path. Orion Telescopes makes a low-cost two-port instrument selector that could be modified for remote control, Optec makes a four-port instrument selector (Perseus) that precisely moves the optical path between the four ports, and there are other possibilities. If a target is centered on a wide-field acquisition camera, one can be confident that it will still be centered when the optical path is switched to a very narrow-field EMCCD camera (behind the Barlow lens).

Equipment Setup

A table could be set up on the floor under the telescope off to one side just below the telescope control console. The camera operator, run (log) manager, and assistants could set up their PCs on this table. A Cat-6 cable could connect the instruments on the telescope with the PCs on the table with appropriate USB-to-Ethernet conversion on each end. In previous runs, we found that it was necessary to run a separate cable for the camera. Whether, with new equipment, this will still be necessary remains to be determined.

Semiautomatic Operation

Speckle interferometry of close visual double stars is a very intense, fast-paced operation. At both the Pinto Valley and Kitt Peak observatories we were able to slew to, acquire, center, and gather 1000 images of our targets in, on the average, only four minutes. This required close (practiced) coordination between the camera operator, the log master, and the telescope operator. Semi-automation of the speckle camera portion of this process could significantly improve the efficiency of observations with the 100-inch telescope. Automated control of the acquisition and speckle cameras, switching the optical path between the two, fine RA and Dec motions, fine focus, and filter selection may all be possible. Efficiency could also be enhanced by automating the target selection process. Given a large number of targets (certainly the case), it should be possible to park the dome facing due south and catch the targets as they move within the slit without moving the dome. Furthermore, a smart target selection program could also reduce both the RA and Dec motions of the telescope.

Telescope Interface

Semi-automatic speckle camera operation would require an interface between the camera control PC and the telescope's control system. The current telescope control paddle (on a long cable), which contains the RA and Dec slow motion controls as well as fine focus control, is being replaced with a small control panel on the telescope near the "eyepiece position" of the telescope. This will facilitate visual observations. A separate control box will be available for engineering or other purposes on the floor. Discussions with Bill Leflang, a JPL retiree who is upgrading the telescope's control system, suggested that it should not be difficult to add a connector to the floor control box that would accept TTL-level discretes from the speckle control computer to control fine telescope motions and focus.

Conclusions

The revitalized 100-inch Hooker telescope at Mt. Wilson Observatory appears to be well suited for speckle interferometry observations of visual double stars with small separations well below the seeing limit. Seeing at Mt. Wilson is often excellent, improving the quality of speckle observations. The somewhat bright skies at Mt. Wilson are not of concern, given our relatively bright objects and short integration times. Our Kitt Peak observing runs were both bright time runs (near full moon, a lunar eclipse actually occurred in the middle of our second run). Significant time will be available on the 100-

inch telescope, particularly bright time during week nights (the telescope is primarily used for visual observations during dark time on weekends).

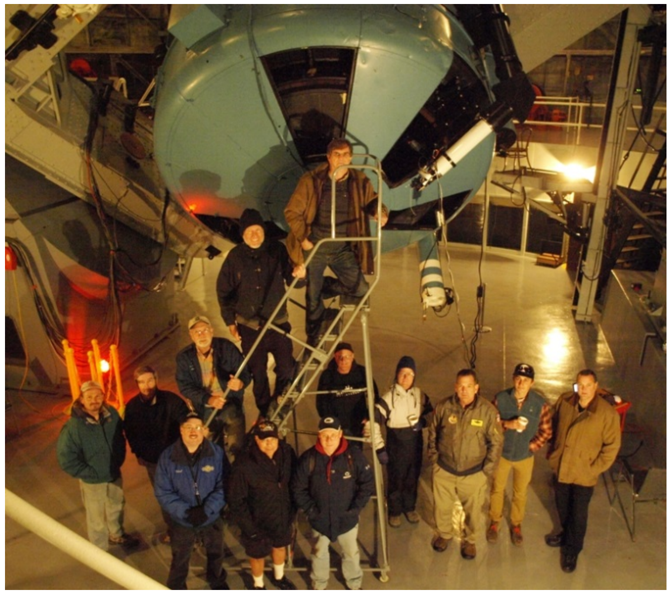

Figure7. Observational team and Mt. Wilson staff poses at the end of the engineering checkout.

The engineering checkout of our speckle camera system on the 100-inch telescope has given us sufficient confidence to move forward. We plan to proceed with development of a speckle camera system capable of semi-automation, devise a multi-objective science observing program with significant student participation, and obtain funding for telescope time and other expenses. We hope to have a full two-night run as early as May 2016.

Acknowledgments

We thank Mt. Wilson Observatory for providing time on their 100-inch telescope for our engineering checkout. We thank Bruce Holenstein and Vera Wallen for reviewing this paper.

Speckle Interferometry of Close Visual Binaries

with the

ZW Optical ASI 224MC CMOS Camera

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5. Eclipse Technologies
6. La Cresta Observatory
7. Brilliant Sky Observatory
8. Sonoran Desert Observatory—Glendale

Introduction

The most influential parameter by far, with respect to the life cycles of stars, is their mass. William Herschel (1803) provided evidence that some close visual doubles were actually gravitationally-bound "binaries," a term he suggested. Observations of close visual binaries over time can establish their apparent two-dimensional elliptical orbit (Kepler's First Law). Kepler's Second Law (of equal areas swept out in equal times) can then be applied to determine the actual three-dimensional orientation of the binary's orbit. If the distance to the binary is known (by Hipparcos or soon more accurately by Gaia), simple trigonometry provides the obit's minor axis in physical, astronomical units, as opposed to angular units. Kepler's Third Law relating orbital periods and semi-major axes can then be applied to determine a binary's dynamical mass, i.e. the sum of the two individual stellar masses. Finally, radial velocity curves can be applied to parse the dynamical mass into its two components.

Currently there are about 3000 binaries with published orbits. Most of these binaries have orbital periods of many decades, centuries, or even millennia. To establish accurate orbits (and hence stellar masses), it is necessary to have at least one nearly complete orbit, and two or more complete orbits are even better. Short orbital periods only occur when the physical separation of the two binary components is small. The result is small apparent angular separations. For a given binary, the further away it is from Earth, the smaller will be its apparent angular separation. The upshot is that the visual binaries of greatest interest—shortest periods—generally have separations below the seeing limit.

Antoine Labeyrie (1970) discovered that the seeing limit could be circumvented for close visual binaries within the isoplanatic patch, a small area of the sky (typically about 5″) where jitter movements are correlated (double stars dance about together). Circumvention was accomplished by taking short exposures that froze out atmospheric variations (the small air cells just not having enough time to change or move very far). Such short exposures produced a speckle pattern of many binary-pair images randomly superimposed on another. Labeyrie found, however, that the position angle and separation of a binary's two components could be recovered from a series of these short, jumbled exposures (typically many hundreds or a few thousand) through Fourier spatial analysis that produced an autocorellogram.

High-speed film was initially used to make speckle interferometry observations. When CCD cameras became available, they were not used in their "barefoot" mode because their read noise at high speed was very high compared to the few signal photons available in the short exposures. However, amplification of the light prior to the CCD camera, i.e. an intensified CCD (ICCD), in conjunction with early portable computers, ushered in the area of practical speckle interferometry of close visual binaries (McAlister 1985). See Figure 1. ICCD cameras were expensive, however, and their intensifiers were inherently nonlinear. Thus while astrometric measurements of position angles and separations could be made, it was difficult to make precise photometric ICCD measurements of close visual binaries.

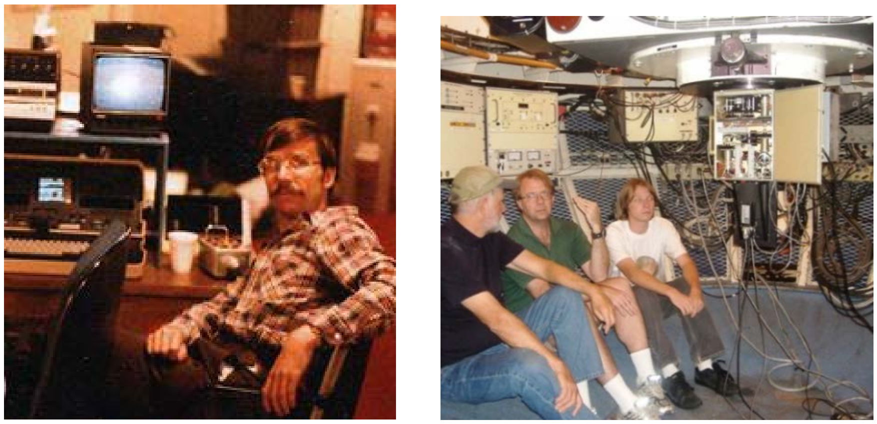

Figure 1. William Hartkopf, in warm room comfort at Kitt Peak National Observatory (left), captures high-speed frames with an early Osborn portable computer from an intensified CCD (ICCD) camera located at the Cassegrain focus of the 4-meter telescope. Russ Genet, Brian Mason, and Jo Johnson in the 4-meter Cassegrain cage (right) with the US Naval Observatory's similar ICCD camera.

Over a decade ago, electron-multiplying CCD (EMCCD) cameras were introduced. A gain register was added between the pixel array and the CCD chip's analog-to-digital (A/D) converter. The gain register, similar to a solid state photomultiplier, amplifies the signal to a level where the read noise, in comparison to other noise sources, becomes insignificant.

These cameras, however, with their back-illuminated, high quantum efficiency e2v chips, are expensive (currently about $40,000 for Andor's top-end iXon camera). They are also sizeable and somewhat heavy (about seven lbs.). While the size, weight, and cost of these EMCCD cameras do not pose a problem for most professional astronomers making speckle observations on large telescopes in funded programs, they do pose a challenge for small-telescope astronomers on a limited budget. Two successful small-telescope solutions were found for this size, weight, and cost problem.

Figure 2. Florent Losse used his 0.4-meter telescope in France to obtain highly-precise measurements of the position angles and separations of many close visual binaries—many of them with separations well below the seeing limit.

The first solution was pioneered by Florent Losse. He took a short exposures with a "regular" CCD camera (around 20 milliseconds), and then read it out at regular, several-second rate. Although his duty cycle (exposure time versus exposure plus readout time) was very low, he patiently took the time to obtain hundreds of short exposures on each target. He modified his popular double-star reduction program, REDUC, to process his results in Fourier space to obtain autocorrelograms.

The second solution was to use a lower cost, relatively small EMCCD camera made originally by Andor Technologies (the LucaS and LucaR) and now others (such as the Raptor) that use a front-illuminated EMCCD chip made by Texas Instruments. While still somewhat expensive (typically over $10,000), these cameras are relatively small and lightweight (about two lbs.). Genet (2013, 2014) used the Andor LucaS and LucaR cameras for observations made at various observatories in the western US, including Kitt Peak National Observatory, while Jocelyn Sérot (2015) used the Raptor Kite for speckle observations on a small telescope in France.

Figure 3. Left: Eric Weise finishes the installation of an Andor Luca-S EMCCD camera on the 0.5-meter PlaneWave Instruments telescope at Rowe's Pinto Valley Observatory in the Mojave Desert Reserve. Right: Raptor Kite EMCCE camera on Jocelyn Sérot's Celestron C-11 telescope in France.

Although these front-illuminated cameras were an important step forward for small-telescope speckle interferometry, they were still somewhat pricy for many amateur and student astronomers. Furthermore, Texas Instruments stopped making the front-illuminated chips used in these cameras. Thus the search continued for a truly low cost, small, lightweight, high speed camera.

Discovery of the ZW Optical ASI 224MC CMOS Camera

Rapid improvements have been made in the design and manufacture of high-speed CMOS cameras with low read noise. Scientific CMOS (sCMOS) cameras appeared on the market a few years ago with performance approaching that of EMCCD cameras. Although sCMOS cameras remained expensive (typically over $10,000), there was hope that the cost of the low-noise CMOS chips would be reduced, allowing them to be incorporated into low-cost, mass-market cameras.

Figure 4. ZWO's ASI 224MC low-noise CMOS camera. The Sony team that developed the IMX 224 chip: back row Mr. Torii, Mr. Azami, and Mr. Yano; front row Ms Tokunaga and Mr. Maruno.

This happened recently. A team at Sony developed a low read-noise (less than 1 electron) chip that has been incorporated in a camera made by ZWO that only costs $359 US, and just weighs 120 g (4.2 oz). Benoit Shillings obtained one of these cameras, placed it on his 0.5-meter telescope in San Jose, California, and, using a list of targets supplied by Richard Harshaw, quickly demonstrated that the new ZWO camera could observe remarkably faint and close double stars. Within days of hearing about this breakthrough, Genet obtained a ZWO ASI 224MC camera from High Point Scientific (442 Route 206, Montague, NJ 07827, USA, 800-266-9590, www.highpointscientific.com), and also obtained remarkable results at his Orion Observatory in Santa Margarita, California.

