Observing Double Stars

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Abstract

Double stars have been systematically observed since William Herschel initiated his program in 1779. In 1803 he reported that, to his surprise, many of the systems he had been observing for a quarter century were gravitationally bound binary stars. In 1830 the first binary orbital solution was obtained, leading eventually to the determination of stellar masses. Double star observations have been a prolific field, with observations and discoveries—often made by students and amateurs—routinely published in a number of specialized journals such as the *Journal of Double Star Observations.* All published double star observations from Herschel's to the present have been incorporated in the *Washington Double Star Catalog*. In addition to reviewing the history of visual double stars, we discuss four observational technologies and illustrate these with our own observational results from both California and Hawaii on telescopes ranging from small SCTs to the 2-meter Faulkes Telescope North on Haleakala. Two of these technologies are visual observations aimed primarily at published "hands-on" student science education, and CCD observations of both bright and very faint doubles. The other two are recent technologies that have launched a double star renaissance. These are lucky imaging and speckle interferometry, both of which can use electron-multiplying CCD cameras to allow short (30 ms or less) exposures that are read out at high speed with very low noise. Analysis of thousands of high speed exposures allows normal seeing limitations to be overcome so very close doubles can be accurately measured.

1. Introduction

Observing double stars has engaged generations of student, amateur, and professional astronomers for the better part of three centuries. Over 100,000 double stars have been discovered. As each year goes by, new doubles are discovered and the observations of already known doubles continue to accumulate.

A wide range of telescopes, instruments, and techniques are currently used to measure the separations and position angles of double stars. Telescopes range from a 3-inch Tasco refractor equipped with a $150 astrometric eyepiece observing relatively wide optical doubles (Grisham *et al.*, 2008) to a 10-meter Keck reflector with adaptive optics/laser guide star observing very close late-M binaries (Dupuy *et al.*, 2012). Instruments include visual eyepieces and filar micrometers, regular CCD cameras, and fast, low noise EMCCD frame transfer cameras. Advanced techniques include blind or other deconvolution strategies, lucky imaging, and speckle interferometry.

Although beyond the scope of this paper, the absolute cutting edge with respect to close separation (and hence short binary periods) is amplitude interferometry arrays such as the Center for High Angular Resolution Array (CHARA) on Mt. Wilson (McAlister 1999). Six 1-meter telescopes in a “Y” configuration interferometer provide milli-arcsecond resolution allowing binaries with orbital periods of just a day to be observed. In this paper we will, after a brief history of double star observations, describe two spreadsheets we have developed to aid us in selecting doubles for observation. We will then describe both visual and CCD observations we make with students that have both scientific and educational goals. Finally, we will describe two advanced techniques we are exploring—lucky imaging and speckle interferometry—to aid us in observing close double stars. Our observations were made on 8- to 32-inch telescopes in California, and 9-inch to 2- meter telescopes in Hawaii.

Most of the coauthors of this paper will be giving talks at the Maui International Double Star Conference in February 2013. In many cases they will be meeting each other for the first time, and will also be meeting other double star observers from around the planet. For details on this conference see *www.AltAzInitiative.org*.

2. Early Double Star Observations

Galileo thought that the sun was the center of the universe and stars were just points of light on a nearby sphere. For those, contrary to Galileo, who thought stars were distant suns, he suggested they should look for and observe close double stars—one bright and one faint that happened, by chance, to appear close together along the line-of-sight from Earth. If the bright star was nearby and the faint one far away, then the nearby bright star should shift its position with respect to the faint star over a six month period due to the rotation of the Earth around the sun (parallax).

Following up on Galileo’s suggestion, William Herschel began measurements of the separation of position angles and separation of double stars in earnest in 1779. Three years later he reported his observations of 269 binaries to the Royal Society (Herschel 1782). Continued observations led, a couple of decades later, to the somewhat unexpected conclusion by Herschel (1803) that many double stars were gravitationally bound binaries. Interestingly, John Michel (1767) had earlier reported to the Royal Society that, based on a statistical analysis of a few bright visual double stars, he had concluded they occurred at a higher frequency than one would expect due to chance alignment alone and hence were probably truly gravitationally bound stars. It is probably a good thing that Herschel was unaware of Michel’s paper or he might not have initiated his search for and a measurement of double stars, as his goal was determining parallaxes.

