Sparse-Aperture Quasi-Meridian Telescopes

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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.

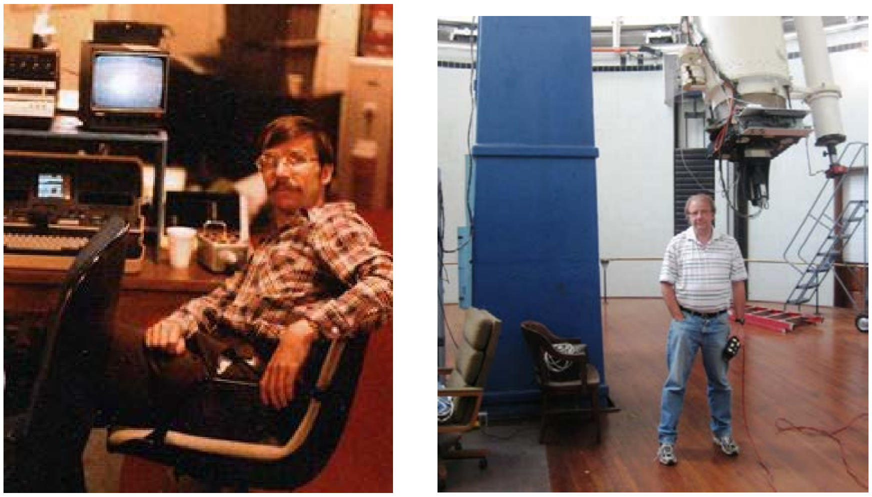

Figure 1. Left: a young William Hartkopf captures high-speed frames with an early Osborn computer from an intensified CCD (ICCD) camera located at the Cassegrain focus of the 4-meter telescope at Kitt Peak National Observatory. Right: Brian Mason with the controls of the 26-inch refractor at the U.S. 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 10th 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.

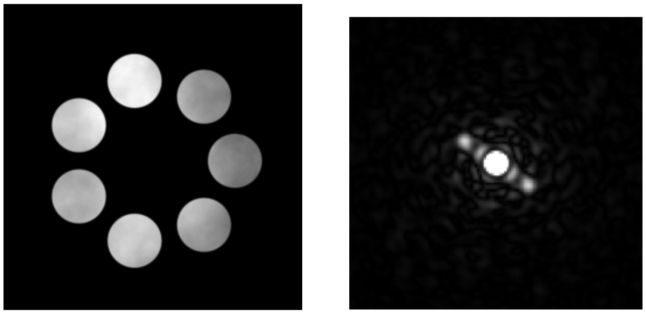

Figure 3: Simulation of two-meter sparse-aperture speckle interferometry telescope.

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.

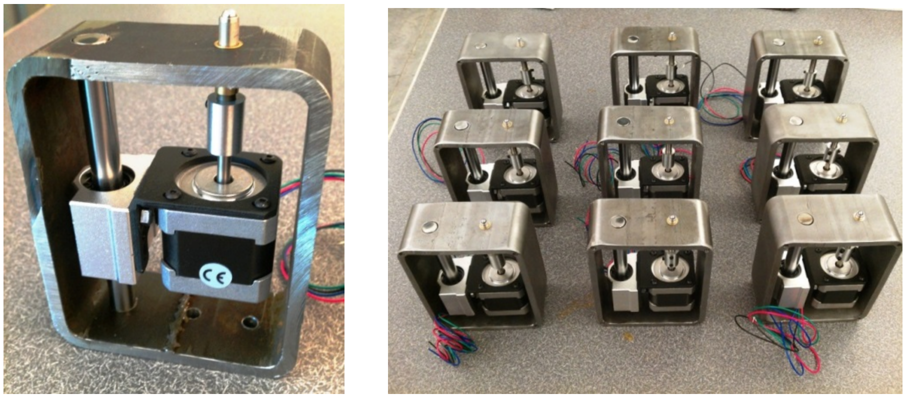

Figure 4. The nine positioners in the laboratory demonstration each use a very fine-pitch thread screw (256 threads/inch) and a motor supported by a linear bearing to position the mirrors in angle and axial displacement.

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.

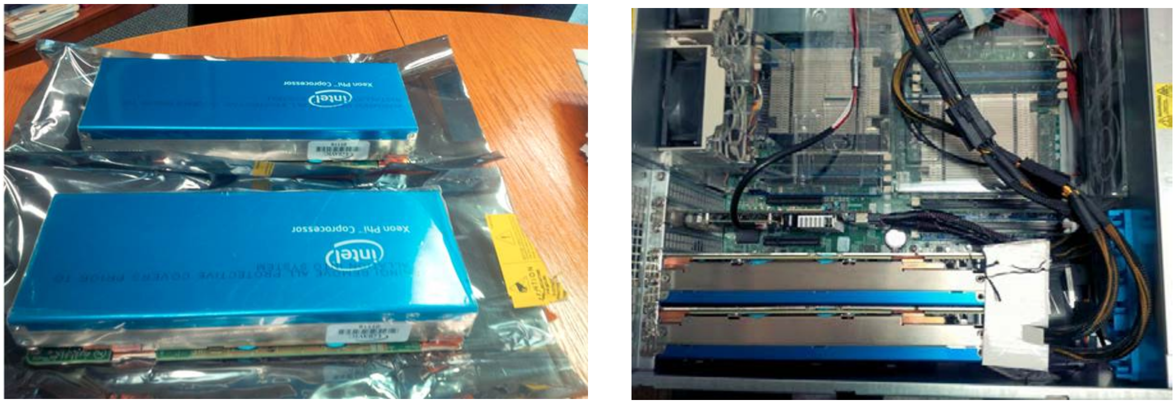

Figure 6. A pair of Intel Xeon Phi 31S1P PCI Express coprocessor cards installed in a desktop computer with an extra muffin fan for cooling.

