Astrometric Speckle Interferometry for the Amateur

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1 Introduction

Today's amateur astronomer has access to technology and reference information that one could barely imagine even just a decade ago. The march of technology has made electronics and computers both more sophisticated and cheaper, encouraging the savvy amateur to try an astronomical technique not usually thought of as being in the amateur arsenal, speckle interferometry.

2 Binary Star Astrometry

Speckle interferometry is used to determine binary star astrometry which is all about two quantities, angular separation and position angle. In a binary star system, the angular separation is the angle between the two stars subtended on the sky, while the position angle is the orientation of the axis connecting the two stars with respect to north. By convention, north is at 0° and east is at 90°.

Making measurements from a perfect image is easy. Due to the circular aperture of the aberration-free telescope that generated this perfect image, an unresolved star along the optical axis has a point-spread function (the two-dimensional intensity distribution in the image of energy from the star, abbreviated PSF) that is radially symmetric, with a bright central core, and a succession of concentric rings. This pattern is known as an *Airy* disk (**NOTE: should point to Airy disk chapter**). Since the Airy disk is radially symmetric, there is a point that can be determined to be the center. If there are now two Airy disks, one from each unresolved star in a binary star system, getting the astrometric information is straightforward – determine the angle and distance of separation in the units of the image, and use knowledge of the scale and orientation of the image to the sky to get astrometric information suitable for publishing.

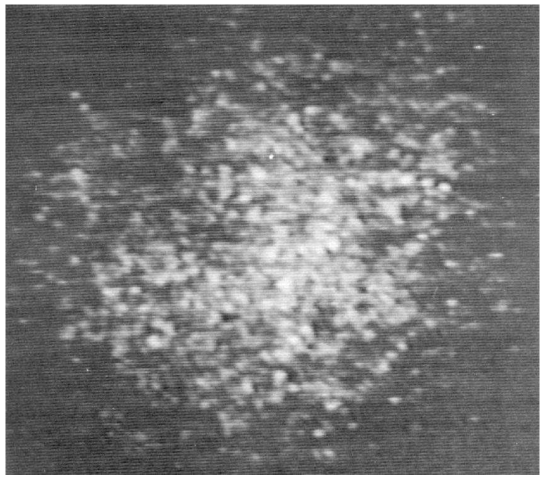

Figure 1: A single speckle frame of the star κ UMa on the KPNO 4-m. Adapted from McAlister et al. (1987). **NOTE: Will need permission from the Astronomical Journal again**

This scenario changes with the introduction of *seeing* – short time scale variations of the image intensity introduced by the atmosphere. Instead of centroiding on the Airy disk, one now has to attempt centroiding on the seeing disk, which, for all but the smallest telescopes, is much larger. If the separation of the two stars is smaller than the size of the seeing disk, the astronomer risks being unable to distinguish between the two stars.

3 Speckle Interferometry

The speckle interferometry technique involves processing the image before the seeing disk becomes the dominant feature of the image. This is usually done by taking short exposures (typically 15 msec or less) of the star and analyzing the pre-seeing-disk structure for information. Under high magnification, the area around the star reveals itself to be many "specks" (or "speckles") moving at random within a relatively confined area. Each of these speckles is actually the PSF of the star system through the telescope. Figure 1 shows a speckle pattern from a 4 meter telescope. Looking at many of these short exposure images in succession, one sees a sort of "shimmering" effect. This is due to interference between the individual speckles, hence the term, "speckle interferometry."

Labeyrie (1970) laid much of the groundwork for using speckle interferometry in a scientific capacity. Although it has been known since the time of Fizeau and Michelson (late nineteenth, early twentieth century), that resolution information lost to atmospheric turbulence can be regained through the use of interferometric techniques, it has only been available on the brightest of objects.

Several groups dabbled in binary star speckle interferometry throughout the mid-1970s, but with the commonplace usage of image intensifiers in observational astronomy by the late 1970s, the true potential of speckle interferometry in binary star science was revealed to the astronomical community (McAlister 1977).

4 Turbulence

The underlying cause of the speckles seen in high magnification, short exposure images is atmospheric turbulence. Coulman (1985) wrote an excellent distillation of atmospheric turbulence and how it applies to astronomy. To simplify for the binary star astronomer, atmospheric turbulence can be thought of as many pockets of air of slightly different temperature moving across the column of air defined by the telescope aperture, in the direction of the object. Because the air pockets are different temperatures, the index of refraction will be different, and the path taken by the starlight will shift, ever so slightly, creating the aggregate seeing conditions. In a time averaged sense, most seeing conditions (an observer's working measurement of turbulence) can be described by two numbers, r_0, a measurement of the diameter of the typical pocket of air passing in front of the telescope aperture, and τ_0, a measurement of how long a typical pocket of air "influences" the wavefront getting into the telescope. The value of r_0 has a wavelength dependence:

$$r_0 \propto \lambda^{\frac{6}{5}}. \tag{1}$$

Typical values of r_0 (at 550 nm) and τ_0 are 10 cm and 15 msec, respectively.