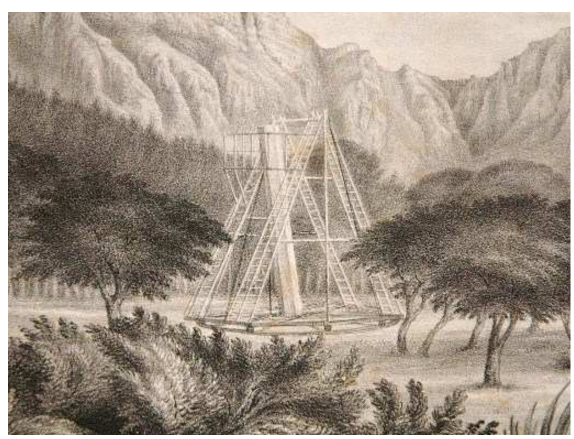

Figure 1. William Herschel’s 20-foot telescope was relocated to Table Mountain near Cape Town, South Africa, where his son John observed double stars in the southern skies.

In the mid 1800's, while he was director of the Dorpat Observatory in what was then Livonia, Friedrich Georg Wilhelm von Struve made micrometric measurements of 2,714 double stars from 1824 to 1837 and published these in his work *Stellarum duplicium et multiplicium mensurae micrometricae.* F.G.F. von Struve's son, Otto Wilhelm von Struve, (1897-1963), continued his father's work using a 15-inch refractor at the Pulkovo Observatory near St. Petersburg, cataloging several thousand double stars. Another notable double star observer was Robert Innes at the Meteorological Observatory in Johannesburg, South Africa. He compiled in 1927 *The Southern Double Star Catalog* consisting of 1,600 entries. Robert Aitken, with the help of collaborator W.J. Hussey, published in 1932 the *New General Catalogue of Double Stars within 120° of the North Pole* consisting of 17,180 doubles. The Lick Observatory at Mount Hamilton near San Jose, CA, published the 1963 *Index Catalog of Visual Double Stars*, containing 64,250 objects covering the entire sky. In 1965 it was transferred to the United States Naval Observatory as the *Washington Double Star Catalog* (WDS) which now contains over 100,000 double stars.

Observations of the double star Zeta Ursae Majoris were indirectly used by Savary (1827) to obtain an orbital solution, while a solution directly using all the observations was provided shortly thereafter by John Herschel. Orbital solutions, when combined with stellar parallaxes and other data, led to the determination of stellar masses, a key parameter influencing stellar evolution. Parallaxes were hard to come by until the Hipparcos satellite accurately determined a large number of parallaxes (Perryman 2011). The *Sixth Orbital Catalog* provides orbits for 2,187 binaries (as of 1 January 2012).

For more detailed historical expositions, please see Aitken (1918), Herrmann (1973), Couteau (1978), Argyle (1986), Tanguay (2003), and Hoskin (2011).

3. Two Spreadsheets

Students in Genet's astronomical research seminar (described below in the next section) have, for many years, used Haas' (2006) catalog of 2,100 doubles to pick out relatively bright, well-separated double stars for their first projects. The Haas catalog was convenient for students to use as it listed doubles by constellation, only provided key information, and just included relatively bright doubles observable with smaller telescopes. However, one had to "manually" page through the catalog to select observational candidates. Furthermore, some vital information, such as SAO and other identifiers, number of past observations, etc., was not included. Increasingly sophisticated students would prefer to use their laptops to help them sort and select potential doubles for observation, while SAO or other identifiers are handy for entry into today's computerized telescopes.

Joseph Carro has prepared a spreadsheet catalog of 3,950 double stars that is ideal for student use. Carro incorporated information from SIMBAD—the astronomical data base operated at the CDS in Strasbourg, France—into a series of Microsoft Excel spread sheets that facilitate sorting and selecting doubles for study. The spreadsheets are arranged by constellation, and include star names, common identifiers, and details on each double star. Summary tables of all 3,950 stars are sorted in various ways as a convenience for the user. A diagram showing the major stars of each constellation is provided. Using the star name as the key, a hyperlink to SIMBAD allows additional information, such as parallax, to be conveniently obtained. Carro's catalog can be accessed at *www.AltAzInitiative.org*, or you can contact him at jcarro@charter.net. Carro is expanding his catalog to include additional double stars and further information.