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.

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References

Ashcraft, C. 2015. Speckle Interferometry with a Low Read-Noise CMOS Video Camera, *Journal of Double Star Observations*, 12, 89.

Dejonghe, J., Arpesella, C., Vernet, D., and Labeyrie, A. 2004. Tests with a Carlina-type hypertelescope prototype. *Astronomy and Astrophysics* 426, 721.

Eyer, L., Holl, B., Pourbaix, D., Mowlavi, N., Siopis, C., Barblan, F., Evans, D.W., & North, P. 2013. The Gaia mission. arXiv:1303.0303v1 [astro-ph.IM].

Fizeau, H. 1851. The hypotheses relating to the luminous aether, and an experiment which appears to demonstrate that the motion of bodies alters the velocity with which light propagates itself in their interior, *Philosophical Magazine,* Series 4 2, 568 —573. Retrieved from: http://babel.hathitrust.org/cgi/pt?id=pst.000068485474;view=1up;seq=586

Genet, R. 2013. Portable speckle interferometry camera system. *Journal of Astronomical Instrumentation,* 2, 134008.net, R. 2013.

Genet, R., Rowe, D., Ashcraft, C., Wen, S., Jones, G., Schillings, B., Harshaw, R., Ray, J., & Hass, J. 2015. Speckle interferometry of close visual binaries with the ZW Optical ASI 224MC CMOS camera. *Journal of Double Star Observations.* Vol.12 No.3, 270.

Hartkopf, W. 1996. Anniversaries and Anticipations: CHARA at Age 20 and Beyond. JAAVSO, 25

Herschel, William. 1782. Catalogue of double stars. *Philosophical Transactions of the Royal Society*. Vol. 72, 112-162.

Herschel, William. 1803. Account of the changes that have happened, during the last twenty-five years, in the relative situation of double stars. Philosophical Transactions of the Royal Society, Vol. 93, 339.

Horch, E. 2006. The status of speckle imaging in binary star research. RevMexAA, 25, 79-82.

Labeyrie, A. 1970. Attainment of diffraction limited resolution in large telescopes by Fourier analyzing speckle patterns in star images. A&A 6, 85.

Lacour, S., Tuthill, P., Ireland, M., Amico, P., and Girard, J. 2011. Sparse aperture masking on Paranal. The Messenger, 18, 146.

McAlister, H. 1985. High angular resolution measurements of stellar properties, ARA&A 23, 59.

Michelson, A. A., & Pease, F. G.. (1921). Measurement of the Diameter of Alpha-Orionis by the Interferometer. *Proceedings of the National Academy of Sciences of the United States of America,* 7(5), 143 —146. Retrieved from http://www.jstor.org/stable/84150

Nakajima, T., Kulkarni, S., Gorham, P., Chez, A., Neugebauer, G., Oke, J., Prince, T., and Readhead, A. 1989. Diffraction-limited imaging II: optical aperture-synthesis imaging of two binary stars. *The Astronomical Journal* 97, 5

Pauls, T. 2001. Observations of stars and stellar systems with the Navy Prototype Optical Interferometer. IAU Symposium, 205

Readhead, A., Nakajima, T., Peason, T., Neugebauer, G., Oke, J., and Sargent, W. 1988. Diffraction-Limited Imaging with Ground-Based Optical Telescopes. *The Astronomical Journal,* 95, 4

Rhodes, W. T., and J. W. Goodman. 1973. Interferometric technique for recording and restoring images degraded by unknown aberrations. *JOSA,* 63, 6, 647-657.

Savary, F. 1830. Mémoire sur les orbites des étoiles doubles and Sur la détermination des orbites que décrivent autour de leur centre de gravité deux étoiles très rapprochées l'une de l'autre. *Connaissance des Tems pour Pan.* Paris, France: Bachelier.

Terziev, E., Law, N., Arcavi, I., Baranec, C., Bloom, J., Bui, K., Burse, M., Chorida, P., Das, H., Dekany, R., Kraus, A., Kulkarni, S., Nugent, P., Ofek, E., Punnadi, S., Ramaprakash, A., Riddle, R., & Tendulkar, S. 2013. Millions of multiples: detecting and characterizing close-separation binary systems in synoptic sky surveys. *ApJS* 206,11.

Tuthill, P. 2013. The unlikely rise of masking interferometry: leading the way with 19th century technology. arXiv:1302.2722 [astro-ph.IM]

Young, T. 1807. A Course of Lectures on Natural Philosophy and the Mechanical Arts. Vol. 1. William Savage. Lecture 39, pp. 463 —464. doi:10.5962/bhl.title.22458.