Calibrating a CCD Camera for Speckle Interferometry

Richard Harshaw
Brilliant Sky Observatory, Cave Creek, Arizona

Abstract Due to advances in high speed CCD cameras, speckle interferometry has now become an area of research for amateur astronomers. This paper describes several approaches to calibrating the pixel scale of a camera and suggests that using a transmission diffraction grating with a monochromatic light source is the best method.

Introduction

Since discovered by Antoine Labeyrie, speckle interferometry has held great potential as an analytical tool for the observation of close binary stars (Labeyrie, 1970). While Labeyrie's approach was labor-intensive and relied upon photographic film, new electronic cameras transfer the data analysis from the domain of hard work and manual computation to the domain of computerized analysis, thereby saving the researcher valuable time and yielding higher accuracy than was possible by manual methods. Since the introduction of intensified CCDs in the late 1980's, astronomy has undergone a revolution in the astrometry of close binary star systems.

These star systems are of immense interest to astronomers because a close pair is likely to be a gravitationally bound pair with a relatively short period. It is the determination of binary star orbits that is the Holy Grail of modern stellar astronomy as the determination of an orbit allows us, with appropriate additional information, to determine the masses of the two stars. With the masses determined and the distance to the pair known, we can determine each star's absolute luminosity and thereby fill in the mass-luminosity diagram with more data points. In a house-that-Jack-built chain of reasoning, the mass-luminosity relationship is the driving force of stellar evolution and dynamics.

Until the last 15 years or so, speckle interferometry has been the domain of large research-grade telescopes and high-end CCD cameras. But recent advances in camera technology have brought the price point of good cameras down to a level where amateurs with sufficient aperture can now do speckle interferometry. See Teiche et al. (2014), Genet (2013), and Wiley (2013). This was the development that led to the speckle interferometry with an 11-inch SCT reported in this paper.

The Equipment

In late 2014, a Skyris 618C color CCD camera was procured. The Skyris is manufactured by The Imaging Source (Germany) under license to Celestron. The Skyris 618 uses a Sony 618 color chip of 640 x 480 pixels, each pixel being 5.6 microns in size, but is run in black and white mode for speckle and CCD imaging of stars (Y800 using FireCapture software). The Skyris was chosen because its integration times run a wide range, from 1 millisecond to 30 seconds. Since speckle is best done in the 10-40 millisecond range (and the lower end of that range is better), the Skyris is a good choice for amateur speckle. The Skyris was mounted to a Celestron C-11 SCT.

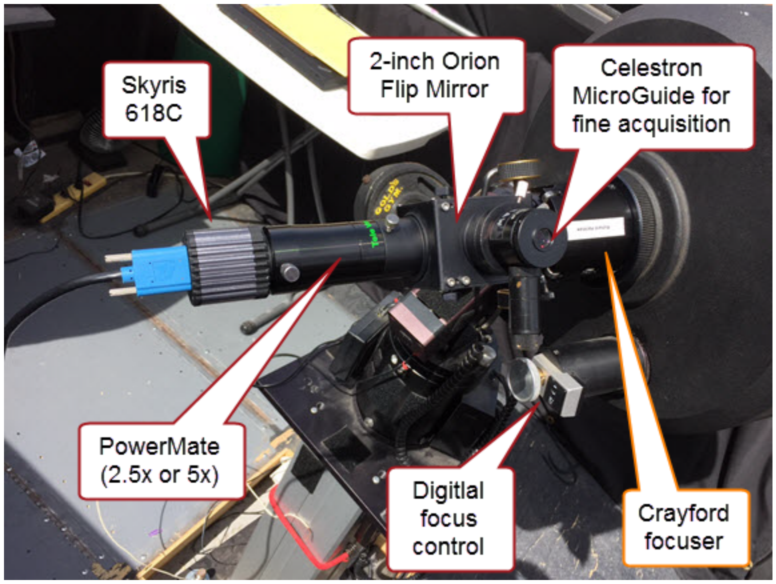

Figure 1. The setup of the C-11 for speckle.

Target acquisition was made by using a 32mm Plössl eyepiece on the flip mirror's acquisition leg. Once the target was centered in this eyepiece, it was replaced with a Celestron MicroGuide for final centering. Once the target was at the center of the MicroGuide, the mirror was flipped and the starlight sent to the camera.

Measures at f/10 were obtained without a PowerMate in the optical train. Measures at f/25 were taken with a 2.5x PowerMate in the position shown in Figure 1, and f/50 measures were obtained with a 5x PowerMate.