To select doubles for advanced projects, such as multiple stars across many constellations, faint double stars, etc., it is helpful to have a way to choose them quickly and easily. Tom Smith created a master catalog using a relational database engine and Structured Query Language (SQL) with the *Washington Double Star Catalog* (WDS) as the foundational catalog. Several other databases of stars were incorporated and relationally linked to the engine, including the *Sixth Catalog of Orbits of Visual Double Stars* (6^{th} Orbital Catalog) and the *Hipparcos 2 Catalog* (Hip2). Many of the desired data fields needed in our studies were not contained directly in any of the original catalogs and were synthesized using various mathematical and astrophysical algorithms. In many cases, the units for some of the data were different across the various catalogs, so new fields were created with uniform units. Smith routinely generates Microsoft Excel worksheets that are convenient for selecting doubles for observation, data manipulations, charting, and generating population statistics.

Genet has sorted and reduced the initially large spreadsheets provided by Smith to short, compact lists of doubles for specific observational programs. This process typically involves removing columns not of interest, narrowing the columns so the relevant data appears all together on the screen, selecting a range of RA and dec of interest, and sorting and selecting on such parameters as separation, delta magnitude, parallax, proper motion, spectral type, etc. Lists have been prepared for high proper motion pairs, faint pairs that include an M star, pairs with a white dwarf, etc.

Our research is incorporating photometry as well as the astrometry of our target double star systems. The new AAVSO Photometric All Sky Survey (APASS) catalog has secondary photometric standards in every field of view. This will facilitate transformations to the standard photometric systems. Please see *http://www.aavso.org/apass* for details.

Figure 2. The twin 8-inch APASS-North astrographs at Tom Smith's Dark Ridge Observatory in Weed, New Mexico.

4. Visual Observations and Student Education

Several different groups of students, educators, and amateur astronomers are working together to provide middle school, high school, and community college students a hands-on research experience. One group, the California Double Star Association, is centered on a research seminar offered by Genet at Cuesta College. This seminar consists, primarily, of students at Arroyo Grande High School. Another group, the newly formed Maui Double Star Association, meets at the University of Hawaii's Institute for Astronomy in Maui, and provides a research opportunity for both middle school and high school students.

In both groups, students, using a Celestron or Meade ruler/protractor astrometric eyepiece, measure the separations and position angles of visual double stars, typically following the procedures outlined by Argyle (2003). Students observe with telescopes supplied and operated by local amateur astronomers. The students analyze their data and write up brief papers describing their observations, analysis, and results. The papers are given extensive internal and external reviews, and then appropriately rewritten. Students present their results at scientific conferences and their final papers are submitted to the *Journal of Double Star Observations* for consideration by its editor, Kent Clark. The entire process is overseen by professional educators and astronomers. See Genet *et al.* (2010) for details.

The intent of the seminar is not to recruit future astronomers, although that is certainly happening, given the enthusiasm level of some of the students. The purpose is to give the students an opportunity to conduct original science research, thus discovering how real science is done. Understanding the nature of scientific research is useful for many different careers, as well as exercising responsible citizenship in today's complex world.

Double star measurements were first made at Cuesta College on California's central coast in the Fall of 2007 (Grisham *et al.*, 2008, Johnson and Genet 2007, and Johnson *et al.*, 2008). The following year the seminar was moved to Cuesta College's South Campus at Arroyo Grande High School (AGHS), which has been the home base for this seminar for the past four years. Published papers, with AGHS students primarily as coauthors, include Alvarez *et al.*, 2009, Brewer 2011, Estrada *et al.*, 2010, Estrada *et al.*, 2011, Grisham *et al.*, 2008, Johnson *et al.*, 2008, Johnson and Genet, 2007, and Marble *et al.*, 2008. The 2011 class was the largest to date, with an enrollment of 17 students – all high school students – divided into three teams. Each team published a paper (Baxter *et al.*, 2012; Fluitt *et al.*, 2012; Warren *et al.*, 2011), and one team published a second paper (Collins *et al.*, 2011). Students may take the seminar up to three times for college credit. Students in their second or third year are team leaders for the students who are enrolled for the first time. A student research seminar was also held at Coast Union High School, in nearby Cambria (Dowdy *et al.*, 2009).