Figure 5. Left: Benoit Shillings, with his 0.5-meter telescope, made the first close double-star speckle interferometry observations with the ZWO ASI 224MC camera. Right: close-up of the instrumentation at Russ Genet's Orion Observatory. The ZWO camera is behind a Tele-Vue 2.5-power Barlow lens.

Clif Ashcraft, at his Perrineville Observatory in New Jersey, quickly joined in the observations, and has, to date, made the most extensive close visual double star, speckle interferometry observation with the ZWO ASI 224 camera. Only a few of his observations are reported here, while his extensive observational results are presented in a companion paper (Ashcraft 2015).

Figure 6. Clif Ashcraft and his Night Assistant, Boomer. Celestron C-11 telescope equipped with the ZWO ASI 224MC camera behind a 3X Barlow lens.

Data Reduction with Plate Solve 3.44

Plate Solve 3 (PS3) was initially developed by David Rowe to obtain place solutions, which it does with unusual rapidity. A speckle interferometry capability was added to PS3 in 2013 that included adjustable high and low pass filters, an interference filter, and, of critical importance, the capability to accommodate single deconvolution stars (Rowe & Genet 2015). PS3 has the capability of pre-processing (obtaining the Fourier transforms and averaging them) automatically in a batch mode, reducing file sizes from gigabytes to megabytes, and greatly speeding up the subsequent reduction and analysis process.

PS3 processes FITS data cubes, although it does have a routine for converting files of FITS images into data cubes. However, PS3 was only programmed to handle monochrome images, so to accommodate the ZWO ASI 224 MC color camera, Rowe developed a routine to parse Bayer FITS data cubes into blue, green, red, and total data cubes. Although the "total" data cubes were used in the results provided below, the other cubes may end up being useful for the speckle multi-band photometry of close double stars.

Sample Results

The results described below were obtained by Clif Ashcraft on the night of October 8, 2015. See Ashcraft (2015) for more comprehensive results and a detailed discussion of how the observations were made, reduced, and calibrated. Here we briefly present selected results.

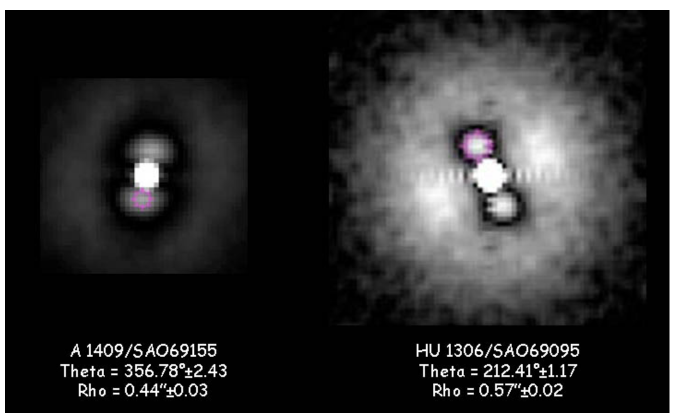

Figure 7. Autocorellograms of A 1409 and HU 1306 deconvolved with a nearby known single star. Ashcraft obtained 10,000 frames of each with an exposure of 30 milliseconds for A 1409 and 50 milliseconds for HU 1306. The ability to obtain such results for 10th magnitude stars separated by less than 0.6" on a Celestron C-11 telescope with a CMOS camera costing $359 USD is quite revolutionary.

A 1409 (WDS 19580+3840) is a very close double with components of magnitudes 8.7 and 10.7. Its last reported measure was θ= 0.1°, ρ = 0. 477 in 2007. Only six measures have been reported since 1906. 10,000 images were obtained of this double with the ASI224MC coupled to the C-11 telescope with a 3x Barlow lens using an exposure time of 30 ms. Some 2000 images of the nearby single star SAO69155 were also obtained. The 10,000 images were made into 10 FITS cubes of 1000 images each and the 2000 images of the reference star were made into a single FITS cube. These cubes were then processed in PS3 to obtain 10 deconvoluted autocorellograms from which the position angle and separation of the components of A 1409 were measured and the standard deviations determined. The result was θ= 356.78°±2.43, and ρ = 0. 44"±0.03. In rectilinear coordinates: x = 0.440"±0.027 and y = -0.025"±0.019.

HU 1306 (WDS 19558+3604) is a 10.16 and 10.13 magnitude pair. The last reported measurement on this system was θ= 209.1°, ρ = 0.596 in 2008. Fourteen measures have been reported since 1905. A set of 10,000 images of this system was obtained with 50 ms exposures with the same setup described above, and 2000 images were obtained from the nearby known single star SAO69095. The images were grouped into FITS cubes as described above and processed in PS3 to give autocorellograms from which the position angle and separation of HU 1306 were measured and the standard deviations determined. The result was θ= 212.41°±1.17, and ρ = 0. 39"±0.04. In rectilinear coordinates: x = 0.476"±0.014 and y = -0.303"±0.021.

In Figure 7 we give an example of one of the ten autocorellograms that were obtained from each of the double stars. For comparison with the autocorellograms, the best 10% of the 10,000 images were also aligned and stacked using Autostakkert2 to give the lucky imaging results shown in Figure 8 along with a single frame.

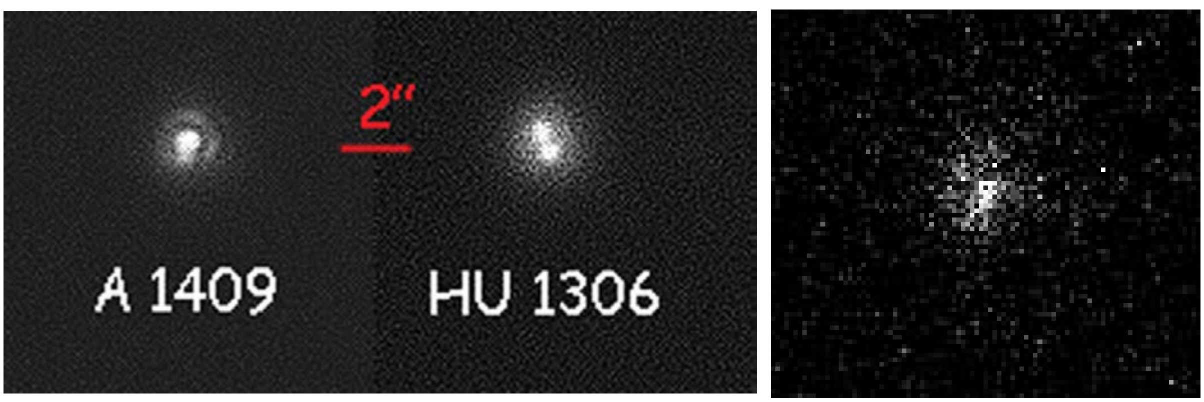

Figure 8. Left: lucky image results on A 1409 and HU 1306 . The red bar is 2 arc seconds long for scale. Right: the central portion of a single pixel image of A 1409 taken with the ASI2245MC and 30 milliseconds exposure on the CPC-1100Edge HD with 3x Barlow at f/31.5.

The ZWO ASI 224 MC Camera

ZW Optical was created by Sam Wen in response to his dissatisfaction with the status quo imaging devices and telescope optics available in China and abroad. Sam is a lifelong amateur astronomer and astro-imager, currently living in Suzhou City, near Shanghai. His early astronomy endeavors took a back seat as he finished his degree in electrical engineering, then establishing a career in that field. Living in the city, planetary imaging became his astronomy area of interest. The Philips SPC 900NC and PCVC 840K were the starting imaging hardware.

Figure 10. Sam Wen (left) and the team at ZWO. Front row Yi Tang, Zhenrong Gu and Vanessa Zhang. Back row: Xueming Lu, Yang Zhou, Yong Yu, Sam Wen, Hongwei Kan, and Junfeng Zeng.

Seeing room for improvement, and with fresh ideas, Sam began making his own cameras and small telescopes, founding ZW Optical in the process. His first imager was the ZWO ASI 130MM which used the same sensor as its QHY5 counterpart, producing similar results. Looking for a higher QE sensor, he saw potential in Sony's Aptina's MT9M034, which delivered the desired improvement. The MT9M034 was at the heart of ZWO's second two offerings, the ASI 120MM (monochrome) / MC (color) cameras. Coupled with support within the SharpCap and FireCapture imaging software, he now had a camera that had the potential to outperform equivalent systems at a significant cost savings.

Figure 11. Left: designing a circuit board. Right: assembling a camera in the clean room.

The ASI 224MC discussed in this paper is ZWO's latest camera. A two-stage Peltier cooled version of this camera is scheduled to be released before year's end. These latest ZWO cameras are built around Sony's IMX224 sensor and are able to push read noise below 1 electron.

The response of this camera extends well into the near-IR. Although a monochrome camera would normally be preferred for scientific astronomical measurements, this color camera performs remarkably well and its color filters may allow it to be used for three-color photometry.

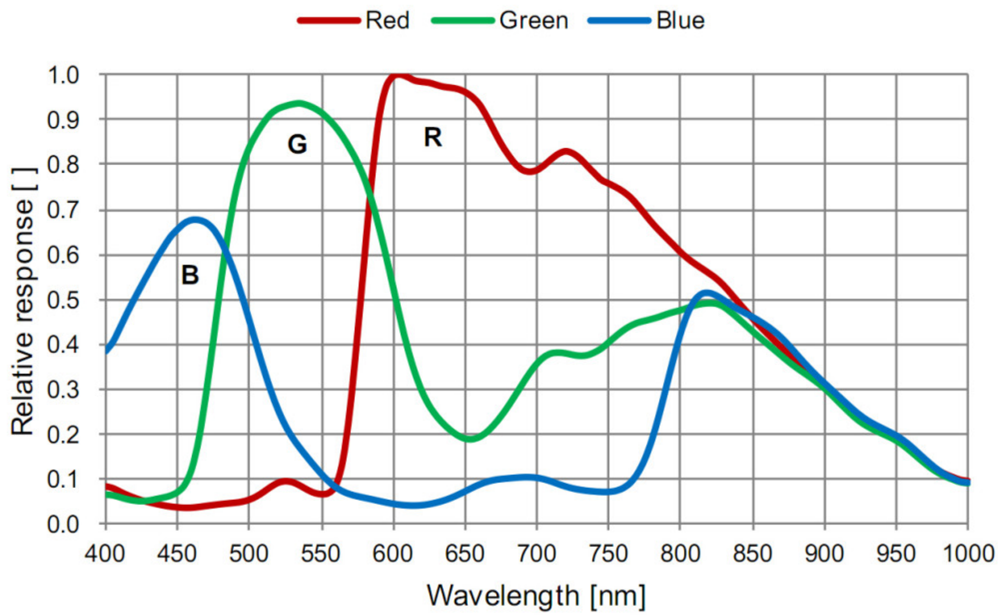

Figure 12. Relative spectral response of Sony's IMX 224 CMOS chip used in ZWO's AST 224MC camera.

Discussion

Although the performance of the ZWO AST 224MC is remarkable, being in color as opposed to monochrome, it is not optimal for the speckle interferometry of close visual binaries. There is about a 2x filter loss on the color sensors, and another 4x loss for the doubling of the f/number, what with 1/4 of the photons per pixel yet the same read noise.

The architecture of CMOS differs from CCD sensors. The CCD sensors in this class have a single readout register, amplifier, and analog to digital converter (ADC). This architecture by its nature normalizes the resultant data, leaving only pixel sensitivity as a variant that is fully normalized with calibration. CMOS sensors have an amplifier and ADC converter for each row or column.

In the case of the IMX224, that is 1213 amplifiers and ADCs (one per column). To reduce the pattern variation produced by the per-column conversion, there is an on-sensor image processing pipeline/Digital Signal Processing system. Since raw data is not available from the CMOS sensor, actual "noise" levels cannot be determined. The term "Temporal Dark Noise" (TDN) is sometimes used to differentiate between this low level noise in CMOS sensors and the classic "Read Noise" from a CCD camera. In general these values cannot be directly compared. In the case of CMOS sensors with unknown processing algorithms, camera-to-camera TDN comparisons should also be done with some care. This pre-processing of data has other ramifications that are specific to a camera. In the case of the ASI224, no dark frame subtraction is used as it produces artifacts.

Jones demonstrated that a high-speed CCD camera could produce nearly as good results as those obtained by Ashcraft with the ZWO AST 224MC camera. Using a Celestron Skyris 618, a classic monochrome CCD camera, images were capture at approximately the same exposure as those with the ASI224 with similar results. Images were processed with dark frames. The Skyris 618 is well behaved, allowing a full calibration if needed.