FireCapture (by Thoren Edelmann, available as a freeware / shareware program from his website, *http://firecapture.wonderplanets.de/*) was used for camera control.

REDUC by Florent Losse (available as freeware by contacting the author at florent_losse@yahoo.fr) was used to determine camera angle. The target star is centered on the camera chip. A momentary switch to disable power to the RA drive motor of the telescope was depressed, allowing the star to drift to the west. It was noted which direction this is on the computer screen, and the drive motor repowered. The star is then moved to just off the east side of the chip, FireCapture started, and the drive motor disabled, letting the star drift across the camera field of view. When the star exits the field, the drive motor is repowered.

REDUC allows one to easily determine camera angles much the same way that using an astrometric eyepiece on a Dobsonian telescope works—the rotation of the earth takes the star from exactly east to exactly west, independent of any polar alignment errors in the mount. See Figure 2 for a sample camera angle determination.

For data reduction and final measurements, Plate Solve Version 3.33 by David Rowe (PlainWave Instruments) was used.

In addition to the equipment described thus far, three transmission diffraction gratings were used of different slit/bar widths ("pitch"). Figure 3 shows the three gratings used.

The 6mm and 12mm gratings were made from 0.032" aluminum sheet and precision cut with a water jet (CSC process) at a local machine shop. The 18.8mm grating was made by gluing two Bahtinov masks together (discarding the slanted slits).

Image files were copied to a 2 TB external hard drive connected to a Lenovo W950 laptop computer.

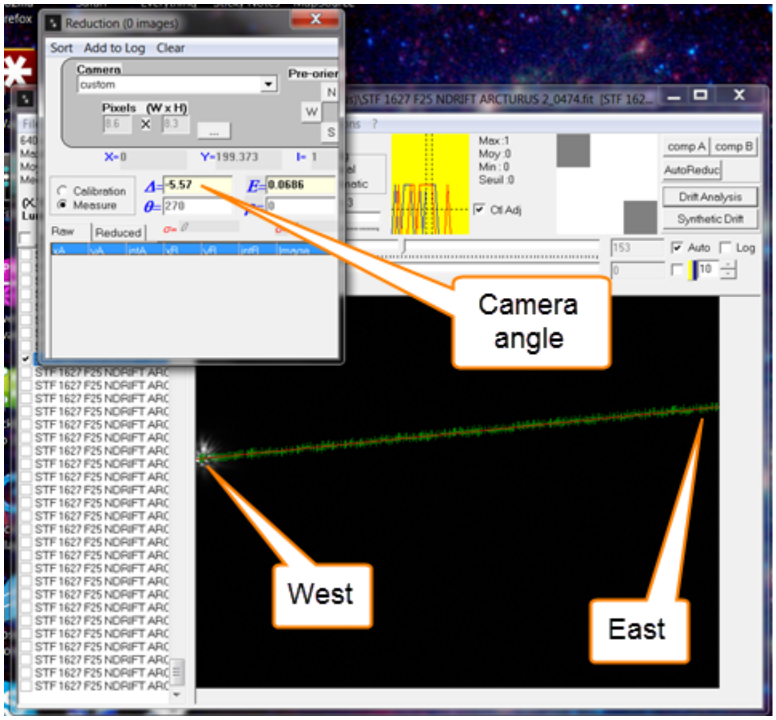

Figure 2. A typical drift analysis by REDUC.

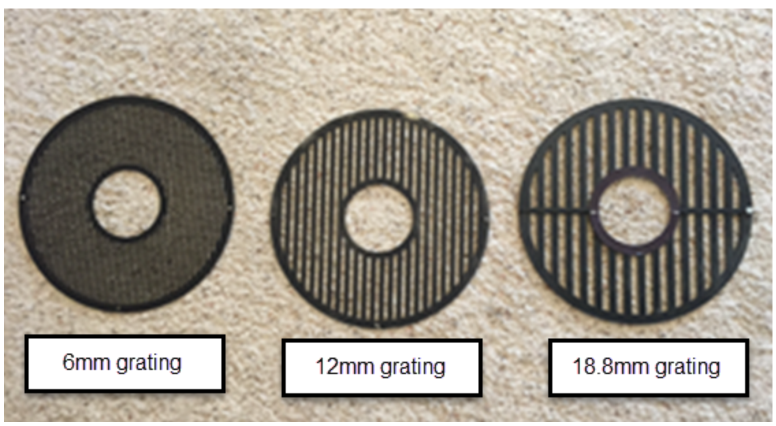

Figure 3. The three gratings used for calibration.