In practical terms, one might hear of the seeing being "1.6 arcsececonds". This is actually a measurement of the "seeing disk", the diameter at the full-width half maximum (FWHM) of a Gaussian (equations of the form e^{-x^2}) representation of the stellar intensity. To translate this into a value of r_0, ten Brummelaar (1992) calculates:

$$r_0 = 1.009D\left(\frac{\lambda}{\theta_{seeing}D}\right)^{\frac{6}{5}}, \tag{2}$$

where λ is the wavelength, D the objective diameter of the optical system, and θ_{seeing} FWHM diameter (in radians) of the seeing disk. So, 1.6 arcsec seeing, as viewed at 550 nm through a 50 cm telescope, translates to an r_0 of about 5 cm.

Measuring τ_0 requires determinations of interferometric visibilities at different exposure times and extrapolating back to the exposure time of 0. Determining object visibilities is a bit beyond the scope of this chapter, so suffice it to say that, for the speckle astronomer, τ_0 determination is a more qualitative exercise. When the highly magnified image of the object meanders "slowly" along its random path, the conditions are said to be those of "slow seeing." If the object appears more animated in its travels, conditions are described as "fast seeing." How τ_0 affects the design and operation of an astrometric speckle system is described in section 8.

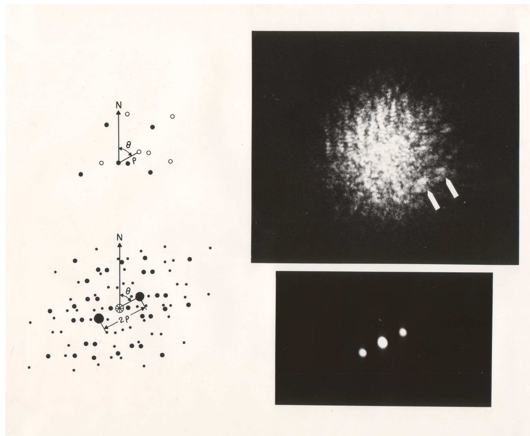

Figure 2: The principle behind speckle interferometry and the autocorrelation procedure. Courtesy of Dr. H. A. McAlister. **NOTE: Will need permission from whoever is publishing Sky & Telescope these days.**

5 Imaging Process in Brief

So, how does one use images of swirling speckles to determine binary star astrometric data? To answer that question, it helps to know a little bit about the Fourier transform and function convolution, and how they play out in the imaging process.

If one assumes a point-source object, the corresponding image intensity, after going through the atmosphere and the optical system, is the convolution of the object source intensity with the Fourier transform of the atmospherically disturbed telescope pupil (the intensity distribution seen in "collimation" mode – most often seen by the amateur astronomer aligning a newtonian telescope). The convolution process alters the original, ideal object source by a combination of atmospheric distortions and telescope aberrations.

The physical manifestation of this procedure can be seen from Figure 2. The top right image shows a short exposure, highly magnified star image taken through a narrowband filter. The envelope of individual speckle images is the seeing disk, in this case, about $1''$ in diameter. Inside the seeing disk, one can see the individual speckles, but more importantly, *pairs* of speckles which have the same orientation and separation (such as that indicated by the arrows). Each pair of speckles represents the components of the binary star imaged at *full* resolution of the telescope (in this case about $0.03''$). The separation of the pair is about $0.27''$ with at position angle of about $293°$. The position angle and separation could be measured directly from this frame, but the power of the speckle method is that is uses many pairs of speckles to increase the reliability of the measurement.

The top left image shows five typical pairs of speckles. These move randomly inside the seeing disk but the relative separation of the speckles in each pair always remains the same. The essence of the Fourier transform is that it assesses the frequency of spatial separations of the speckles – each speckle from every other speckle. It can be seen from Figure 2 that there is a wide range of separations between speckles of different pairs, but underlying this, the most often occurring separation is that between the speckles representing the binary. However, because we are considering the separation of each speckle from every other, there are just as many pairs of speckles at position angle 113° as there are at 293° – a 180° ambiguity. Resolving this is treated in section 7.