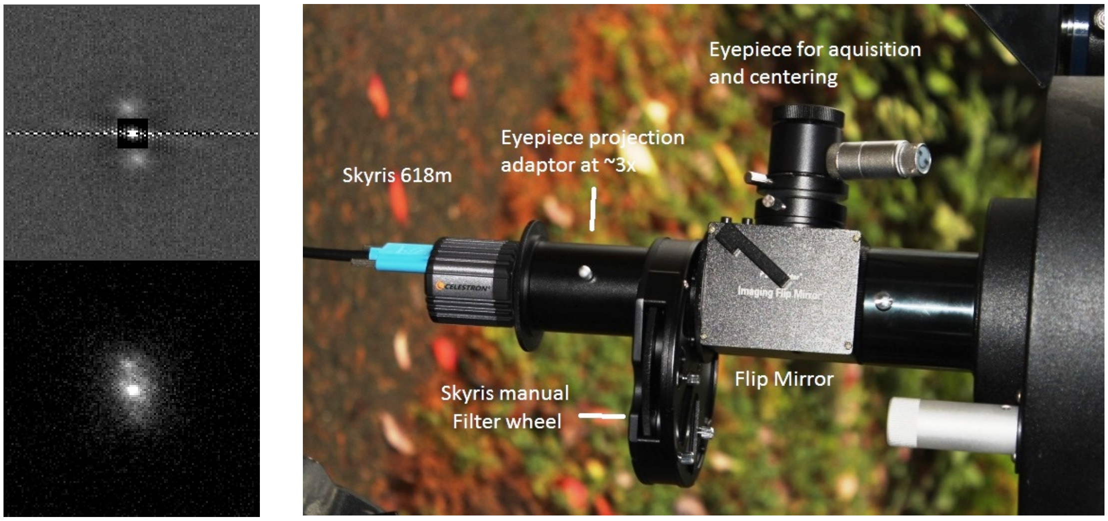

Figure 13. Top left is the autocorrelation of 20449+4332 (rho 2", 10.4 and 10.8 magnitude pair) obtained with the Skyris 618m followed by a "lucky image" below. Both were obtained from the same data set captured without filters at 250ms exposure. A data set with 150ms exposure also yielded measurable results. The back of the 8" SCT and imaging train used to acquire the dataset is at the right. At f/32 the final f-ratio is slightly longer than the optimal f/28 for this camera.

The ASI-224 uses the Sony IMX224LQR image sensor. This is an Exmor Starvis (progressive scan) CMOS sensor. Pregius is the Sony designation for their line of sensors with Global shutters. Both progressive and global shutter sensors are effective for speckle, with a slight benefit to the global shutter option if it does not affect limiting magnitudes.

Sony has announced several sensors and two new technologies beyond that in the IMX-224LQR. Exmor R moves to back side illumination and Exmor RS extends this with better NIR response, deeper well depth and a stacked configuration offering better fill (80%+ vs. ~50%). All these moves are to improve QE of the sensors. Further reduction in TDN is also expected.

The IMX 290, a monochrome Exmore RS Starvis sensor, is expected early in 2017. This sensor is expected to be as good as or better than a monochrome IMX224, which is not planned. The IMX273 Exmore RS Pregius sensor is also expected by the end of 2017 and may be the best senor for low cost speckle work if all else holds.

For speckle interferometry, both the delta mag and the sum of the intensities of the two components are important. Also important are the composite stellar spectra, the QE vs. wavelength curve, filtering, if any, and seeing. If a monochrome CMOS camera shows up with <= 1e- RMS effective read noise and at least 50% QE in-band, then a C-11 should get to about mag 12.5 composite intensity with 70 mS exposures, assuming the delta brightness is less than 1 stellar magnitude and the seeing is good (10 cm Fried cell diam). This should hold down to separations that are roughly the radius of the first diffraction ring. For a C-11, this is about 0.65 arcseconds at V-band. There are many parameters to consider, and they can affect the results by more than a stellar magnitude.

As read noise is reduced, a point will eventually be reached where other noise sources become dominant, and further reductions in read noise will not significantly improve performance for this particular application. Based on our observational data, we estimated that the read noise of the ZWO224 camera was approximately 0.85 e- RMS. In making this estimate, we made a number of assumptions about the transparency of the atmosphere, optical throughput, quantum efficiency, etc.

There are two dominant noise sources in speckle interferometry: read noise and photon shot noise. Even if the read noise were effectively zero, photon shot noise would still limit the magnitude of the double that can be observed. Rowe used his double star speckle interferometry simulation program

(ASD), which incorporates both read noise and Poisson shot noise statistics, to make simulated FITS cubes that were then processed by PS3.

Using Ashcraft's C-11 aperture and image scale, a camera with 0.85 e- RMS read noise, a Fried cell diameter of 10 cm, a double with a separation of 0.65", 1000 FITS images per cube, and a double star having a secondary/primary intensity ratio of 0.5 approximately, some 500 photoelectrons are necessary to detect and measure the double in PS3. If the read noise were zero, the necessary number of photoelectrons drops to ~150. This implies that the read noise is reducing the detection limit by about 1.5 magnitudes over a camera with no read noise.

For faint doubles, Ashcraft found, empirically, that the optimal integration times were upwards of 100 ms. Under conditions of good seeing and using an I-band filter, even longer integration times may be optimal. We speculate that as telescope aperture increases, the integration time must be reduced to avoid smearing images of the increasing number of high resolution speckles. It may be somewhat fortuitous that smaller telescopes can make longer integrations (at wider bandwidths), thus offsetting, to some extent, their lack of light-gathering power.

Conclusion

The ZWO ASI 224MC low noise, low cost CMOS camera, with its Sony IMX224 chip, is a significant technical breakthrough for affordable speckle interferometry of close double stars on smaller telescopes. We are only beginning to explore the full capabilities of this camera, and invite others to join us in this exploration.

If a monochrome version of this Sony chip were incorporated into a camera, this would significantly improve the performance with respect to speckle interferometry. While further reductions in read noise will improve performance, a limit will eventually be reached where read noise becomes insignificant and photon shot noise, which cannot be reduced, will dominate.

Acknowledgements

We thank Sony and its design team for developing the IMX224 chip. We thank the U.S. Naval Observatory for the use of the Washington Double Star Catalog to formulate our target lists.

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Speckle Interferometry with a Low Read-Noise CMOS Video Camera

Clif Ashcraft

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Abstract This paper demonstrates that speckle interferometry of close double stars (Rho < 1″) can be done with a small (11 inch aperture) telescope equipped with a sensitive, low noise, and low read-noise CMOS camera.

Introduction

For the past several years I have not been active in double star observations while I became quite involved with high resolution planetary imaging. In the early years we did this with ordinary webcams like the Philips ToUcam, but more recently we began to use what I call "industrial strength" webcams: cameras developed by firms like The Imaging Source and Point Gray for machine vision and surveillance applications, but inexpensive enough for amateurs to afford and quite suitable for high resolution planetary work. For this we employed the so-called "lucky imaging" approach of aligning and stacking the best frames from videos taken at focal ratios long enough for Nyquist sampling of the planetary images.

This area of amateur involvement has progressed rapidly to the point that we can now routinely take images of the Moon, Mars, Jupiter, and Saturn that not too many years ago took a NASA mission to obtain. For much of this period the cameras we used were based on mature CCD technology, but in recent years, cameras based upon sensitive, low noise CMOS sensors have become available, notably, the ASI series of cameras from ZWO. The amateur planetary imaging community immediately began to use them. As a result, when I read (on the Binary-Stars-Uncensored Yahoo discussion group) that the new low read-noise chips from Sony might make it possible for amateur astronomers to get into speckle interferometry, a province heretofore only possible with 2 meter class telescopes and very expensive EMCCD cameras, I found that I already had in my possession just the camera to try this out. In the report that follows, I present my speckle interferometric measures of close double stars made with this remarkable camera, a modest eleven inch aperture telescope, and the formidable number crunching capability of a home computer running software developed by fellow amateur astronomers.

My Equipment

I use a Celestron CPC-1100EdgeHD telescope. The telescope is fork mounted and computer controlled with GoTo RA and Dec capability. It is an excellent telescope for planetary imaging and, as it turns out, speckle interferometry. Its native focal ratio is f/10, but for the observations reported here, I used a 3x Televue Barlow lens to amplify the focal ratio to f/31.14. A remote motorized focuser is needed for both the planetary work I do and is very helpful for the speckle imaging too. Mine is a Baader SteelDrive Crayford type focuser. I initially set it at 1.5 cm and adjust the focus with the mirror moving focuser, and then lock the mirror down and do all subsequent focusing with the motorized focuser. This is to maintain the same focal ratio and image scale throughout all my observations.

My primary imaging camera is the ZWO ASI224MC with an uncooled 4.8x3.6 mm Sony IMX224 sensor having a 1296x960 array of 3.75 micron pixels overlaid by a Bayer matrix RGB filter. The camera is described in detail elsewhere in this journal (Genet et al. 2015). I also use an Imaging Source DBK21 camera fitted with a 70mm, f/1.3 C-mount lens as a video finder. Without the video finder, locating the faint doubles in the light polluted skies of central NJ would be difficult if not impossible, even with a GoTo telescope mount. My setup is shown in Figure 1.

Figure 1. Telescope with attached cameras

Software and Computer

The cameras are connected by USB cables to my personal computer running Windows 10 Pro. I use Torsten Edelmann's FireCapture[1] to record the speckle images from the ASI224MC. I use IC Capture (supplied by The Imaging Source[2]) to give a 2.4x1.8 degree view of the sky through the video finder using the DBK21. An overlay with a movable double crosshair from Al's Reticule[3] allows me to accurately position faint double stars so they become visible in the tiny 1.69' x 1.25' field of the imaging camera.

To process the speckle images, I use David Rowe's PS3 program[4], initially developed as a plate solve program, but with added tools for constructing and processing FITS cubes and for displaying speckle autocorrelograms and interferograms. For drift calibration and other functions I use Florent Losse's REDUC[5] and MaximDL[6]. For the lucky imaging comparison with speckle results I used Emil Krailkamp's Autostakkert 2.5[7] and Cor Berrevoit's Registax6[8].

[1] http://www.firecapture.de/
[2] http://www.astronomycameras.com/products/software/iccaptureas/
[3] http://www.iceinspace.com.au/forum/showthread.php?t=21798&page=3
[4] http://jdso.org/volume10/number4/Genet140912.pdf
[5] http://www.astrosurf.com/hfosaf/uk/tdownload.htm
[6] http://www.cyanogen.com/maxim_main.php
[7] http://www.autostakkert.com/wp/download/
[8] http://www.astronomie.be/registax/

My computer was built for me by PC Warehouse and contains a 7-core Intel processor running at 3.6 gigaherz and is equipped with 7.25 terrabytes of hard disc storage and 15 gigabytes of RAM. For this work, you need lot of storage space.

Calibration

My camera calibration was based upon a trailed exposure of Albireo giving a camera angle (Delta) value of 0.4465°. The scale factor (E) of 0.0889″/pixel was from the measurement of the separation of the components of Albireo in a lucky image stack using MaximDL for measuring the separation of the centroids of the components. After the measures on September 12, the camera was rotated slightly and a new Delta calibration obtained using REDUC on a series of FITS images taken of Albireo while the star drifted through the field of the camera. The new Delta value of -12.75° was used for the remainder of the measures.

I intend to calibrate the focal length of my system by imaging a bright star through an H-a filter and a coarse grating. The plate scale from this calibration will be used in my future observations.

The Targets

My initial speckle interferometry targets were picked from a list prepared by Richard Harshaw from entries in the WDS. Additional targets were taken from the 20-hour RA section of WDS, as the targets from Richard's list began to be significantly west of the meridian when I began my observing sessions. I tried to pick known doubles with Rho values below 2 arc seconds and brighter than 12th magnitude, and I attempted to make my observations when the stars were as close to the meridian as possible.

The Results

Table 1 shows my measures on 19 stars, several of which are discussed below.

WDS 19177-2302

The first set of five measures was done on BU249AB, a 5.43, 8.75 magnitude pair with a Rho value of 1.7″, last measured in 2013. I chose this double as an easy target to start with and to see how reproducible my measures were. I used relatively high gain settings on the camera, in the range of 492-600 (maximum is 600) and exposures of from 2.9 to 7.5 milliseconds. My average Theta of 126.6 ± 2.1° and Rho of 1.74 ± 0.02″ are consistent with the most recent WDS measures.

WDS 19224+4205

I also took multiple measures of A 592, a severe test for an 11-inch aperture and low cost camera, since the last reported value for Rho was only 0.6″, and both components are fainter than 10^{th} magnitude. I obtained an average Theta of 238.8 ± 6.2° and an average Rho of 0.69 ± 0.02″ from my five observations. Compare this with the last reported values in the WDS of 247° and 0.6″. The large uncertainty in Theta is in part due to the closeness of the pair.