First Test: Drift Calibrations

A well-known expression exists for correlating the camera's pixel scale (defined as the number of arcseconds each pixel of the camera measures) to the telescope's focal length and is given by

$$E = \frac{P_{um}\ x\ f}{206.5}$$

where E is the pixel scale, P_{um} is size of the camera pixels in microns, f is the telescope's focal length, and 206.5 is a constant that converts radians to degrees. For telescopes with well-known focal lengths (such as those custom built for observatories), this approach is satisfactory.

But for an SCT, which achieves focus by moving the primary mirror, the f-ratio is not constant. The published value given by a manufacturer is the mean the engineers design for, but any one factory-produced telescope may have actual focal ratios that can vary by several millimeters from the published value.

For wide-field imaging, this poses no problem. But for speckle interferometry, where even a calibration error of 0.1 seconds of arc can lead to unreliable results, this approach is simply not usable. The first attempt at calibration was with a series of star drifts across the eyepiece, a similar approach being used for the Skyris after Iverson and Nugent (2015). The test consists of placing a star off the east edge of the camera field of view and letting it drift across the total field. A count of the number of frames between the entrance and departure of the star is made. FireCapture writes a text file for each exposure detailing the exact length of the exposure, so knowing the exposure length and number of frames exposed, one can easily compute the milliseconds per frame. Knowing this, and the number of frames between entrance and egress, and the pixels between the entry and egress points, one can calculate the field diameter using this expression:

$$FOV = \frac{T_t\ x \cos(\Delta) * 1.0027379}{4}$$

FOV is the field of view diameter in arc seconds. T_t is the transit time in seconds, Δ is the star's declination, and 1.0027379 is a constant that converts sidereal time to solar time. The result is then divided by the number of pixels along the transit path to determine the pixel scale.

Eighty transits of bright stars were made (Rigel, Betelgeuse, Sirius, and Arcturus) and results averaged. Standard deviations were computed for each focal ratio and standard errors calculated. Any measurement that was more than three standard deviations from the mean was discarded (five such measures had to be deleted). The pixel scale derived from these tests is shown in Table 1.

F ratio	Mean "E"	St. Dev.	St. Error	Data points
25	0.162"	0.004"	0.0008"	28
50	0.076"	0.005"	0.0001"	47

Table 1. Pixel scale from drift tests.

These results were then tested with two "calibration pairs." (Calibration pairs are stars that are members of the U. S. Naval Observatory's "Calibration Candidates" as given at this web page: *ad.usno.navy.mil/wds/orb6/orb6c.html.* However, please note the disclaimer by the U. S. Navy: "Caveat emptor!") While calibration binaries may produce adequate results for traditional astrometric methods such as micrometers and CCDs, they may produce misleading results for such high precision systems as speckle.

Data was taken on Gamma Leonis and Gamma Virginis, both members of the Calibration Binaries list. The results of the measures are shown in Table 2.

		Predicted Values		Measured		Residuals	
Star	Date	Theta	Rho	Theta	Rho	Theta	Rho
γ Leo f/25	2015.241	126.2°	4.627"	128.1°	4.873"	+1.8°	+0.246"
γ Vir f/50	2015.241	6.6°	2.230"	9.8°	2.456"	+3.2°	+0.226"

Table 2. Results of measuring Rho with the drift pixel scale.

The residuals are out of line for such small values of rho, so it was decided that the drift method was not satisfactory. The reason for the discrepancies will be covered in the Discussion section.

Second Test: Series of CPM Stars

For the next test, it was decided to select 14 common proper motion stars (CPM stars) that met these criteria: 7 of them must be good f/25 candidates and 7 of them good f/50 candidates. In all cases, stars were chosen that had shown no significant motion in almost 200 years of observation (especially in the last 100 years). Each star chosen was selected based on a graphical plot of its measurement data (obtained from the U. S. Naval Observatory), using a spreadsheet written in Excel.

This spreadsheet allows the user to enter the measurement histories of double stars in the text format in which the data is sent from the Naval Observatory. The spreadsheet adjusts values of theta for precession, and plots the measurements on an X-Y coordinate plane. Figure 4 shows a typical case.