Figure 3. Cuesta College 2011 research seminar students pose in front of Nimbus II, a 22-inch Dobsonian telescope built by Reed and Chris Estrada, used to observe double stars with an astrometric eyepiece.

The seminar class is conducted as a graduate-level seminar. Several student groups are formed. The groups are given a general directive to collect position angle and separation data on a visual double star pair. Specific double star systems are selected by the students. Each group is responsible for observations, data analysis, literature research, and a written paper. The various groups are the initial editors of each other's papers. Student research is valuable in its own right as it adds to the knowledge base of double stars. It is also contributes to student academic careers. It is rare indeed for a student to be a published science researcher before leaving high school, a point recognized with respect to college admissions and awarding of scholarships. Most of the seminar's graduates have been accepted to their first choice college and have also received scholarships based on their published research.

Having a local supportive community of educators and amateur astronomers has been vital. They have donated their time to instruct and demonstrate, to edit student work, and generally be science role models. Also vital are mentors—often amateur astronomers who are professional educators in fields other than astronomy. As Joseph Carro points out, the primary task of a mentor is to organize information so that a coherent and meaningful learning session can be achieved.

Based now on many years of double star seminars, the instructor and advisors note several factors that contribute to the success of published student research:

- Students can and should complete scientific research projects in a single semester. (Once the semester is over, students rarely complete projects.)
- Double star projects are more amenable to this short time frame than most others.
- Requiring the publication of research is vital, as are outside reviews prior to publication.
- It helps to have a mix of experienced and inexperienced observers.
- Student research teams can exercise their diverse talents and experience by allocating their skills to the various aspects of scientific research.

Based on the success of the early Cuesta College seminars, Genet initiated a student summer workshop in 2008 at University of Oregon's Pine Mountain Observatory east of Bend, Oregon. Although student contact hours remained the same, the summer workshop differed from the fall seminar by being concentrated into a single long weekend. During the four consecutive summers of 2008-2011, students and science teachers from several high schools and undergraduate colleges in Washington, Oregon, Idaho, and California participated in and successfully published double star research projects. Double star research is complex enough to challenge students without being so extensive as to require months of observation and analysis. This makes their study appropriate for students engaged in a several-day, hands-on research workshop.

At each workshop, students were broken up into research teams led by an experienced double star observer. Most attendees had never engaged in quantitative research before, so they received training in this area on the first day of the workshop prior to taking measurements that night. This was followed by daytime data analysis and paper writing and further observations, as required, at night.

Figure 4. Although they used smaller telescopes for their double star observations, students and instructors pose in front of the 32-inch telescope at the University of Oregon's Pine Mountain Observatory 2009 Student Research Workshop.

A total of eight papers have been published in the *Journal of Double Star Observations* from these Pine Mountain Observatory workshops. Most papers report on the separation and position angle of a double star such as Iota Boötes (Schrader *et al.*, 2010), Beta Lyrae (Carro *et al.*, 2012), 61 Cygni (Baxter *et al.*, 2011), and Delta Boötis (Estrada *et al.*, 2012). However, Frey *et al.* (2011) and Alduenda *et al.* (2012) reported observations of multiple star systems. Another team measured the double star STTA 123 AB and, in determining its components to be bound by gravity, estimated a rough orbit (Brashear *et al.*, 2012).

Another group, The Maui Double Star Association, consists of middle and high school students, and amateur and professional astronomers living on the island of Maui in Hawaii. Genet, who spends each winter in Hawaii, helped found and is a part-time member of the group. The students, who attend different schools, meet at the University of Hawaii's Institute of Astronomy (IfA). IfA astronomers J. D. Armstrong and Joe Ritter, and Haleakala Amateur Astronomers member Steve McGaughey lead the group.

For their visual observations they are using Steve McGaughey's Celestron C-9.25 at the Haleakala Amateur Astronomers observatory on the summit. McGaughey and Genet have developed procedures for student visual observations at the summit (McGaughey and Genet, 2012).

Figure 5. Maui Double Star Association: (back row) Eric Rohzinski, J.D. Armstrong, McKayla Wandell, Audreanna Leatualii, and Stephen McGaughey, and (front row), Noah Rohzinski, Aaron Rohzinski, and Isaac Sato.