Calculation of the Fourier transform of the above described image intensity produces a picture frequently referred to as the power spectrum of the image. The power spectrum represents the distribution of image "power" among the available "spatial frequencies." As an example, consider a stream of (one-dimensional) audio data. If this data represents two pure musical tones, the combined audio waveform will be the mixture of two sinusoids with different periods and (most likely) different amplitudes. If one were to take the Fourier transform of a finite section of this mixed waveform, the resulting diagram would reveal the constituent waveforms (and their relative amplitudes). Returning to the two-dimensional realm of astronomical imaging, the frequencies encountered are spatial rather than temporal. In the case of imaging a binary star system, the most likely spatial frequency to occur in the individual speckle snapshots is the separation between the two stars. In this case, the combined power spectrum of many snapshots will show bands of light and dark. The crest-to-crest distance is mapped to the separation of the two stars, while the axis perpendicular to the bands represents the position angle.

The reader interested in learning more about the Fourier transform and convolution is strongly encouraged to seek out a book by Bracewell (1999). Alternately, most undergraduate level text books on optics will have sections describing these two concepts as well (see, for example, Klein and Furtak (1986)).

6 Speckle Measurements

To aid further the determination of the binary star astrometry, the Fourier transform can be used yet again. By calculating the transform of the power spectrum, these bands of light and dark can be converted into a sequence of three co-linear, circularly symmetric peaks. Binary star astronomers call this picture the *autocorrelogram*. The autocorrelogram consists of a large central peak and two smaller peaks, one on either side of the central peak, exactly 180° apart. Figure 3 shows a typical autocorrelogram. These peaks are the result of a random process, which gives them a Gaussian profile. Therefore, centers are easy to determine. The distance between the centers of the central peak and one of the other peaks gives the separation angle. The angular orientation of the line of three peaks gives the position angle, though with a 180° ambiguity.

This process of creating the power spectrum and the autocorrelogram can be done using analog or digital techniques. Gezari et al. (1972) describe a typical

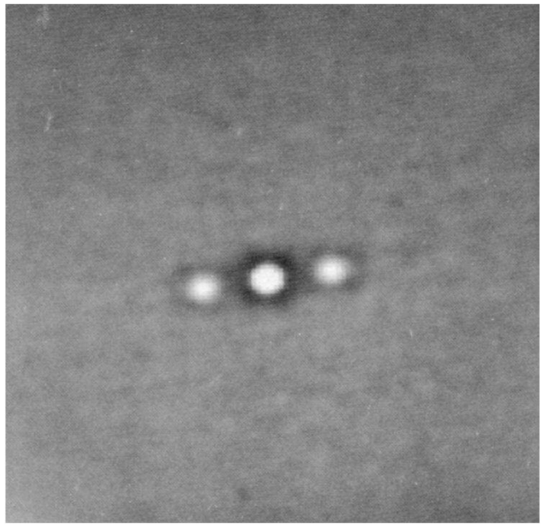

Figure 3: A background subtracted autocorrelogram of the binary star κ UMa. Adapted from McAlister et al. (1987). **NOTE: Will need permission from the Astronomical Journal again**

analog autocorrelogram generating process. They start with a standard 35 mm film camera attached to an image intensifier tube. The camera is equipped with a rapid film advance system to more efficiently use telescope time, though, in the strictest sense, it is optional. The camera records a sequence of short exposure, high magnification images. This film is then developed and negative reversed (so the film is now a positive image). Each individual frame is stepped through a laser-illuminated optical system (employing the classical aperture/image relationship of coherent optics) and individually exposed onto a separate emulsion to form the power spectrum. This process is done again to form the autocorrelogram. This is usually a slightly toxic process in that an index-matching fluid to the film has to be used to keep laser scattering from micro-scratches from ruining the power spectrum and autocorrelogram emulsions. For traditional 35 mm film, this fluid is usually a variant of the standard dry cleaning fluid, naphthalene.

This whole process can be done digitally if digitized frames of the individual speckle frames are available. While one can digitize the individual photographic frames, video frames from a bare CCD or intensified CCD are the more likely source. One then merely has to take the Fourier transform of each individual frame and co-add them all to form the power spectrum, and take Fourier transform again to generate the autocorrelogram.

In the digital realm, there is a shortcut, a way to go straight from individual speckle frames to the autocorrelogram. One merely has to correlate every pixel in the individual speckle frame with every other. To see this, imagine an "autocorrelogram canvas" four times the size of an individual speckle frame. For each individual frame, a value of one is assigned to pixel values above a certain threshhold, and zero below. For each above-threshhold value in the individual frame, its pixel address is aligned with the center of the canvas and the frame is added to the canvas (remember that the frame is now a collection of ones and zeros). Morphologically, this procedure produces a diagram much like that of generating the autocorrelogram through the use of Fourier transforms. In fact, taking into account the multi-bit nature of the data, and adjusting the threshhold value, these numerical techniques can be shown to be the same.