WDS 19338+4222

The final system for which I have variance information is A 597. My five observations of gave an average Theta of 81.9 ± 0.6° and an average Rho of 1.69 ± 0.07″. Compare these values with 84° and 1.4″ as the last reported values in the WDS.

The remainder of the observations reported here consist of only one set of FITS files each consisting of 300 to 3500 speckle images that were processed into autocorrelograms which resolved the components of the double and allowed me to estimate the Theta and Rho values, but with no information about the variance.

WDS 19202+3411

HU 1300 is notable in being quite a close pair with a last reported Rho of only 0.7″. I got 0.74″ with a Theta of 184.23° compared with the WDS last reported Theta of 182°.

WDS 19214+4831

TDS 983 is also notable in that there was only one previous measure and that by the Hipparcos satellite. My measures of Theta = 82.34°, Rho = 1.12″ are close but not identical to the 1991 value of Hipparcos of 79° and 0.9″, but in 24 years perhaps this much motion could take place.

WDS 19238+3119

A 2196BC is part of a triple star system with AG 230A,BC. The very close BC pair with a Rho of only 0.7″ is probably at the very edge of the capability of my telescope and camera system and is not completely resolved in my autocorrelograms. My measure of Rho is 0.77″ and I get a significantly different Theta of 188° compared with the 2008 value of 234° in the WDS. I also report a measure for the wide pair in the system AG 230A,BC. I get Theta = 71.11°, Rho = 5.64″ in reasonable agreement with 70°, and 5.5″ as last reported in the WDS.

WDS 10010+3742

Another very close double is BU 1289AB. The WDS last reported values from 2012 are Theta = 54°, and Rho = 0.7″. I got 55.11° and 0.73″.

If you plot my measures of all 19 stars against the latest measures in the WDS you get a reasonable correlation except at very small Rho values. This is most likely uncertainty in the measures, but it could be actual changes in the positions of the stars. More observations are necessary to verify whether this is the case. Figure 2 is a plot of my observations of Theta vs the last reported values in the WDS and Figure 3 is a plot of my observations of Rho vs the last reported values in the WDS.

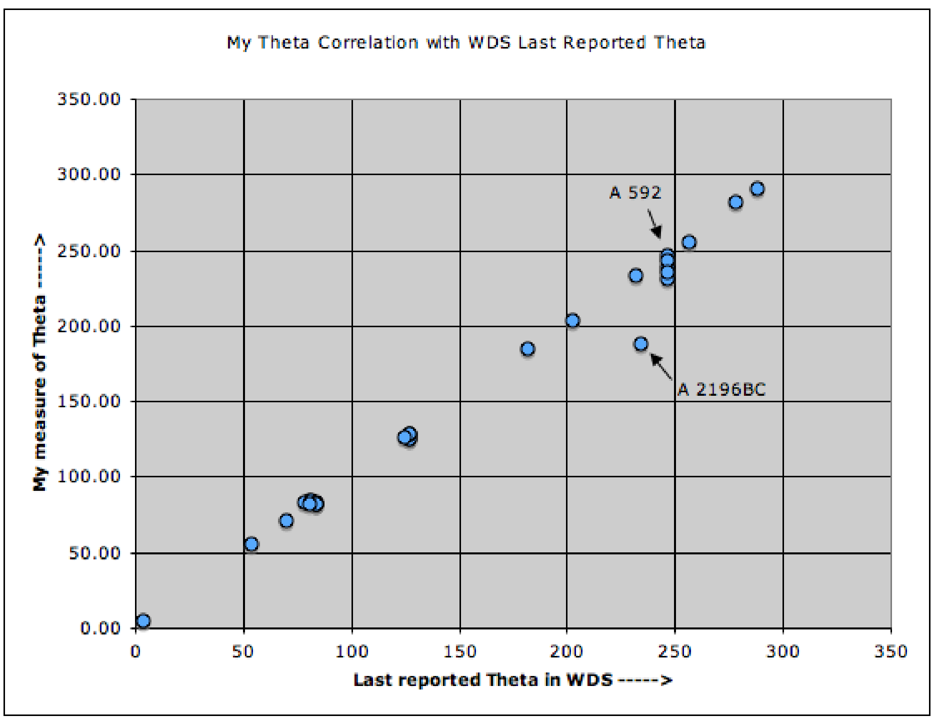

Figure 2. My measures of Theta vs. last reported value in WDS

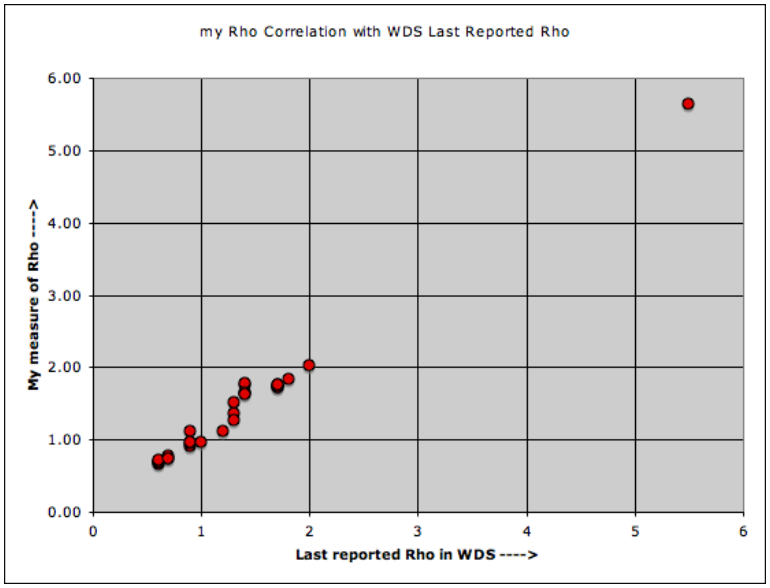

Figure 3. My measures of Rho vs. last reported value in WDS

I was also able to obtain lucky images for several of the stars to compare with the autocorrelograms from speckle interferometry. These images were obtained by aligning and stacking the best 5% of the frames from either AVI files or the FITS that were used to make the FITS cubes for the speckle work using the program Autostakkert 2.5. The result were sharpened with wavelets using Registax6. This comparison is shown below in Figure 4. Measurements of the double stars could be made from the lucky images, but would not be nearly as high in precision as those obtained from the autocorrelograms. They are useful, however, in helping to resolve the 180 degree phase ambiguity of speckle interferometry. Thus far, any double I have resolved by speckle interferometry has also shown at least partial resolution (enough to resolve the ambiguity) by lucky imaging.

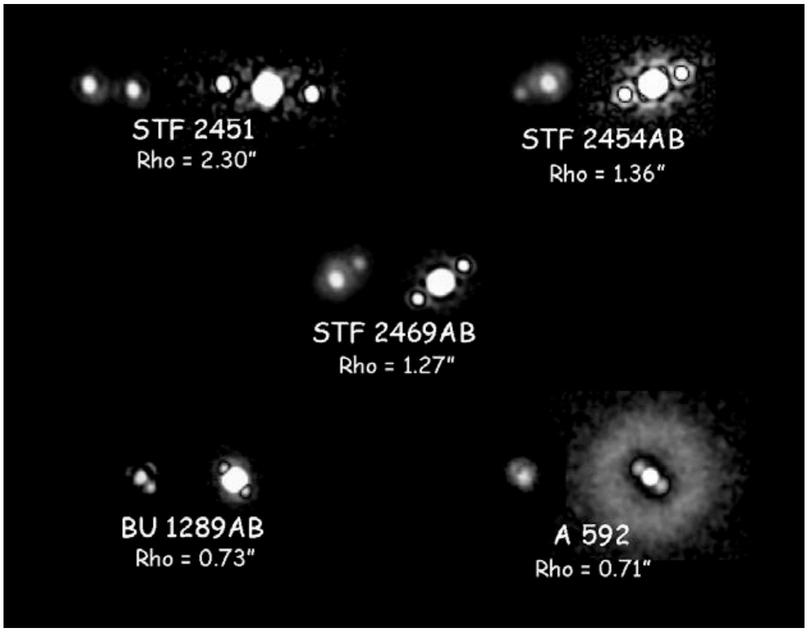

Figure 4. Comparison of Lucky Images with Autocorrelograms

Conclusions

These results demonstrate that one can resolve close double stars by speckle interferometry using the new low read-noise CMOS cameras on small telescopes. I plan to continue work in this area to better define its potential and to make measures of double stars with Rho values in the 1″ to 5″ and magnitudes as faint as 10 or 11 suitable for inclusion in the WDS, and to use the ASI224MC for speckle work on larger telescopes, such as the 24” Ritchey-Chrétien at Sperry Observatory. A particularly useful application of this technology would be to check suspected close doubles for later measurement with speckle cameras on larger telescopes.

Acknowledgements

Review of this paper by Russell Genet and Vera Wallen is acknowledged.

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Table 1. Observations

See below

Table 1. Observations

WDS Identifier	Discoverer Code	Epoch First	Epoch Last	# Obs.	Theta, ° First	Theta, ° Last	Rho " First	Rho " Last	Magnitudes Pri	Magnitudes Sec	Date M/D/YY	Camera Gain	Exp. ms.	Frames taken	Theta degrees	Rho arc sec.	Notes
					Camera oriented with North approximately down in final image, camera angle = -0.4465 degrees												1
19177+2302	BU 248AB	1875	2013	62	125	127	1.9	1.7	5.43	8.75	9/1/15	583	7	4152	124.3	1.73	
19177+2302	BU 248AB	1875	2013	62	125	127	1.9	1.7	5.43	8.75	9/2/15	582	7	3307	124.2	1.71	
19177+2302	BU 248AB	1875	2013	62	125	127	1.9	1.7	5.43	8.75	9/5/15	492	3	1471	128.3	1.76	
19177+2302	BU 248AB	1875	2013	62	125	127	1.9	1.7	5.43	8.75	9/5/15	600	3	2225	128.2	1.74	
19177+2302	BU 248AB	1875	2013	62	125	127	1.9	1.7	5.43	8.75	9/5/15	481	8	652	127.9	1.77	
20396+4035	STT 410AB	1843	2013	131	23	4	0.5	0.9	6.73	6.83	9/6/15	556	7	1208	4.5	0.92	
19030+5135	STF 2451	1831	2011	53	58	81	2.6	2	9.29	9.47	9/7/15	532	59	508	84.0	2.03	
19062+3026	STF 2454AB	1831	2013	175	205	288	0.8	1.3	8.34	9.72	9/7/15	532	61	494	290.9	1.36	
19078+3856	STF 2469AB	1831	2010	51	121	125	1.3	1.3	7.93	9.13	9/7/15	532	42	669	126.3	1.27	
19190+3916	STF 2502	1831	2012	19	206	203	1.8	1.2	8.06	10.3	9/7/15	532	42	708	203.4	1.12	
19202+3411	HU 1300	1904	2012	15	172	182	0.8	0.7	8.92	9.56	9/8/15	532	57	528	184.2	0.74	
19214+4831	TDS 983	1991	1991	1	79	79	0.9	0.9	9.78	11.12	9/8/15	532	94	321	82.3	1.12	
19222+2230	BU 141AB	1873	2010	41	85	82	0.4	0.9	7.61	9.21	9/8/15	556	7	3229	83.9	0.94	
19224+4205	A 592	1903	2010	14	217	247	0.3	0.6	10.11	10.52	9/8/15	532	99	305	246.4	0.67	
19238+3119	AG 230A,BC	1902	2008	16	74	70	5.5	5.5	9.76	10.8	9/11/15	600	100	901	71.1	5.64	
19238+3119	A 2196BC	1910	2008	8	234	234	0.6	0.7	10.8	11.2	9/11/15	600	100	901	188.0	0.77	
19241+4626	STT 373	1843	1991	20	233	232	1.8	1.8	7.63	9.93	9/11/15	600	26	3515	233.5	1.84	
19258+2328	DOO 74	1904	1991	5	252	257	1	1.3	10.04	10.99	9/12/15	600	100	901	254.9	1.52	
					Camera rotated about 12 degrees counterclockwise before next data set, camera angle = -12.75 degrees												2
19224+4205	A 592	1903	2010	14	217	247	0.3	0.6	10.11	10.52	9/13/15	600	97	6172	238.3	0.69	
19338+4222	A 597	1903	2008	33	154	84	1.1	1.4	8.28	10.8	9/14/15	500	75	4003	81.6	1.64	
19338+4222	A 597	1903	2008	33	154	84	1.1	1.4	8.28	10.8	9/15/15	500	80	7958	83.0	1.76	
19338+4222	A 597	1903	2008	33	154	84	1.1	1.4	8.28	10.8	9/15/15	500	75	7959	81.9	1.78	
19224+4205	A 592	1903	2010	14	217	247	0.3	0.6	10.11	10.52	9/17/15	600	80	2245	231.1	0.70	
19338+4222	A 597	1903	2008	33	154	84	1.1	1.4	8.28	10.8	9/17/15	600	40	4470	81.5	1.64	
19224+4205	A 592	1903	2010	14	217	247	0.3	0.6	10.11	10.52	9/17/15	600	100	1801	243.4	0.69	
19224+4205	A 592	1903	2010	14	217	247	0.3	0.6	10.11	10.52	9/17/15	600	120	1501	235.0	0.72	
19338+4222	A 597	1903	2008	33	154	84	1.1	1.4	8.28	10.8	9/17/15	600	80	2246	81.8	1.63	
20137+1609	STF 2651AB	1830	2011	84	280	278	1.6	0.9	8.41	8.44	9/19/15	600	20	8912	282.0	0.97	A 592
20074+3543	STT 398AB	1845	2012	31	62	81	0.8	1	7.45	9.2	9/19/15	600	20	8897	82.0	0.96	
10010+3742	BU 1289AB	1899	2012	19	58	54	0.8	0.7	8.15	9.2	9/23/15	600	40	5000	55.1	0.73	