Figure 6. Stephen McGaughey and his Celestron C-.925 at the Haleakala Amateur Astronomers observing location at the 10,000 foot summit of Haleakala.

5. CCD Observations and Student Education

A program of student education via CCD observations of double stars was initiated this past winter at the University of Hawaii's Leeward Community College (LCC) on Oahu. LCC is one of the seven community college campuses of the University of Hawaii's system, with some 6,200 students. It is located to the west of Honolulu over looking Pearl Harbor.

LCC's Kilohoku Hale observatory is equipped with an Optical Guidance Systems 0.5-meter *f*/8.2 telescope and an Apogee Alta U6 CCD camera which was used for observations of the multiple star system Beta 321 in Lepus (Church *et al.*, 2012).

Figure 7. The Leeward Community College observatory is not far from Pearl Harbor.

Figure 8. Left to right: Rebecca Church (student), Kakkala Mohanan (LCC instructor), and Russ Genet (visitng). The telescope is a 0.5 meter Optical Guidance Systems Cassegrain.

The Maui Double Star Association (MDSA) is fortunate in that 30% of the time on the Las Cumbres Observatory Global Telescope (LCOGT) 2-meter Faulkes Telescope North (FTN) has been allocated to the University of Hawaii for student education and public outreach. Thus the MDSA is in a good position to pursue advanced double star projects using this telescope. FTN can be conveniently operated in a Real Time Interface (RTI) mode from the University of Hawaii's Institute for Astronomy Maui headquarters at the base of Haleakala. Although initially clouded out, the weather was clear on the night of March 31st when J. D. Armstrong, Cindy Krach, Auddreyanna Leatualii, Steve McGaughey, Aron

Rohzinski, Noah Rohsinski, and McKayla Wandell, were at the controls at IfA, while Russ Genet participated via speakerphone.

Figure 9. Steve McGaughey, J.D. Armstrong, Russ Genet, and John Pye stand in front of the 2-meter Faulkes Telescope North on the summit of Haleakala. An in-person observational session scheduled for that night were clouded out but was successfully completed remotely at a later date.

Brian Mason at the U.S. Naval Observatory had suggested that observations of late M-star doubles, doubles with a white dwarf, and high common proper motion pairs—especially the faint pairs only observed a single time by Luyten (1997) could be usefully observed by the 2-meter FTN. Smith and Genet worked together to develop three observational lists—one for each of these areas. Rafael Caballero, a member of Agrupacion Astronomical Hubble in Spain, has suggested the observation of faint common proper motion pairs (Caballero, 2012). He developed a new list of high common proper motion pairs for us that contained a mix of known pairs (in the WDS) and potential new double stars that could, if observationally confirmed, be added to the WDS as new discoveries. Genet narrowed the list down to 9 "Rafa" systems (with stars from 14^{th} to 19^{th} magnitude) of which 7 were observed in the allotted two hour observing window. Maui students operated the telescope under the supervision of Armstrong and McGaughey, while Genet participated via speakerphone, sending Aladin Previewer images via the Internet. A paper reporting these observations is being prepared.

6. Lucky Imaging

High spatial resolution is vital to obtaining accurate measurements of close visual double stars. The atmosphere compromises image resolution, limiting the minimum separation of the systems that can be studied. However, when short exposures—on the order of 0.1Hz or less—are collected, one is essentially imaging instantaneous atmosphere configurations. In lucky imaging (Law *et al.*, 2006), targets are observed at >10Hz cadence, and only the images least affected by the atmosphere—typically only 1% in the R band, less in bluer bands—are selected. Those "lucky" exposures, once stacked, can reconstruct a highly spatially resolved image, often diffraction limited, of a sky region of one to a few tens of arc seconds, the nominal size of an isoplanatic atmosphere patch. Note that the majority of the data is not used in the image reconstruction, thus this technique is extremely time consuming. Thus observations must be planned for 10 to 100 times the conventional image exposure required to achieve the desired signal-to-noise ratio.

Figure 10. B.J. Futon, Russ Genet, and John Martinez at the Las Cumbres Observatory Global Telescope's BOS 32-inch telescope. With Federico Bianco, they used the EMCCD Andor Luca-R camera on this telescope for lucky imaging and speckle interferometry observations.