7 Directed Vector Autocorrelogram

Now, what does one do about the 180° ambiguity in the typical autocorrelogram? Bagnuolo et al. (1992) describe a variation of the direct image-to-autocorrelogram numerical technique that resolves the quadrant ambiguity for most binary star systems. Instead of merely assigning the above-threshhold value to one, its multi-bit value is retained. The concept of aligning the frame multiple times on a larger canvas is replaced by an analysis of each of the unique pairs within the frame. In the case of the former concept (the pure autocorrelogram), the net effect is to sample each unique pair twice, aligning the frame on each component of the pair. It is very easy to see that this will lead to a peak on either side of the central peak, exactly 180° apart. In the case of the latter concept, each unique pair is sampled only once, aligning the pair only on the brighter value. This will tend to emphasize the outlying peak that, along with the central peak, will define the true position angle of the binary star system. However, if both stars are about the same brightness, the method breaks down. This variation of the autocorrelogram is called the *directed-vector autocorrelogram*. Figure 4 shows a surface plot of a directed-vector autocorrelogram.

8 Speckle Sensitivity

As was alluded to in section 4, τ_0 highly influences the sensitivity of any speckle observation. The "faster" the seeing is, the shorter the camera exposure time has to be to get enough non-overlapping speckles to process. A shorter exposure time implies a brighter magnitude limit. Also, to first order, a larger collecting aperture does not increase sensitivity. A larger telescope creates a physically smaller Airy disk as well as more speckles. In order to be able to use the techniques of speckle interferometry, one has to magnify the image and/or shorten the exposure time to get enough non-overlapping speckles, thereby offsetting the increased light-gathering power of the larger aperture size. A larger aperture merely gives better resolution. In twenty years of using speckle interferometry for binary star research, Hartkopf (2001) finds that the best results occur when the number of detector pixels across the central peak of the Airy disk is between 10 and 30. For wider systems (those where the speckles of the individual com-

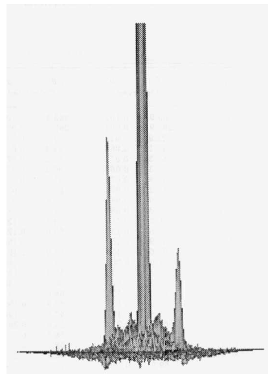

Figure 4: A background subtracted directed-vector autocorrelogram of the binary star 21 Oph. The central peak has been truncated for clarity. Adapted from Bagnuolo et al. (1992). **NOTE: Will need permission from the Astronomical Journal again**

ponents barely overlap, and wider), better sensitivity can be gained by pushing the number of pixels below 10. However, it is not a good idea to go below 2 – one runs the risk of losing a significant amount of light to the space between the pixels. There is nothing special about these values, and the curious user is encouraged to experiment with them. They were determined empirically – autocorrelograms of the same collection of binary star systems were taken over a wide range of image scales and the results compared. Chapter XX (**NOTE: should point to Airy disk chapter**) describes how to determinem the size of the central peak of the Airy disk, and using that size to design a system will be described in section 9.7.

9 Equipment Considerations

9.1 Telescopes

Speckle interferometry works with any telescope design. Because the necessary field-of-view is quite small, no complex optical system is necessary to get good astrometric results. The most important descriptive number of a telescope system is the *objective focal length*, $f_{\rm obj}$. If it is not listed on the telescope, an approximate value is easy to calculate. It is the focal ratio multiplied by the objective diameter. In the case where the main telescope is only one part of a more complex optical system, $f_{\rm obj}$ can be calculated from a simple measurement in the image plane of an object of known angular extent. For example, the angular extent of a certain object is known to be $2.3''$. After passing through the optical system, the size in the image plane is measured to be 14.5 μm. So,

$$f_{\rm obj} = \frac{14.5\,\mu\rm m}{2.3\,\rm arcsec}\frac{206265\,\rm arcsec}{1\,\rm rad}\frac{1\,\rm mm}{1000\,\mu\rm m}$$
$$= 1300.4\,\rm mm.$$

Note that in the above calculation, the radian "units" have been ignored. Radians are a unitless measure. In order to do optical calculations, all angular measurements need to be converted to the "natural" units, radians.

9.2 2-D Cameras

Which camera or camera system to choose is a matter of cost, convenience, and/or complexity. While one could go for for a standard, large-format, digital imaging system, the long readout times of the CCD or CMOS array make processing thousands of frames very inconvenient. In addition, many of the imaging CCDs are not equipped with accurate or reliable enough shutters. High frame rate digital CCDs (Teledyne Dalsa makes this type of camera, see section A.4) are another option. The disadvantage is in complexity. These cameras typically require building a custom electronic interface and writing a low-level device driver to get the image data into a location in computer memory. Low-cost consumer digital cameras using flash memory are a possibility, but would require more planning, both figuring out image scales (the lenses usually cannot be removed, requiring an eyepiece-projection type optical system) and coordinating an external, fast shutter with the camera. So, this leaves video cameras. For speckle interferometry they fall into two classes, intensified and non-intensified. Both types are useful, they simply need to have a standard video output (RS-170 or PAL). Which to choose is mostly a matter of price – intensified video cameras cost 10-50 times their non-intensified counterparts.