Notes

1 Albireo, drift gives delta = -0.44656 degrees, stack of all frames gives FITS file measured in MaximDL for scale factor= 0.0889" per pixel

2 Albireo trail of FITS REDUC gives Delta = -12.75 degrees, no change in scale factor.

Sparse-Aperture Quasi-Meridian Telescopes

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2. PlaneWave Instruments
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5. California State University, Los Angeles
6. Gravic Labs
7. Concordia University, Irvine

Abstract Speckle interferometry has been routinely used for four decades to observe close visual binaries with separations below the seeing limit, filling out their orbits with position angle and separation measurements during numerous runs on two- to four-meter class telescopes. Unfortunately, as the number of potential or actual close visual binaries needing coverage has grown, the time available on these telescopes has fallen, as has the number of astronomers with time to make the observations. A couple of large robotic telescopes dedicated to observing close visual binaries could provide the needed coverage. The challenge is to provide this capability at low cost. While telescopes with single mirrors appear to be too expensive, a telescope with multiple, small, spherical mirrors arranged might be affordable. A three-mirror laboratory demonstration suggested that the individual mirrors can be positioned with high precision at low cost. By observing targets as they neared the meridian, the cost of the telescope's mount and the observatory enclosure could be greatly reduced.

Introduction

Starting with William Herschel (1782), visual double stars have been observed on a regular basis for over two centuries, with generations of astronomers reporting the changing position angles and separations between the primary and secondary components. Herschel (1803) discovered that some of the doubles he observed had curved trajectories, and he correctly deduced that the two stars were gravitationally bound. He named them binaries. Felix Savary (1827) estimated a mathematical orbit for a binary, ξ UMa.

Once an apparent orbit is established, Kepler's Laws can be used to determine the dynamical mass of a binary pair. Radial velocity curves can then be applied to parse the dynamical mass into the individual stellar components, providing a direct determination of stellar mass—key to understanding stellar evolution.

For separations greater than the seeing limit, the periods of most binaries are on the order of many decades or centuries. Anton Labeyrie (1970) came up with a way to overcome seeing limitations—speckle interferometry—that allowed the theoretical resolution limit of a telescope to be achieved and hence much shorter-period binaries to be observed. By taking many very short exposures with a high-speed film camera, Labeyrie froze out atmospheric effects. The observations were then analyzed in Fourier space to extract the position angle and separation values for a binary star (i.e. an autocorrelogram).

Harold McAlister (1985) and colleagues used speckle interferometry on the 2.1- and 4.0-meter telescopes at Kitt Peak National Observatory to obtain the first high precision astrometric orbital measurements of many well-known short-period spectroscopic binaries. Combining the astrometric and spectroscopic measurements yielded individual stellar masses for these binaries. Operating a high-speed film camera from inside the Cassegrain cage on the 4-meter telescope was challenging, but once portable computers and intensified CCD cameras became available, convenient warm-room observations were possible.

Speckle interferometry measurements of close visual binaries were routinely carried out on the 4-meter telescopes at Kitt Peak National Observatory and Cerro Tololo Inter-American Observatory, the 3.5-meter WIYN telescope, the 2.5-meter telescope on Mt. Wilson (until it was shut down), and the Russian 6-meter telescope at the Special Astrophysical Observatory in the Caucasus Mountains (Horch 2006). Brian Mason and William Hartkopf have used the historic 26-inch refractor at the U.S. Naval Observatory for decades, making the largest number of speckle interferometry measurements with any telescope.

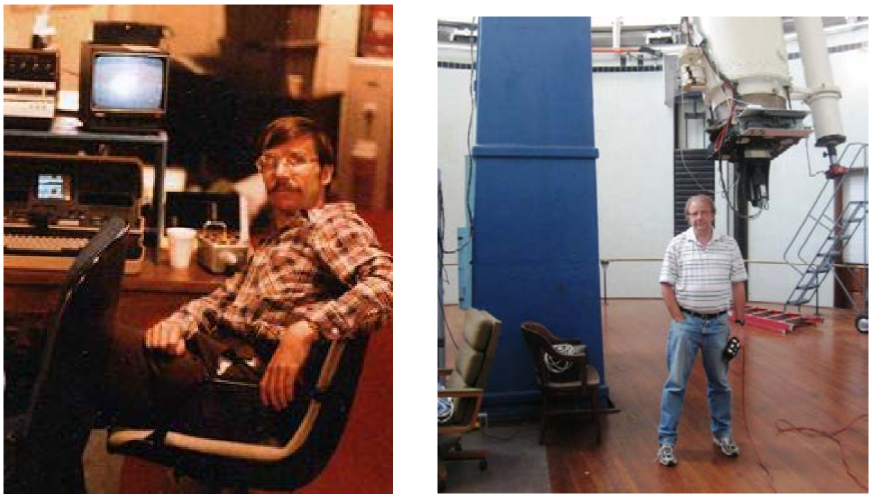

Figure 1. Left: a young William Hartkopf captures high-speed frames with an early Osborn computer from an intensified CCD (ICCD) camera located at the Cassegrain focus of the 4-meter telescope at Kitt Peak National Observatory. Right: Brian Mason with the controls of the 26-inch refractor at the U.S. Naval Observatory in Washington. The ICCD-based camera is permanently mounted on the telescope.

Florent Losse, a French amateur astronomer, pioneered speckle interferometry observations of close binary stars among amateurs with his 0.4-meter telescope. He developed convenient software (REDUC) for reduction and analysis of speckle observations.

An electron multiplying CCD (EMCCD) has been used as the heart of a portable speckle interferometry camera used by an eclectic mix of professional, amateur, and student astronomers on a number of different telescopes including two week-long runs on the 2.1-meter telescope at Kitt Peak National Observatory (Genet, 2013).

More recently, it has been found that the recently introduced low-noise CMOS cameras using sensors manufactured by Sony and costing less than $500 can provided good results on smaller telescopes. For example, using such a camera on a Celestron C-11, doubles can be resolved with separations as close as 0.5″ and doubles fainter than 10^{th} magnitude (Ashcraft 2015, Genet et al. 2015). The advent of low cost cameras suitable for speckle interferometry is making this technique increasingly available to amateur and student astronomers.

Over the years, the number of known binaries that need continued observations to firmly establish their orbits has grown, as has the number of potential new binaries needing observations to verify that they are in fact binaries. The Hipparcos astrometric space telescope added thousands of new candidate binaries to the list of potential binaries, while the recently launched Gaia telescope is expected to add many more (Eyer et al. 2013). While survey telescopes such as the Large Synoptic Survey Telescope are seeing limited, they can reveal slightly elongated images of double stars, providing a rich source of potential new binaries (Terziev et al. 2013).

As the number of observations that could be fruitfully observed has grown, the number of professional observational astronomers in this area of research has dwindled. Also, time on 4-meter-class telescopes for speckle observations of closer binaries has almost vanished as these telescopes have increasingly been used for observations of faint objects with permanently mounted instruments. Recognizing this mismatch between observational opportunities and wherewithal, the authors of this paper—an eclectic group of professional, amateur, and student astronomers—have been exploring possibilities for the design, construction, and operation of ultra-low-cost 2- to 4-meter class telescopes that would be dedicated to observations of closer visual double stars. We realized from the outset that filled-aperture telescopes with 2- to 4-meter mirrors would be beyond our budget, so we considered the possibility of low cost multi-mirror interferometers.

Multi-Mirror Interferometers

An interferometer makes measurements by exploiting the wave nature of light, using the interference patterns to extract information from the observations. One of the earliest examples of this process was Young's double slit experiment, where the diffraction patterns helped to establish the wave-nature of light (Young 1807). Taking advantage of this property, Fizeau (1851) demonstrated an interferometer that shares many elements with modern stellar interferometers by combining two collimated beams of light to produce interference fringes. This type of interferometer proved to be useful for making very precise measurements of the flatness of surfaces, indices of refraction, and displacements.

This principle was extended to astronomy by using two or more separate mirrors whose beams are collimated and combined to give the higher angular resolution of a single larger mirror. In 1920 Michelson and Pease equipped the 100 inch Hooker telescope at Mt. Wilson Observatory with a 20 foot interferometer. This configuration was used to make the first angular stellar diameter measurement of Betelgeuse. Michelson noted that interferometers are less susceptible to the atmospheric distortions that normally prevent large telescopes from being diffraction limited (Michelson and Pease 1921).

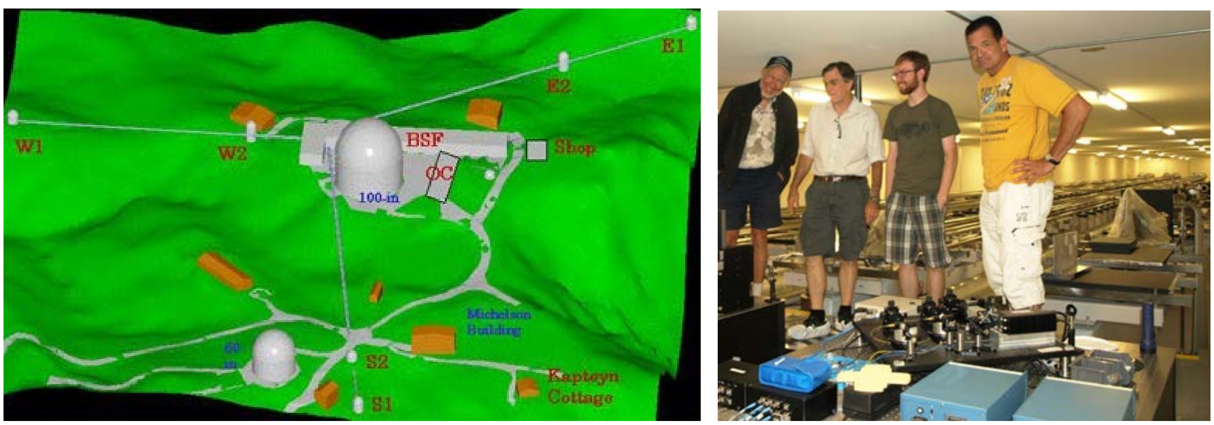

Figure 2. Diagram of CHARA array on Mt. Wilson Observatory. Russ Genet, David Rowe, Alex Teiche, and Reed Estrada in the optical trombone room of CHARA

An example of a modern telescope using separated reflective elements to increase angular resolution is the Center for High Angular Resolution Astronomy (CHARA) array on Mt. Wilson. This array uses six 1-meter telescopes that feed central instrumentation through vacuum pipes. The longest effective baseline is 330 meters, giving the array a maximum effective angular resolution of 200 micro-arcseconds. In order to keep the path lengths between the six telescopes equal as the Earth turns, "optical trombones" compensate for path length differences to a fraction of a micron (Hartkopf, 1996). This concept was taken even further with the Navy Precision Optical Interferometer (NPOI), with a maximum baseline of 439 meters for even higher angular resolution measurements, although the individual telescopes each have a much smaller aperture. Baselines on this scale require very expensive, complex assemblies for accurately transporting, compensating, and finally combining the light from all the telescopes (Pauls 2001).

Single-Mirror Sparse-Aperture-Mask Telescopes

Starting in the 1970s, aperture masks were installed on the collimated beams from large single-mirror telescopes in an attempt to improve both their resolution and dynamic range as compared with an unmasked, filled aperture telescope. The sub apertures in these masks were placed in a non-redundant configuration, such that each pair of sub apertures was positioned at a unique angle and distance. Each pair of sub apertures contributes a sinusoidal fringe pattern to the image, creating a complicated interference image in the spatial domain. Due to the non-redundant nature of the mask, each spatial frequency amplitude/phase component arises from only one set of sub apertures. If there were redundant pairs of sub apertures, the redundant fringe patterns would not add in phase in the presence of aberrations. This creates "redundancy noise", degrading the contrast and SNR of the image. Because a filled aperture pupil effectively is composed of an infinite number of apertures, with an infinite number of redundancies, the filled aperture image has high redundancy noise and thus lower contrast/SNR compared to the non-redundant mask image (Rhodes 1973).