Lucky imaging was used as early as the 1920s for planetary observations. However, the typical brightness of close double stars and multiple star systems rendered them too faint to be imaged at the necessary high cadence. The advent of high sensitivity, low noise cameras over the last decade, particularly EMCCDs, has unlocked the potential of this technique. Although the cost of EMCCD cameras began in the $40,000 range, new cameras can now be purchased for less than $8,000, and some used cameras have been purchased for as little as $2,500.

On a 2-meter telescope, such as Faulks Telescope North (FTN), lucky imaging is feasible in presence of a 12th magnitude or brighter guide star within 10 or a few tens of arc seconds of the target and, provided that the pixel size is sufficiently small, the optical limit of the telescope is routinely achieved by selecting the luckiest few percent images. Furthermore, frame transfer CCD and EMCCD cameras, which can download one image while recording another, maximize the imaging duty cycle, reducing total time requirements. When a guide star – possibly the target itself – is used, the lucky exposures are selected on the basis of the Strehl ratio, a measure of the sharpness of the star image. The images are then aligned on the brightest pixel, nominally taken as the peak of the diffraction or optics limited point-spread-function (PSF), although more sophisticated methods that exploit cross correlation or wavelets can provide a more accurate reconstruction of the image.

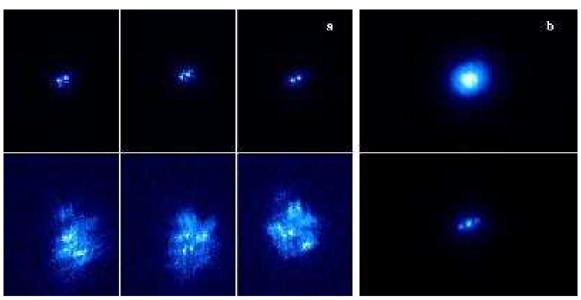

Figure 11. A selection of images of the double star Zeta Bootis from data collected at the 32-inch BOS telescope at ~30Hz cadence, and a reconstructed "lucky" image.

In the figure, panel (a) is a selection of images of the double star Zeta Bootis. The data was collected at BOS at ~30Hz cadence (each exposure was ~0.034sec) by an Andor Luca-R EMCCD camera with an SDSS r' filter and a x2 Barlow. The three sharpest, as well as the three least sharp images in the series are shown on the top and bottom respectively. Panel (b) at the top is a stack of the first 200 frames in the series, equivalent to a single 3.4 second exposure. Panel (b) at the bottom is the reconstructed lucky image – a stack of the sharpest 200 frames (a 1% selection) – for a total exposure of 3.4 seconds. Frames were selected and aligned using the brightest pixel in the star image. The ghost star appearing at the roughly 2 o'clock position in the lower right panel is an artifact of the shift-and-add these technique used to create the lucky image, known as *tripling.* The pair, which at the time of the observation had a 0.45 arc second separation, is clearly resolved.

7. Speckle Interferometry

When observed at a sufficiently high cadence, star images reveal the presence of "speckles," resulting from the atmosphere producing multiple sharp images of the target. In the case of a single star, these speckles will be randomly distributed inside the Gaussian seeing envelope on the detector. However, in the case of a binary, there will be a characteristic separation and position angle that the speckles will follow. These duplicated images of the star are randomly distributed, and simply summing the images or a long exposure will blur out this high-frequency information, leaving only a Gaussian seeing envelope.

It was first suggested by Labeyrie (1970) that Fourier analysis of speckles could allow the position angle and separations of close binaries to be measured with great precision. This technique is now known as "speckle interferometry". Harold McAlister and his associates at George State University pioneered speckle interferometry, while Brian Mason and associates at the US Naval Observatory, Elliott Horch at Southern Connecticut State University, and others have launched sizeable double star speckle interferometry observing programs. Horch (2006) reviewed the history and current status of speckle interferometry.

Since Fourier decomposition is blind to phase shifts, the location of each of the duplicated double star images on the detector is lost, but any correlations between speckles in different locations remains. By summing the 2-dimensional Fourier power spectrum of the high-cadence images, one can discern any patterns in the speckles that are common throughout the dataset.

If the target is an unresolved binary, the resulting power spectrum will form a set of fringes. The separation of these fringes is inversely related to the projected sky separation, thus making it possible to measure the separation of binaries that are closely spaced, down to the diffraction limit (or pixel scale) of the telescope.