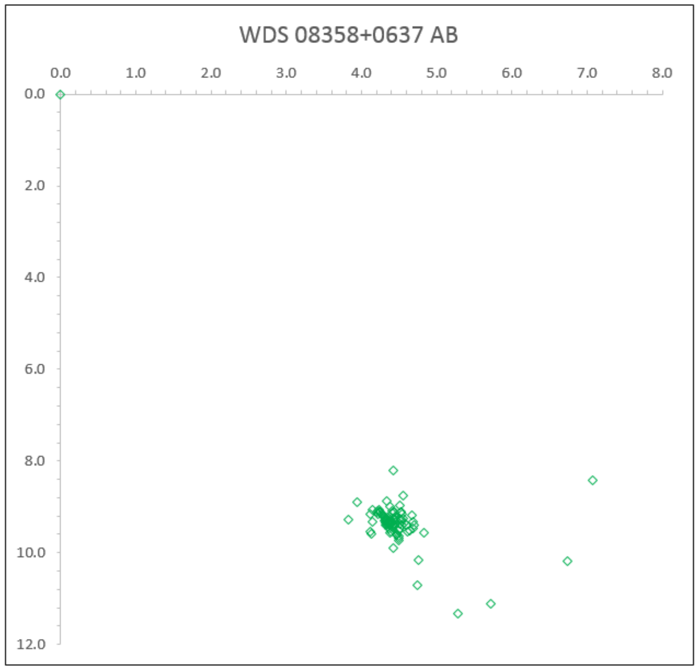

Figure 4. Typical CPM pair measurement plot of stars chosen for tests. The scale is in arc seconds.

None of the pairs chosen were speckle candidates as they were all too wide in separation to qualify. (Speckle stars should be 5" or closer to each other.) However, by using the Skyris as a CCD and carefully analyzing the results with Plate Solve, it was possible to establish a value for the camera pixel scale. The results of these 14 tests are shown in Table 3. These results are significantly different than the drift tests and confirmed suspicions about the drift tests.

Focal ratio	f/25	f/50
	0.156"	0.069"
(Drifts)	*0.162"*	*0.076"*
(Deltas)	*+0.006"*	*+0.007"*

Table 3. Results of CPM Star Tests.

Transmission Diffraction Grating Tests

The transmission diffraction gratings shown in Figure 3 were designed to fit over the secondary mirror mount of the C-11 and rest on top of the retainer ring for the corrector plate. The slit spacing (or "pitch") was determined for each grating by counting 20 pairs of bars and slits (10 for the Bahtinov grating) and measuring that distance with a high-precision machinist's rule marked in mm. The results were divided by 20 (or 10 for the Bahtinov).

The grating is based on Thomas Young's famous double slit experiments of 1803. Stars viewed through such a grating produce a bright central image flanked by "ghost" images of 1st, 2nd, 3rd order (etc). See Figure 5. A slit experiment works best with monochromatic light, and since no star emits light of one wavelength, the trick is to get a broad-spectrum light source to behave as a monochromatic source. The solution, of course, is narrow-band filters.

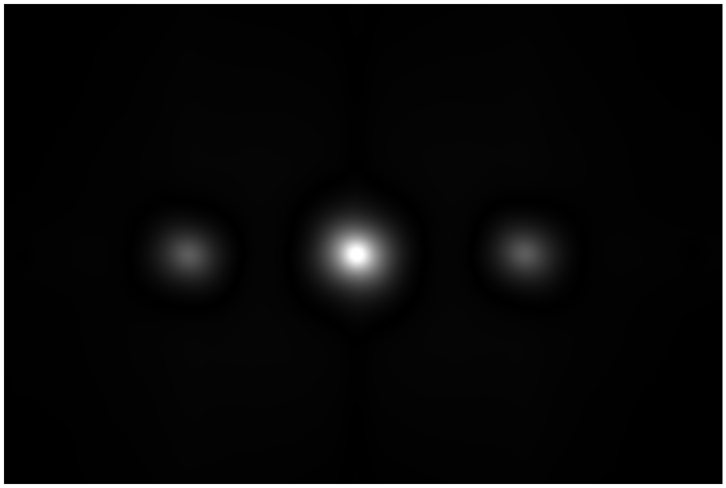

Figure 5. Typical Main and n-order images through a grating.

When the grating tests were begun, an O-III filter was used, as it was the narrowest band-pass filter available at that time. But the results were so far off from what the CPM tests had shown, they were rejected outright.

An H-Alpha filter was then obtained from a local fellow astronomer (David Douglass) and used to produce acceptable light for the tests. In this way, 60 images of Arcturus were made allowing for a high confidence / low standard error result. Two tests were run using the 12mm grating, and one test each with the 6mm and Bahtinov gratings. The results are shown in Table 4.