While the Rayleigh resolution limit of a filled-aperture telescope is 1.2 λ/D, aperture masking lowers this to 0.5 λ/D. Aperture masking has also been shown to be useful for systems requiring high contrast, low separation detection (Lacour et al. 2011). Many observational successes have been recorded for systems requiring high contrast detection at high resolution such as low-mass binary systems, brown dwarfs, and young transitional disc systems (Tuthill et al. 2013).

This non-redundant sparse aperture mask technique was used by groups led by Baldwin with the University of Hawaii's 88-inch telescope, Frater on the 3.9-meter AAT telescope, and Readhead et al. at Palomar observatory, to increase the capabilities of these telescopes for viewing bright, small targets. These groups had past experience with using closure phase and aperture synthesis in radio astronomy, and they applied similar techniques to optical astronomy with new, high quantum-efficiency image sensors (Readhead et al. 1988). Successes were made in imaging binary stars, showing these techniques had potential for imaging high contrast targets near the diffraction limit (Nakajima et al. 1989).

More modern examples of sparse aperture masking are to be found at the VLT at Paranal and Keck I on Mauna Kea. One of the 8.2-meter VLT telescopes at Paranal (Unit 4) has occasionally employed a non-redundant mask with seven holes that reduces the telescope's light gathering area from 49 square meters down to less than 8 square meters, eliminating 85% of the light. Without a mask, the resolution of the observation is limited by the high levels of speckle noise caused by the many wave front errors over the large mirror. The mask improves the achievable resolution of the telescope at the cost of reducing the photons captured in the image, restricting this technique to brighter targets (Lacour et al. 2011).

Multiple-Mirror Sparse-Aperture Telescopes

Introduction

It makes sense to use sparse aperture masks occasionally on large telescopes to improve their resolution and dynamic range when observing brighter objects such as binary stars and disc systems within the isoplanatic patch. For telescopes that would be totally dedicated to high resolution, high contrast observations over a narrow field-of-view, using an expensive and heavy single mirror and then tossing away the majority of the light probably may not make economic sense.

When an aperture mask is used on a full-aperture telescope to improve its resolution and dynamic range, the masked-off "sub mirror" segments are off-axis parabolas. For a dedicated sparse aperture telescope with a number of small mirrors instead of a single large mirror, the various small mirrors could be off-axis parabolas, but these would be expensive to manufacture. Given that the field of view of interest is very small—just the isoplanatic patch—it is possible to correct the spherical aberration with refractive lenses at prime focus or, for a Cassegrain-configuration, a Pressman-Carmichael secondary mirror. The use of spherical mirrors in a sparse aperture telescope has been reported by Dejohghe et al. (2004).

We have considered two basic approaches for a sparse aperture telescope. One approach would be very similar to sparse aperture masking described above. Small mirrors would be arranged in a non-redundant manner and bispectrum analysis or similar phase closure analysis would be employed.

The second approach would use fewer, somewhat larger mirrors in a redundant pattern that covered all the baselines, and would use autocorrelation analysis with a single deconvolution star. We simulated the performance of a seven-mirror telescope with the Atmospheric Distortion Simulator (ASD) developed by Rowe. In this simulation, the sparse aperture overall "mirror" had an outside diameter of 2 meters and contained seven sub-aperture mirrors, each 50 cm in diameter. A double star with 0.2" separation and 3.0 magnitudes brightness difference was simulated. The mirror configuration is shown if Figure 3 (left), along with a typical instantaneous image (middle), and the simulated speckle reduction results for a FITS cube of 500 images (right). A reference star was used for deconvolution. The Fried cell diameter was 10 cm and the simulations were noise-free and aberration-free.

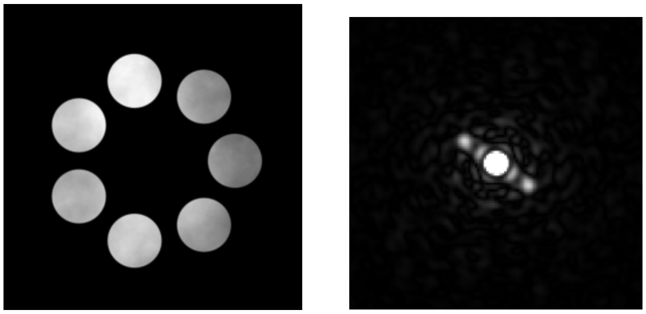

Figure 3: Simulation of two-meter sparse-aperture speckle interferometry telescope.

Lab Experiments

To explore the sparse aperture telescope concept a small-scale "lab" demonstration system was assembled that contained three 0.25-meter diameter spherical primary mirrors as well as a light source and EMCCD camera mounted on a vertical test stand at the radius of curvature. The set of three mirrors with matched 0.25-meter focal lengths for this laboratory demonstration was made by Hubble Optics. Their focal lengths were matched during manufacture to within less than 2 mm.

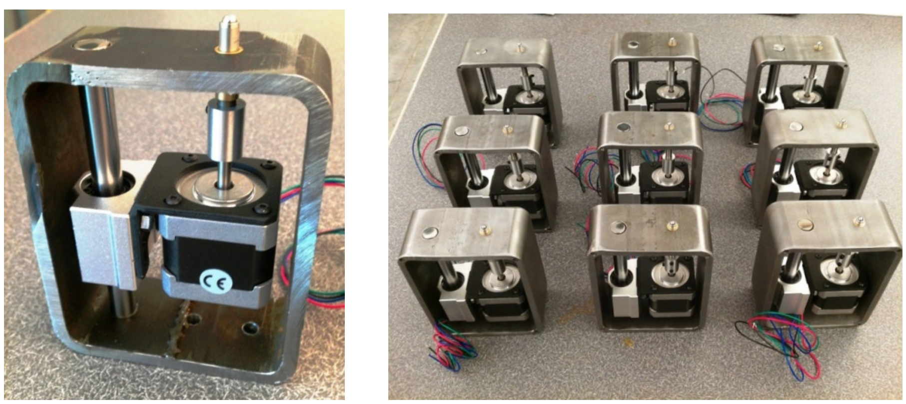

Figure 4. The nine positioners in the laboratory demonstration each use a very fine-pitch thread screw (256 threads/inch) and a motor supported by a linear bearing to position the mirrors in angle and axial displacement.

Each mirror was positioned with three precision actuators, for a total of nine actuators. The heart of each actuator was a fine-thread screw and bushing with a hemispherical tip that contacts one of three sapphire plates on the bottom of the mirror. With 256 threads per inch, the pitch was so fine that the screws resemble machined shafts rather than threaded ones. Stepper motors, riding on a linear bearing, turned the fine-pitched screws. Positioning resolution was better than 100 nanometers.

Figure 5. The three mirrors on their positioners with the control electronics and the vertical test stand.

The test stand was basically a hexapod tower with a bright LED, small precision pinhole aperture, and high speed camera. The focal length of the mirrors was 2.5-meters, while the light source and camera were placed at the radius of curvature of 5 meters.

The next logical step might be to automate the alignment of these mirrors and confirm that these alignments could be held over a period of observing. Using a high coherence point light source as a simulated star, correctly aiming the mirrors should result in the airy disc PSF of a mirror producing fringes visible from the interference pattern of the 3 mirrors. This alignment process could, hopefully, be automated, likely using a point source as a reference and the image on the science camera as feedback. With this process automated, studies would need to be done to confirm that this alignment could realistically be held over a period of observing where thermal expansion and other effects could cause misalignment.

Sparse-Aperture Quasi-Meridian Telescopes (SAQuMeTs)

An optical manufacturer, Hubble Optics, has evaluated manufacturing a set of seven 50-cm spherical primary mirrors with closely matched focal lengths. The cost for the mirrors appears to be modest.

The cost of the positioners also appears to be modest. The cost for the parts and materials for the nine individual (three mirror) positioners for the laboratory demonstration was only $1500. The cost of the telescope’s stiff space frame has not been estimated, although it is not expected to be high.

The calculations required for speckle interferometry are computationally intensive. Using the currently available software, the processing of speckle images requires many hours for a commonly available desktop computer to process the image data from a single night's observations. In order to speed up the process of speckle image processing, the use of multiprocessing is being investigated. Two approaches which show promise are distributed multiprocessing and the use of high-performance multiprocessing hardware. Distributed multiprocessing is widely used in high-performance computing applications; examples include computational fluid dynamics software such as OpenFoam and image processing software such as KISIP, both using the OpenMPI distributed processing interface. The KISIP software uses bispectrum analysis for speckle interferometry data reduction of solar images, and its use is being investigated for use with double star images. It may be advantageous to use dedicated high-performance hardware for speckle image reduction. The team has secured a donation of a pair of Intel Xeon Phi 31S1P coprocessor cards; each coprocessor has 8GB RAM and contains 57 Intel Pentium cores running at 1.1GHz. As of November, 2015, the world’s fastest supercomputer, the Tianhe-2, is built using 48,000 Intel Xeon Phi coprocessor cards. The current speckle interferometry project will not need Tianhe-2’s 55 petaflops of computing power, but 1+ teraflops of computing power will be able to process image cubes in near real-time. Both distributed multiprocessing and the use of high-performance dedicated hardware is being investigated to speed up speckle data processing.

As the cost of the optics is decreased and the effective aperture increased, the cost of both the mount and enclosure becomes significant. We have been considering using quasi-meridian telescopes with matching enclosures that would observe objects as they near the meridian. Such mounts and enclosures should somewhat reduce the overall costs of complete systems. Instead of a telescope that can move to objects over the entire sky, only objects along a narrow north-south strip need to be observed, simplifying the telescope's mount. Similarly, instead of needing a large and expensive dome, the enclosure can simply be a north-south narrow slit.

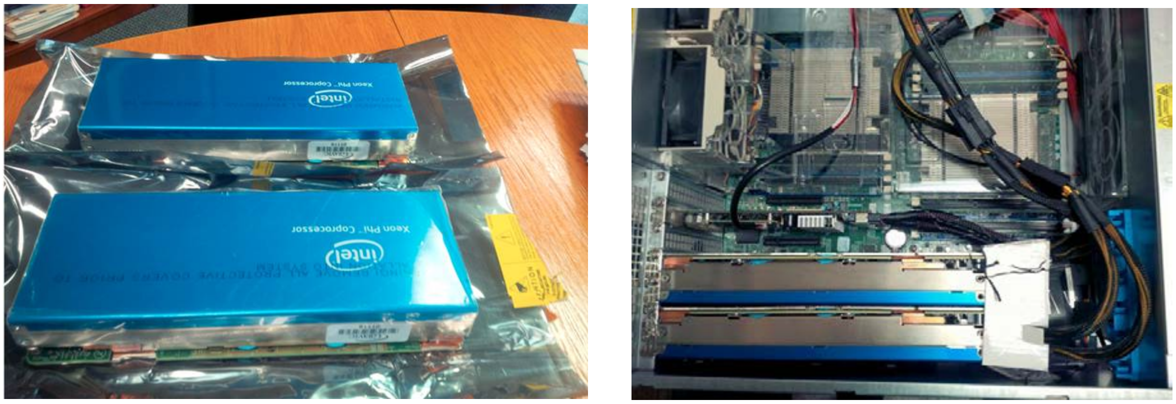

Figure 6. A pair of Intel Xeon Phi 31S1P PCI Express coprocessor cards installed in a desktop computer with an extra muffin fan for cooling.

For a dedicated, quasi-meridian, speckle interferometry survey telescope, the range in Declination observed on any given night (or set of nights) could be restricted to a small value (such as 10 degrees). Other Declination bands would be covered over time. This would improve observational efficiency (less time moving back and forth in declination). It would also reduce the enclosure's opening to the sky. Observing in Declination bands could also reduce gravitational effects during a night's run that could misalign the multiple mirrors, causing them to lose phase lock.

Conclusion

Large, sparse-aperture, quasi-meridian telescopes with several small mirrors may be able to provide needed speckle interferometry coverage of close visual binaries at an affordable cost. Two overall approaches to such a telescope could be taken: one very similar to non-redundant sparse aperture masking; the other a redundant system with larger mirrors. A laboratory evaluation suggested that matching focal-length spherical mirrors and precision positioners could be made at low cost. However, it has not been demonstrated yet that phasing the mirrors and maintaining phase under typical operating conditions could also be achieved at low cost. Operating these telescopes in a quasi-meridian configuration could significantly reduce the cost of the mounts and enclosures, while fully automating these telescopes could reduce their operational costs.

Acknowledgement

It is a pleasure to thank the Concordia University Alumni Association for a special grant to purchase of one of the sparse aperture test mirrors.