This method of speckle interferometry creates 180 degree degeneracy in the position angle that must then be resolved using other imaging techniques (such as lucky imaging) or more advanced interferometry methods (e.g. bispectrum image reconstruction, Lohmann *et al.*, 1983). In most cases we use a combination of speckle interferometry and lucky imaging to measure the position angle, separation, and flux ratio of each binary pair.

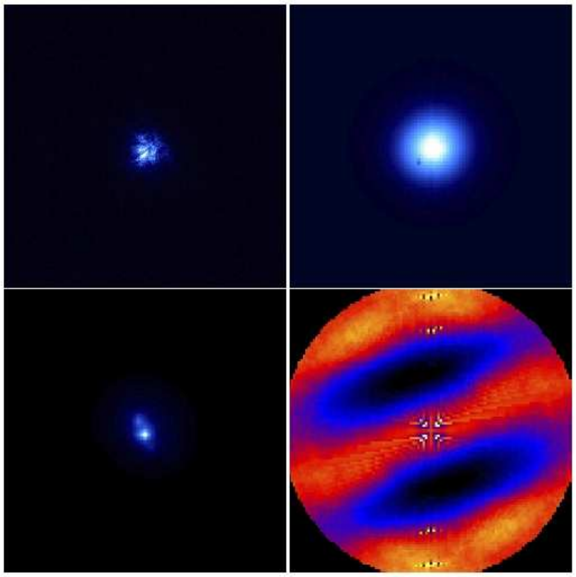

Figure 12. Results for the close visual binary HD 23985. See text for explanation.

Figure 13. The Orion Observatory's Andor Luca-S camera and 10-inch telescope equipped with a Sidereal Technology control system.

We observed HD 23985 (WDS 03503+2535AB) with LCOGT's BOS 32-inch telescope. An x2 Barlow and I filter were used in conjunction with the Andor Luca-R EMCCD camera. The components of the binary HD 23985 are reported in the WDS as magnitude 5.75 and 6.52. Referring to the figure, upper left is a single 34 ms exposure of HD23985, also known as a speckle. Upper right is a 10 second exposure of HD23985. Lower left is a 1% Lucky image of HD23985. The separation of the two components is 0.325". Lower right is a speckle interferogram of HD 23985 created by summing the 2-D Fourier power spectrum of all 5,000 34 ms images.

At Genet's Orion Observatory, an Andor Luca-S EMCCD frame transfer camera is being used for lucky imaging and speckle interferometry of double stars, as well as high speed photometry of X-ray binaries and other variables stars. The Andor Luca cameras are lightweight and are easy to transport, install on large aperture telescopes as a guest observer to achieve higher resolution, or use in portable field operations to observe asteroid or Trans-Neptunian Object occultations.

8. Conclusions

Measuring the separation and position angles of double stars is cooperative activity that has engaged many astronomers – students, amateurs, and professionals – for well over two centuries. Observations are welcome for publication in the *Journal of Double Star Observations* and similar journals. Once published, the observations are incorporated in the *Washington Double Star Catalog* along side those by William Herschel and all the other contributors.

Visual double observation projects using a low cost astrometric eyepiece on small telescopes have proven to work well for student seminars and summer camps where published results are a requirement. While somewhat more complex, CCD double star observations provide students with an opportunity to learn advanced techniques, and with larger telescopes, such as the 2-meter Faulkes Telescope North, to observe unusually faint doubles.

Finally, the advent of relatively affordable EMCCD frame transfer cameras is extending lucky imaging and speckle interferometry to fainter magnitudes, allowing atmospheric degradation to be circumvented and the resolution limits of telescopes to be achieved.

9. Acknowledgements

We thank the Las Cumbres Observatory Global Telescope for observational time on their 0.8-meter telescope at Santa Ynez and 2.0-meter telescope on Haleakala. This research was supported in part by NASA through the American Astronomical Society's Small Research Grant Program which funded the Andor Luca-S camera at the Orion Observatory. This research made use of the Washington Double Star and other catalogs provided by the U.S. Naval observatory. We thank CDS in Strasbourg, France for use of Aladan, the SIMBAD database, and access to various catalogs. Finally, we thank Richard Berry for supplying the lithograph from John Herschel's report from the Cape.

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