When choosing a video camera for use in a speckle system, be sure to get information on the physical size of the CCD detector, not just the number of pixels along each dimension (though this is handy to know as well). This video camera will be used in conjunction with a frame grabber (see section 9.5) or direct-to-disk digitizer which will rescale the output video. If this information is not available, all is not lost. Simply make sure the speckle system design has enough flexibility to optimize the Airy disk size to the output pixel size.

Any video camera will do, even a color camcorder. It just needs to output RS-170 (NTSC if it is color) or PAL analog video. For sensitivity purposes, a monochrome video camera is better. For the adventurous (and moderately wealthy), a video camera with adjustable gating can increase performance on brighter objects or under faster seeing conditions. An RS-170 video camera outputs 30 frames per second, a PAL camera, 25. Normally the CCD detector exposes for the whole frame time. Through either creative "charge dumping" (reading out the CCD several times during the frame time, and only "remembering" the last readout) or an LCD shutter, the time the detector sees the sky can be less than an individual frame time while keeping the video frame rate unchanged. This process is known as *gating*.

The dedicated amateur with a bit of money to spend might consider an intensified video camera. Intensification adds an additional 4-5 magnitudes of sensitivity, and thereby increase the number of available objects 10- or even 100-fold. There is a penalty. Intensifiers are electronically noisy. They use phosphors to create electrons from the original photons, amplify these electrons about a million-fold through a series of high voltage cathodes, and use phosphors again to create many photons out of the amplified electrons. An input of a photon creates an output of about a million photons. If, during the early stages of amplification, a stray thermal electron enters the series of cathodes, it gets amplified right along with photon generated electrons. A detector peering at the output of the intensifier cannot tell an object photon from a thermal electron. For binary star astrometry, using an intensifier limits the magnitude difference between the stars to about 3 (Mason 1994).

The final issue about the camera is its size and weight. Lightweight and compact cameras are easier to use on all types of telescopes. In addition, many cameras come with the camera head (containing the detector) and the controlling electronics as separate units connected by a cable. This makes for a more modular and easier to handle system.

9.3 Eyepiece Projection

Frequently, with the typical amateur telescope, the most appropriate method to match the Airy disk size with the detector pixel size is the technique known as *eyepiece projection*. An eyepiece is placed between the chain of telescope optics and the detector which steepens the effective input angle to the detector, increasing the effective focal length of the optical system. Mathematically,

$$f_{\mathrm{effective}} = \frac{d_{\mathrm{eye}} f_{\mathrm{obj}}}{f_{\mathrm{eye}}}, \tag{3}$$

where d_{eye} is the eyepiece–image plane distance, and f_{eye} is the eyepiece focal length.

Using the example optical system from section 9.1, in conjunction with a 28 mm focal length eyepiece, a 2000 mm effective focal length can be attained by setting d_{eye} to 43.1 mm,

$$\begin{aligned} d_{\mathrm{eye}} &= \frac{f_{\mathrm{effective}} f_{\mathrm{eye}}}{f_{\mathrm{obj}}} \qquad (4) \\ &= \frac{2000\,\mathrm{mm}\; 28\,\mathrm{mm}}{1300.4\,\mathrm{mm}} \\ &= 43.1\,\mathrm{mm}. \end{aligned}$$

Eyepiece projection systems can be bought commercially (see section A) or custom-built using standard machine shop tooling. In practice, d_{eye} is fixed to give the desired $f_{\mathrm{effective}}$, and the whole projection apparatus is moved to adjust focus. Finally, keep in mind that not all eyepieces will physically fit in a commercial system. The wide angle, large eye relief eyepieces (TeleVue Nagler, Meade Ultra Wide Angle, etc.) have significantly larger housings than the more traditional Kellners, Orthoscopics, and Plössls.

9.4 Filters

For pure astrometry, the choice of filter is somewhat arbitrary. Roughly, the number of speckles is proporitional to the diameter of the telescope aperture and inversely proportional to the wavelength (assuming a not too broad bandwidth):

$$N \propto \frac{D}{\lambda}. \tag{5}$$

The speckle size has a wavelength dependence as well as a weaker bandwidth dependence. A speckle is essentially an image of the Airy disk, dominated by the central peak. Equation XX (**NOTE: should point to an equation in the Airy disk chapter**) shows the functional form, which is for an infinitesimally narrow bandwidth. If a finite bandwidth is used, each wavelength "bin" creates its own Airy disk, each of a slightly different size. The net effect is to "fuzz out" the Airy disk edges, which makes the speckles bigger, and merges more of them together. In addition, for wide bandwidths, the atmosphere will chromatically split the object light, creating an elongated speckle. This effect is more prominent with larger telescopes and objects at a significant angle down from zenith. A filter with a more narrow bandwidth lessens this problem and makes astrometry more precise.