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Sparse Aperture Telescope Active Optics Report

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Abstract Conventional large aperture telescopes required for binary star research are typically cost prohibitive. An automated, sparsely populated aperture design would be an economically feasible solution to expand binary star research. An inexpensive telescope active optics system is needed for sparsely populated apertures to expand binary star research. For this project, a prototype active optics system was created and fitted to a telescope frame using low cost components. The active optics system was capable of tipping, tilting, and elevating the mirrors to align the images of simulated star light. The low cost mirror position actuators are accurate to 31.25 nm, which is accurate enough to perform speckle analysis on red spectrum light. The success of the prototype makes this is a significant step towards a full form, fully automated sparse aperture telescope.

Statement of Problem

Various 4 meter class telescopes have been used to build up observational records of many short-period binaries over the past several decades. However, observing time on 4 meter class telescopes is becoming increasingly difficult to obtain. Our observational record for known binary stars may no longer be able to continue and recently discovered short-period binary stars may receive no observation at all. A dedicated telescope is needed for the observation of binary stars to continue.

Purpose of Study

A dedicated 4 meter class telescope would greatly benefit the observations of close binary stars. Conventional large aperture telescopes required for binary star research are typically cost prohibitive however. An automated telescope with a sparsely populated aperture could be an economic solution to this problem. To align the mirrors of a sparse aperture, an inexpensive active optics system is needed.

Active optics is the technology used to protect a telescope mirror from deformations due to temperature, wind, and structural deflection. In addition, active optics is absolutely essential in the alignment of segmented mirrors for larger telescopes. Active optics should not be confused with adaptive optics however; active optics will not correct atmospheric turbulence or earthquake vibrations.

General Approach

The Sparse Aperture Telescope is meant to be a low cost, high resolution solution to expand the research astronomers can do on Earth. The prototype, seen in Figure 1, measures light through a pinhole, simulating the brightness of binary stars. The telescope mirror is composed of a sparse array of small mirrors, spaced apart to maximize aperture resolution while ensuring desired wavelengths of light are still detectable.

Mirror and Optical Requirements

Speckle analysis requires a surface accuracy roughly one quarter the wavelength measured. This system was designed for 800 nm wavelength light. Therefore, the active optics system needed to be accurate to at least 200 nm. Each mirror needs to be able to travel 1 cm to focus the image. Tip, tilt, and elevation control are required to align segmented mirrors, requiring at least 3 position control points.

The three mirrors were placed to create a 27” aperture. This diameter was chosen to give the best aperture resolution while still allowing for speckle analysis. If the mirrors are spaced too far apart, shorter wavelengths of light can no longer be analyzed using speckle analysis. This mirror spacing was then simulated and found to be valid by Dave Rowe using his speckle simulator and analysis software.

Figure 1. Completed sparse aperture active optics test assembly

Mirror Properties

The three spherical mirrors used for this project were created as a matched set by Hubble Optics. Each mirror has a radius of curvature of 4972 mm, giving a focal ratio of 7.25 with the 27" aperture. Each Pyrex glass mirror is 10.25" in diameter and 25 mm thick, theoretically allowing for simple 3-point support. Each mirror was supported at three evenly spaced points on two-thirds the mirror's diameter. No whiffletree was used to support the mirror, giving a stiffer design but subject to higher surface error. Finite element analysis (FEA) was used to determine the mirror surface deflection due to gravity was less than 200 nm. As seen in Figure 5, the surface deflects like a trefoil.

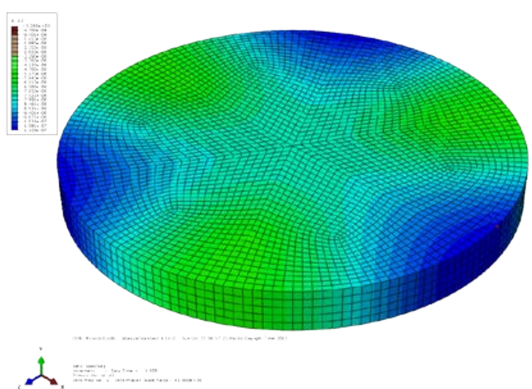

Figure 2. FEA analysis of mirror surface deflection

Mirror Cell Mounting Plate

The mounting plate was made from ¼" plate steel. Three actuators are connected to each mounting plate using two ¼" screws each. These actuators are mounted so that the actuator tip is at two-thirds of the diameter of the mirror. A ½-6" bolt is threaded through the center of the mounting plate to connect the mirror support fixture. This bolt can be adjusted to set the mirror's minimum height. Each mounting plate has ½" holes through which the plate can be bolted to the mirror support frame.

Mirror Support Frame

The frame has three mounting locations for mirrors. The mirror cell mounting plates bolt to the support frame to ensure a rigid connection. Each mounting plate is fitted to a unique set of mounting holes on the frame. This is due to the thermal expansion caused from welding the frame. This thermal expansion offset the plate mounting position up to 1/8”. The mirror support frame uses a bolt to set it into place on the base of the test frame, preventing movement. Additionally, FEA analysis indicates this support frame should have a first harmonic above 20 Hz, protecting from most common noise factors.

The frame was constructed from steel square tubing because of its high strength and low cost. Additionally, this common steel is simple to machine and weld. The effects of thermal expansion were minimized during welding by a careful distribution of heat during fabrication. Figure 6 shows the final test fitting of the support frame to the telescope base, a critical step before the final welds.

Figure 3. Mirror support frame being fitted to telescope base

Active Optics Actuator

The actuators used in for the active optics system secure to the mirror cell mounting plate by two screws. Using an Arduino with RAMPS board, the actuator is capable of making adjustments of 31.25 nm. Each actuator is also equipped with a limit switch to ensure the mirror cannot collide with the steel housing of the actuator. The actuator consists of a steel housing, limit switch, linear bearing, stepper motor, solid shaft coupling, and a fine adjustment screw. The compact design of the finished set of actuators is seen in Figure 7. These components are protected from dust and other contaminates via an ABS side cover. This actuator design is open loop, utilizing no feedback other than a limit switch.

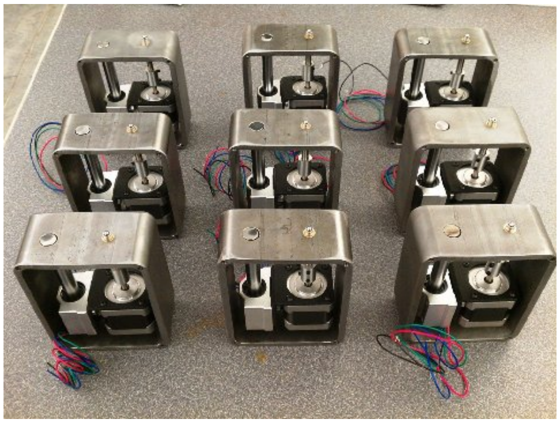

Figure 4. Active optics actuators before attaching side covers

Actuator Housing

The actuator housing is a custom part made from 4” x 5” steel tubing. Holes are drilled into the housing to press fit the shaft for the linear bearing. Another hole is drilled to loose fit the fine adjustment screw bushing. Two tapped holes are located on the bottom for mounting. Each housing has tapped holes on its side to secure plastic side covers. ABS side covers were laser cut to fit the housing. Additionally, holes were laser cut into the ABS side covers to mount the limit switch and to route the stepper motor wires.

Fine Adjustment Screw and Bushing

The actuators used Kozak fine adjustment screws with matched threaded bushings, seen in Figure 8. The adjustor screws are ¼” in diameter with 254 threads per inch. Each screw supports up to 40 lb axially, being primarily limited by its threads. The adjustor screws are made with 303 stainless steel which helps to minimize the risk of part failure due to corrosion. Each adjustor screw is 2” long, but has approximately 2 cm of travel once installed in an actuator. Each fine adjustor screw has a steel ball bearing tip with which it pushes on the back of the mirror. Seen in Figure 9, a sapphire pad is adhered to the back of the mirror surface using Cyanoacrylate. This sapphire pad is used to prevent wear on the mirror and ensures a known, low coefficient of friction.

The adjustor screws operate best in non-condensing conditions. Additionally, the threads are susceptible to dust and dirt and should be covered when not in use. The bronze bushing is self lubricating, meaning this part should not be lubricated. Each threaded bushing is slip fit into its housing and secured with epoxy as recommended by the manufacturer. Due to the tight tolerances of the thread, press fitting the bushings could result in interference. Failure to follow these guidelines could cause the thread to seize.

Figure 5. Kozak 1/4-254 TPI fine adjustment screw

Stepper Motor

The actuators use standard NEMA 17 size stepper motors. This project used commonly available 4-wire, bipolar stepper motors available at reasonable prices from numerous retailers. The motors have a 1.8° step, with 200 steps per full revolution. Each stepper motor is attached to a linear bearing using an aluminum motor mount.

Stepper motors were chosen for their low cost and availability. When paired with a microstepping motor driver, stepper motors can rival the precision of a servo motor at a fraction of the price. They also retain a light holding torque when unpowered, which helps to prevent loss of position when the motor is powered off.

Mirror Support Fixture

The support fixture provides lateral mirror support while allowing vertical actuation. This fixture design uses 0.06” thick ABS, laser cut to the desired geometry. Access to a laser cutter makes this part fast and cheap to produce. This fixture design, using 0.06” thick ABS, is capable of vertical deflection exceeding 2 cm. Furthermore, it limits horizontal deflection to less than 2 mm. A ½” nut is fixed onto the fixture using Cyanoacrylate (super glue) for attachment to the mirror support plate.

Figure 6. Attached mirror support fixture and sapphire pads

Linear Bearing

A linear bearing is used to secure the stepper motor under the fine adjustor screw. Once properly adjusted, the stepper motor is free to travel vertically with minimal rotary backlash. Due to its placement in the assembly, backlash is not a concern. It is because of this reason an inexpensive linear bearing can be used.

Coupler

A solid shaft coupler connects the stepper motor shaft to the fine adjustor screw. A solid coupler ensures minimal torsional deflection. Two set secure the coupler onto a matching shaft, ensuring the matching shaft does not slip even without a milled flat.

Arduino

An Arduino Mega 2560 was used to control each mirror cell. This microcontroller can be programmed using C++ and has an extensive set of preexisting Arduino libraries. The board operates at 16 MHz, allowing plenty of time for motor control and communication protocols. A programming header is also available for the installation of a real time operating system.

Motor Shield

RAMPS 1.4 is a motor shield made popular by 3D printing enthusiasts. The RAMPS board is capable of powering the Arduino board, simplifying project wiring. Each board supports up to 5 stepper drivers. Each motor controller only uses 3 stepper drivers, which leaves room for expansion. The board supports up to 6 limit switches. Basic limit switches require no special hardware because the Arduino MEGA utilizes internal pull-up resistors. An I2C header is available making connecting to the Arduino simple. This allows a large number of Arduino control boards to be deployed and controlled through one control program using I2C protocol. The RAMPS and attached Arduino are powered by a 12V power supply. Higher voltages may damage the connected Arduino, but the RAMPS board can be modified to prevent this.

Each stepper motor is given enough current to ensure no steps are skipped due to friction. If the RAMPS board loses motor power but the Arduino remains powered through USB, the Arduino has no method to detect the loss of motor power. If the Arduino main program tries to send a step command to an unpowered motor driver, the main program will no longer reflect accurate position due to lack of feedback. Because of this, it is important to double check all power connections prior to operation. Alternately, an external pull-up resistor could be used to detect power loss, but was not done for this project.

Stepper Driver

The A4988 motor driver is available on a breakout board made to interface with the RAMPS 1.4 shield. This motor driver is capable of 1/16 microstepping, giving the stepper motors chosen for the project 3200 steps per revolution. With a 254 TPI screw, each motor has a step increment of 31.25 nm. Motor torque can be manually adjusted by increasing the motor current via a potentiometer on each motor driver. Motors can be turned off when not in use, which conserves power and prevents unwanted heat. Powered off motors will not lose their position under normal circumstances, but may be vulnerable to heavy vibration or user handling.

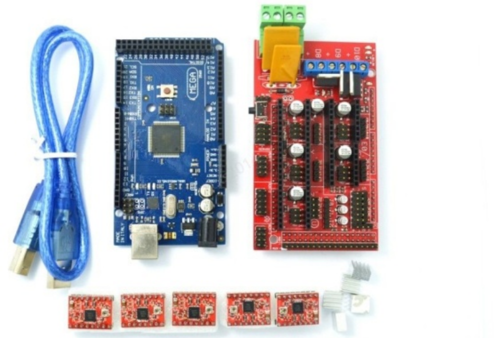

Figure 7. Arduino MEGA (left), RAMPS 1.4 (right), A4988 motor controller (bottom)

Camera

The QHY5L-II M astronomy camera was used for the fine mirror alignment tests. This camera has an internal Barlow of approximately 2.5 times magnification. The camera was mounted to facilitate course adjustment over a range of approximately 2”. This rough adjustment was used to get the mirrors close to focused before using the actuators for fine adjustment.

Light

A green LED with an approximate bandwidth of 10% was used for the fine mirror alignment tests. A 10 um pinhole was placed over this LED to simulate starlight. This light simulates the light power of a binary star, but will only generate one point of light.

Figure 8. QHY5L-II M monochrome astronomy camera

Software

The QHY CCD camera was used with the free software FireCapture. This software allows for exposure and gain control of the QHY, along with a fast capture option for rapid image acquisition.

A custom Arduino control program was written for the actuating the mirrors during these tests. The program is capable of controlling each actuator individually, outputting mirror tip, tilt, and elevation. Communicating with the Arduino control program requires a serial USB connection. Additionally, the Arduino control program uses ANSI escape commands to refresh the display values. The free software PUTTY was chosen to interface with the control program. PUTTY is available for Windows and UNIX systems.

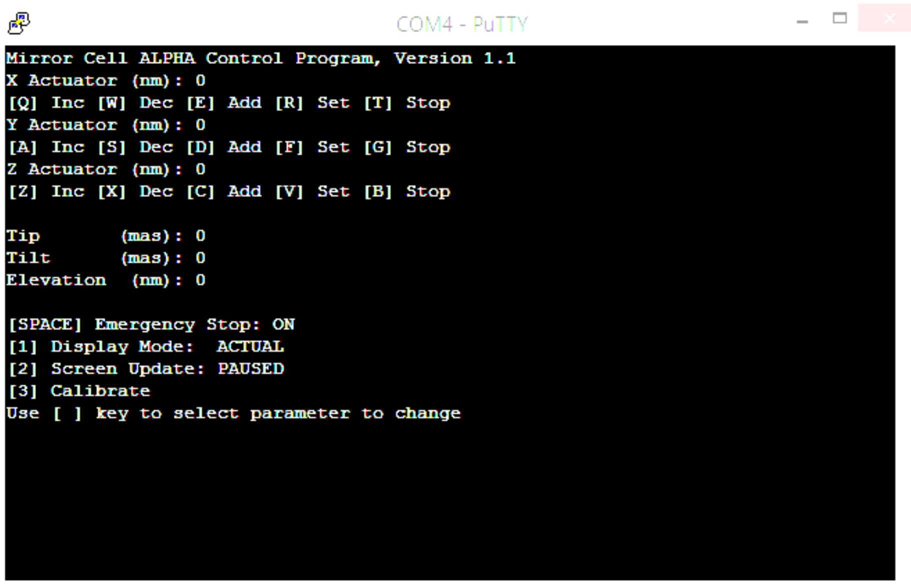

Figure 9. Arduino command program interface through PUTTY

Alternate Rejected Designs

Differential threads were considered in earlier versions of their design, but were later rejected due to susceptibility to backlash, short travel, market availability, and prohibitive cost.

A planetary gearbox was considered for use with a stepper motor as it provides a significant step up in accuracy. Low cost gear boxes have several degrees of backlash however, which would make mirror calibration difficult. Higher precision, low backlash versions were also considered but were highly cost prohibitive.

Voice coils were considered due to their simple construction, accuracy, and travel. They have no backlash and incredible accuracy, some better than 1 um. The downside being voice coils are substantially higher in cost and may not be able to handle the weight of larger mirrors.

Piezo actuators are well suited for astronomy applications. They have no backlash, high accuracy, and can support mirror weight. This unfortunately makes them very expensive, well above the budget for this project. Additionally, piezo actuators often require higher voltages, which could pose a potential safety hazard.

Adjustor Screw Position Testing

A green laser was mounted to the top of the adjustor screw, measuring angular displacement across a known distance. Using an Arduino with a stepper driver, the adjustor was actuated to test for positional error against a target position. As seen in

Figure 13, positional error was found to be within 100 nm of the target. This is due to the backlash of the thread between the adjustor screw and bushing, approximately 180 nm. When the effects of backlash are accommodated for, positional accuracy is within 100 nm. This position can be repeated to within 16 nm.

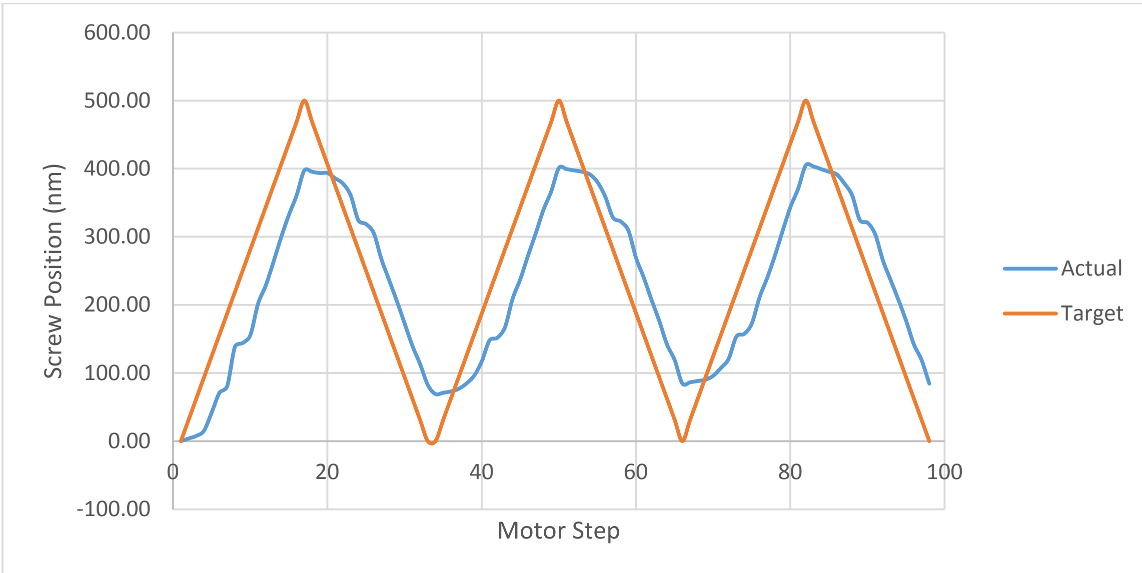

Figure 10. A4988 microstepping test results

Mirror Phasing: Coarse Positioning Testing

The finished sparse mirror array, seen in Figure 14, was tested using a webcam and a bright white LED. To isolate the mirrors, black dust blocking buckets were places on top of the mirrors to block the image. Two mirrors were individually positioned such that the LED circuit was in focus on the webcam, seen in Figure 15. Then, a roughly 100 um pinhole was put onto the LED to simulate a bright star image. Both mirrors were then refocused and aligned to one another. The webcam was limited in that it could not capture an airy disk from the LED. Chromatic aberration and air turbulence were also key factors to the image quality as seen in Figure 16.

Figure 111. Sparse active optics test setup

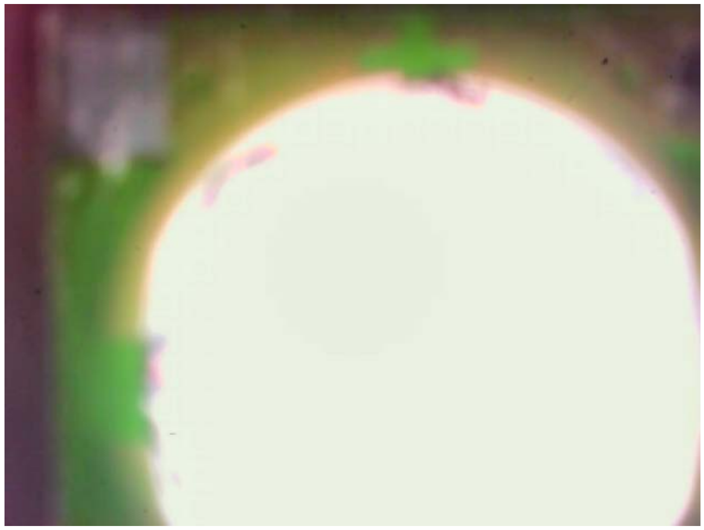

Figure 12. Focused LED circuit with pinhole removed

Figure 13. Webcam capture for alignment mirrors using white LED

Mirror Phasing: Fine Adjustment Testing

The webcam was replaced with a QHY astronomy camera and the large pinhole was replaced with a 10 um ± 1um precision pinhole. The white LED was replaced with a green LED with an approximate bandwidth of 10%. As before, each mirror was setup, focused, and aligned using this new configuration.

During this test, an airy disk was present for each mirror image. However, trefoil aberrations were an issue as seen in Figure 17. Additionally, air turbulence in the room with the trefoil aberrations made it difficult to confirm if the aligned mirrors were able to generate an interference pattern. The overexposed image seen in Figure 18 highlights the detrimental effects from air turbulence. Despite these problems, focusing and aligning the mirrors was successful according to the design goals of this project.

Figure 14. QHY capture for aligned mirrors using green LED

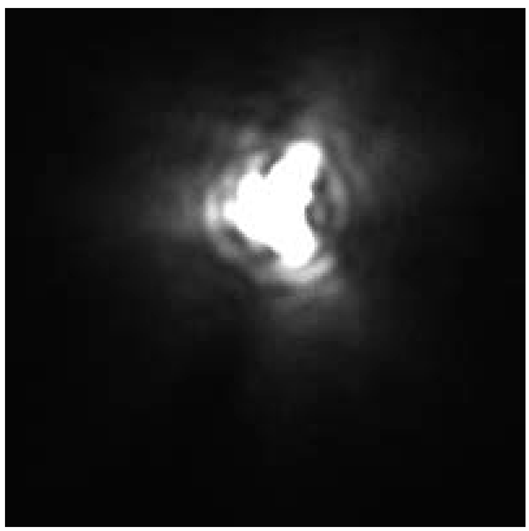

Figure 15. QHY overexposed capture

Contributions to Astronomy

The success of the active optics prototype makes this is a significant step towards sparse aperture telescope. The cost of the active optics components significantly lowers the barrier of entry for large aperture segmented mirror telescopes. This will hopefully contribute to the future development of low-budget telescopes everywhere.

Design Strengths

The active optics actuators are made using low cost parts, offering an economic solution to expensive off the shelf alternatives. With the exception of the actuator housing, each actuator is made from readily available parts. The actuator design is relatively simple, making future maintenance and repair straight forward. If a component fails, it can easily be replaced with simple tools. Assembly requires several wrenches, screw driver, needle nose pliers, a hex key, and Cyanoacrylate (super glue).

Design Weaknesses

Simulation of the mirror deflection indicated a whiffletree should not be needed, but during testing this was proven otherwise. Captured image show trefoil aberrations caused by the simple 3 point support. This trefoil aberration makes detecting an interference pattern challenging.

The actuator housing requires a fair amount of custom machining to make. Without access to tools capable of machining steel, the housing may be costly to reproduce. Some changes to the design need be made to simplify the machining process.

Future Work

A simple, low cost whiffletree is needed before future testing can take place. Ideally, the whiffletree should have a high stiffness with low to no backlash. Alternately, an air filled bag support could be used to “float” the mirror’s weight similar to the WIYN telescope.

The actuator housing would benefit from some minor design changes. The side covers should be attached using another method; this would remove eight tapped holes from the prototype design. Additionally, the mounting holes should be changed. One precision hole should be placed directly under the mounting hole for the fine adjustor screw, with the other mounting hole being less critical. This will ensure a better positional accuracy when mounted to the mirror cell mounting plate. The placement of the matching holes on the mounting plate would need to be adjusted to accommodate for this.

During testing, vibration from the stepper motors was detected when actuating. This vibration was low in amplitude and decayed quickly, posing no serious consequence other than annoyance. This is simple to resolve however, cork NEMA 17 gaskets for reducing vibration are cheap and readily available. These gaskets, while not an urgent necessary, should be included at some point for future testing.

The laser cut ABS mirror support fixture fully satisfied the design requirements for this test setup. If the aperture is pivoted on an angle however, the fixture may not tolerate the weight of the mirror laterally. A thinner fixture made of steel would be needed to support the lateral weight. Additionally, the fixture may need to be redesigned to allow room for a whiffletree.

One actuator experienced 3 times its normal backlash during testing which initially made aligning the images difficult. It was determined this extra backlash was due to a loose bolt holding the stepper motor inside the actuator. Future versions should include a mechanism to prevent this.

Conclusion

The success of the prototype makes this is a significant step towards a full form, fully automated sparse aperture telescope. The active optics system was able to focus and align the mirrors through manual adjustment. Interference patterns could not be found, but this seemed due to a lack of a whiffletree, not because of the positional accuracy of the active optics system. With the addition of image processing, this system has the potential to be completely automated. The components required to build this system are relatively cheap, effective, and will hopefully lead to a fully automated sparse aperture telescope in the future.