Astronomers mostly use the Johnson *UBV* (Johnson and Morgan 1953) and Cousins *RI* (Cousins 1976) filter systems. These are fairly wide bandwidth filters. Another system that is frequently used is the Strömgren *ubvy* (Strömgren 1956; Crawford and Barnes 1970) system. These are quite a bit narrower and may give more precise astrometry. Additional information about astronomical filter systems can be found in the *General Catalogue of Photometric Data* (Mermilliod et al. 1997, visit http://obswww.unige.ch/gcpd/gcpd.html). Again, for pure astrometric work, any filter that produces good, sharp speckles will suffice.

9.5 Frame Grabbers

The final piece of equipment to discuss is the frame grabber. The frame grabber digitizes each RS-170 or PAL frame and saves it to a location in computer memory, where the DVA program applies its thresholds and extracts the relevant data. With the memory and speeds of today's computers and frame grabbers, the DVA program can process nearly every frame in real time. Because RS-170 and PAL signals are a sequence of analog scan lines, the frame grabber will effectively resize the pixels. For example, the video camera may have 780 detector pixels across the CCD. This row of pixels gets converted to an analog signal, the scan line. The frame grabber then re-digitizes the scan line into a row of, say, 256 pixels. Recall from section 8 that the sensitivity of the system is based on the number of *detector* pixels across the Airy disk. The frame grabber pixelation value chosen is simply a matter of processing speed.

In recent years, frame grabbers have been deprecated in favor of direct-to-disk video digitizers. These are usually little boxes that connect to the computer by means of USB and have standard composite video and audio, RCA jack (the yellow, red, and white stereo component connectors) inputs. They usually have a little utility that installs on the computer, and they often encode the video stream to a standard video format. These can still be used. There are programs that convert the standard video format to individual data frames that can be processed by the code described in Section 9.6.

9.6 DVA Computer Code

The DVA computer code has been rewritten. It now consists of a hardware-independent library that performs the DVA algorithm and a sample hardware-dependent program (using the Matrox Meteor frame grabber under Linux) which calls the DVA library. There is also a stand-alone utility showing how one can take a block of individual data frames (perhaps a modified output of a direct-to-disk digitizer) and calculate a DVA on the block. To download and get details on the code, visit: http://www.chara.gsu.edu/∼nils/dva.html

9.7 An Example System

As an example, it is decided to build a speckle system around a typical Meade or Celestron 8 inch, $f/10$ Schmidt-Cassegrain telescope. For these systems, $f_{\mathrm{obj}} = 2000\,\mathrm{mm}$. This will be used in conjunction with a CCD video camera that has 540 pixels across a scan line and 15 μm pixels. In addition, an eyepiece where $f_{\mathrm{eye}} = 13\,\mathrm{mm}$ is available for use. First, calculate the necessary $f_{\mathrm{effective}}$ to get the central core of the Airy disk to span about the right number of pixels. To get the core to span 10 pixels, the Airy disk core needs to be about 150 μm in size. From equation XX (**NOTE: should point to an equation in the Airy disk chapter**),

$$
\begin{aligned}
f_{\mathrm{effective}} &= \frac{D_{\mathrm{Airy}} D}{(2.44)\lambda} \\
&= \frac{150\,\mu\mathrm{m}\; 203.2\,\mathrm{mm}}{(2.44)\; 550\,\mathrm{nm}} \\
&= 22712\,\mathrm{mm}.
\end{aligned}
$$

Using equation 4,

$$
\begin{aligned}
d_{\mathrm{eye}} &= \frac{22712\,\mathrm{mm}\; 13\,\mathrm{mm}}{2000\,\mathrm{mm}} \\
&= 148\,\mathrm{mm}.
\end{aligned}
$$

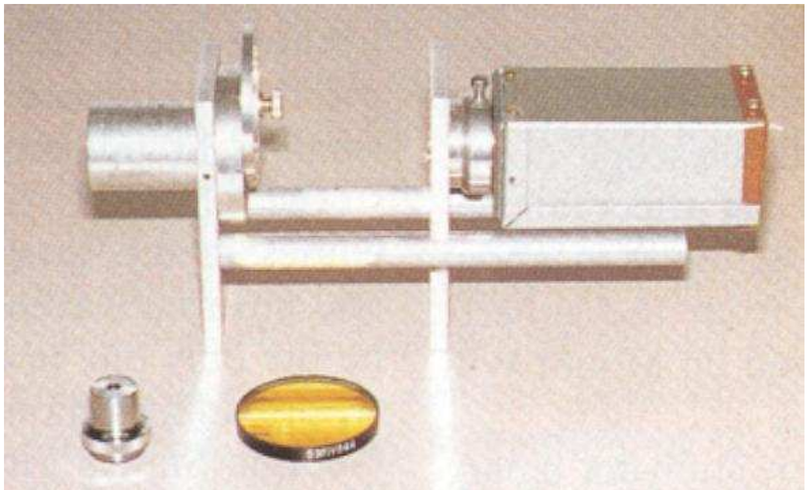

Figure 5: The amateur speckle camera built in early 1992. **NOTE: Will need permission from whoever is publishing Sky & Telescope these days.**

To calculate the field-of-view (fov) in seconds of arc along the scan line,

$$\begin{aligned} fov &= \frac{\text{(No. of pixels) (pixel size)}}{f_{\text{effective}}} \\ &= (540\,\text{pix}) \frac{15\,\mu\text{m}}{1\,\text{pix}} \frac{1\,\text{rad}}{22712\,\text{mm}} \frac{206265\,\text{arcsec}}{1\,\text{rad}} \\ &= 74\,\text{arcsec.} \end{aligned}$$

As can be seen from equation 4, to shorten d_{eye} for a given $f_{\text{effective}}$, either use a shorter focal length eyepiece or a longer focal length telescope. One can use a barlow lens to get a longer effective focal length. In certain cases, changing to a longer effective focal length or shorter focal length eyepiece is not practical. In these cases, one may have to replace the eyepiece in the projection setup with a microscope objective. Because microscope objective focal length parameters are not described like those of an eyepiece, using one typically involves a bit of trial and error. Start with the lowest power (typically 5X) objective. If the image scale is still not quite right, change to a higher power objective. A bit of simple machining will be required to make an adaptor to fit the objective into the projection apparatus. Remember that the threads of the objective are pointed towards the camera.

Figure 5 shows a photograph of the prototype amateur speckle camera, built and tested in early 1992. It uses a microscope objective and a Philips monochrome CCD video camera. A description of its performance can be found in Turner et al. (1992) (visit http://www.chara.gsu.edu/~nils/1992cadm.conf..577T.pdf).

10 Scientific Program

Astronomers at the United States Naval Observatory (USNO) maintain a list of all the visible measurements, published in the literature, of binary stars. They make available on the world wide web a summary list (visit http//ad.usno.navy.mil/proj/WDS/wds.html). Also at the USNO web address are lists of single stars, and multiple star systems with orbital elements. By observing single stars, one can test new data reduction techniques. Systems with known orbital elements are useful for determining the exact scale and orientation of the optical system on the sky.

The above mentioned summary list makes a good starting point for a project of study. For the data to be useful, it is necessary to calibrate the data accurately. The best way to do this is to look at known, slow moving systems – a system that has not changed position angle and separation significantly for the last 200 years is a good candidate for scale and orientation calibration. It is necessary to observe several of these systems before taking apart or modifing the optical system.

A Appendix

This is a partial listing of equipment available to build a speckle system. It is by no means complete. Because this author lives in the United States, the list has a distinctly North American slant. The interested astronomer is encouraged to seek out local resources when building a system. Amateur magazines are good resources for the local distributors of the products of international manufacturers (such as Celestron or Meade) as well as local manufacturers of similar products.

A.1 Eyepiece Projection Systems

Commercial systems are available from Meade and Celestron. Contact a local distributor. Section A.8 lists the contact information for these companies.

A.2 Eyepieces

Eyepieces for eyepiece projection systems are available from numerous manufacturers and distributors. Again, be sure the eyepiece purchased will fit the projection system. Some manufacturers include the usual suspects, Meade, Celestron, Tele Vue, and Apogee. Section A.8 lists the contact information for these companies. In addition to the well-known international companies, the following companies also market eyepieces.

Orion Telescopes & Binoculars 89 Hangar Way Watsonville CA 95076 USA http://www.telescope.com
Pentax 600 12th St Suite 300 Golden CO 80401 USA http://www.pentaxwebstore.com/products/sport_optics/eyepieces
University Optics PO Box 1205 Ann Arbor MI 48106 USA http://www.universityoptics.com/eyepieces.html

A.3 Filters

Filters can be purchased from the companies listed in the table. Several of these companies (Andover, Custom Scientific, and CVI Melles Griot) specialize in custom applications. As a result, they are more expensive. The best bets for inexpensive (but non-standard) filters are Edmund Scientific (contact information is listed in section A.8) and Lumicon. The contact information is listed below.

Andover Corp. 4 Commercial Dr Salem NH 03079 USA http://www.andovercorp.com
Custom Scientific, Inc. 3852 North 15th Ave Phoenix AZ 85015 USA http://www.customscientific.com
CVI Melles Griot 200 Dorado Pl SE Albuquerque NM 87123 USA http://www.cvimellesgriot.com
Lumicon 750 E Easy St Simi Valley CA 93065 USA http://www.lumicon.com

A.4 High-Speed Digital Cameras

Below are two sources for high frame rate digital cameras. These are expensive, research grade detectors. Significant computer code would need to be written to use detectors from these companies. Edmund Optics markets a number of digital cameras (contact information is in section A.8).

Andor Technology 7 Millennium Way Springvale Business Park Belfast BT12 7AL UK http://www.andor.com/scientific_cameras/neo_scmos_camera/
Teledyne Dalsa 605 McMurray Rd Waterloo Ontario Canada N2V 2E9 http://www.teledynedalsa.com

A.5 Video Cameras

Below is a selection of manufacturers of RS-170 video cameras. Many of these companies also market PAL versions of these. Whether it is RS-170 or PAL is not as important as it may seem. Almost every frame grabber card is capable of either RS-170 or PAL signal capture.

Astrovid 2000 AVA ASTRO CORP DBA – Adirondack Video Astronomy 72 Harrison Ave Hudson Falls, NY 12839 USA http://www.astrovid.com
Cohu Electronics 12367 Crosthwaite Cir Poway CA 92064 USA http://www.cohu-cameras.com
Watec Incorporated 720 Route 17M Suite 204 A Middletown NY 10940 USA http://www.wateccameras.com

A.6 Intensified Video Cameras

These are video cameras for the adventurous (as well as wealthy). Due to export restrictions, US-based companies might not be able to ship internationally.

Andor Technology 7 Millennium Way Springvale Business Park Belfast BT12 7AL UK http://www.andor.com/scientific_cameras/istar_iccd_camera/
Axiom Optics 1 Broadway 14th floor Cambridge MA 02142 USA http://www.axiomoptics.com/index_HICAM.html
PhotonicsTech PO Box 2288 Salt Lake City UT 84110 USA http://www.photonicstech.com/intensified_ccd.htm
Photonis PO Box 1159 Sturbridge MA 01566 USA http://www.photonis.com/industryscience/products/image_intensifiers
Photon Lines Ltd Bloxham Mill, Barford Road Bloxham, Banbury Oxfordshire UK OX15 4FF http://www.photonlines.co.uk/cameras-and-image-intensifiers/intensified-cameras/I2-cam-intensified-ccd.htm

A.7 Frame Grabbers

A quick web search for frame grabbers will turn up dozens, if not hundreds, of frame grabbers. Many of these will have proprietary drivers that will require you to use a variant of Windows to do the video capture. Using a proprietary driver frame grabber is entirely possible – one simply has to write a utility to convert the output video format into a block of video frames for input to the DVA code.

If the interest is toward running everything under Linux, the best bet is a BT878-based frame capture card. Since late in the Linux 2.4 kernel series, discrete frame grabber drivers were deprecated in favor of a unified interface known as Video 4 Linux (V4L), concentrating on the video capture chip rather than the make of the card. In the Linux 2.6 kernel series, this interface was updated to V4L2. If one happens to have an older frame grabber, no longer in production, such as the Data Translation DT2851, one might have to use an older kernel or make extensive modifications to the Linux driver. Almost all BT878-based frame grabbers work under V4L2. The following is an inexpensive example.

PV-149 4-port
Blue Cherry
2635 Fairway Drive
Fulton MO 65251 USA
http://store.bluecherry.net/

Alternatives to frame grabbers are direct-to-disk video encoders. A typical one of these connects to a USB port on a computer and encodes the analog video stream to a standard video format, saving it to disk. As described in section 9.5, one can write a utility to extract the individual frames from the encoded video and feed them to the DVA code. A simple web search of "usb video encoder" will bring up thousands of possibilities. Below is an example from Pinnacle Systems.

Pinnacle 8230-30002-01
Pinnacle Systems
280 North Bernardo Ave
Mountain View CA 94043 USA
http://shop.avid.com/store/category.do?category=pinnacle-video-capture-dvd-creation

A.8 Large Scale Vendors

This is a listing of vendors that make appropiate products in more than one of the above listed categories.

Celestron International 2835 Columbia St Torrance, CA 90503 USA http://www.celestron.com
Edmund Optics 101 East Gloucester Pike Barrington NJ 08007 USA http://www.edmundoptics.com
Meade Instruments Corp. 27 Hubble Irvine CA 92618 USA http://www.meade.com
OpticsPlanet, Inc. 3150 Commercial Ave Northbrook IL 60062 USA http://www.opticsplanet.net/telescope-accessories.html
Tele Vue Optics, Inc. 32 Elkay Dr Chester NY 10918 USA http://www.televue.com

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