Test	Value of "E"	Std. Dev.	Std. Error	Measures
f/25, 6mm	0.154"	0.014"	0.004"	40
f/25, 12mm (1)	0.156"	0.230"	0.059"	40
f/25, 12mm (2)	0.156"	0.082"	0.026"	10
f/25, Bahtinov	0.155"	0.053"	0.012"	20
f/50, 6mm	0.069"	0.146"	0.038"	40
f/50, 12mm (1)	0.069"	0.092"	0.024"	40
f/50, 12mm (2)	0.069"	0.043"	0.010"	20
f/50, Bahtinov	0.068"	0.057"	0.018"	10

Table 4. Results of diffraction grating star tests.

Green Laser Field Test

One final test remained to be done to solidify the calibration results. This test consisted of using a green laser reflected off a convex mirror to generate an artificial star of 532nm wavelength and was inspired by a copy of a personal note from Andrei Tokovinin of the Cerro-Tololo Inter-American Observatory to Russell Genet (2013) regarding use of a laser to calibrate a camera.

This test involved the fabrication of a convex mirror affixed to a piece of plywood painted flat black and mounted on a steel pole that could be pounded into the ground, letting the telescope be set up some distance away (Figure 6).

Figure 6. The convex mirror target for the laser tests.

This mirror, along with the C-11 and field mount, was taken to a flat desert location and set up 0.72 miles (1,159 m) from the telescope. With the help of two local astronomy students, a green laser was placed on a stand about 3 meters from the mirror and turned on. The images at the telescope were recorded. The results are shown in Table 5.

Test	Value of “E”	Std. Dev.	Std. Error	Measures
f/25, 12mm laser	0.156"	0.161"	0.042"	20
f/50, 12mm laser	0.069"	0.019"	0.005"	20

Table 5. Results of the Green Laser Test.

Summary of All the Calibration Methods

Table 6 presents the results of all the calibration tests. In the table, the weight refers to the confidence placed in the method as a determinant of the final calibration.

Discussion

You will note from Table 6 that no weight was given to any of the drift tests or the O-III filter tests.

The drift tests were initially done to replicate the work of Iverson and Nugent (2015). But it was discovered that even a tool as useful as REDUC can be in determining pixel scale, the method itself has drawbacks. First, when one works at f/25 or f/50, star images dance around on the camera chip. On some nights, this dance could describe an area nearly 5" in diameter! At high magnifications, a sudden jump could mean dozens of pixels. Trying to determine when a star actually enters the camera’s field of view (and not merely choosing an early “jumper” as the starting point), or egress frame, is difficult at best. Even though the frame selection was varied within the same AVI file to help eliminate these errors, it was simply not possible to get consistent results (as evidenced by the large standard error). No doubt it works well for CCD calibration, but speckle is a whole order of magnitude more demanding.

It is not necessary to get the camera precisely oriented along the east-west axis of the sky, since REDUC provides an X-Y readout of each star’s position for each frame. Knowing the X-Y positions of the starting and ending stars allows one to easily calculate the total traverse by finding the hypotenuse of the subtended triangle.

F Ratio	Method	Value of "E"	Weight	Wtd Total	Wtd Mean
10	12mm H-Alpha	0.375	4	1.5	**0.375**
	18.8mm H-Alpha	0.372	4	1.488	
25	Star drift	0.162	0	0	**0.154**
	γ Leo	0.141	2	0.282	
	6mm H-Alpha	0.154	4	0.616	
	12mm H-Alpha	0.156	4	0.624	
	18.8mm H-Alpha	0.155	4	0.620	
	7 CPM Pairs	0.156	3	0.468	
	12mm O-III	0.092	0	0	
	12mm Laser	0.156	4	0.624	
50	Star drift	0.076	0	0	**0.069**
	γ Vir	0.069	2	0.138	
	6mm H-Alpha	0.069	4	0.276	
	12mm H-Alpha	0.069	4	0.276	
	18.8mm H-Alpha	0.068	4	0.272	
	7 CPM Pairs	0.069	3	0.207	
	12mm O-III	0.041	0	0	
	12mm Laser	0.069	4	0.069	

Table 6. Summary of all the calibration methods.

The O-III filter tests were discarded because the 100nm or so wide band pass of the filter made the images of the star and its n-order offspring too spread out for Plate Solve to do an accurate job of determining the centers of each point spread function. It also appears that the O-III filter "leaked" light at other bandwidths as there were ghost images scattered between the 0, 1, 2… n order (bright) images. The calibration pairs tests were given moderate weight in keeping with the Naval Observatory's "Caveat emptor!" warning.

A much higher trust level was placed with the CPM pairs in this study, knowing that if a pair has not significantly moved in over 100 years (and especially the last 50), it would likely remain relatively fixed in the year or so since last measurements.

The H-Alpha and green laser tests yielded the highest level of confidence due to their extremely small standard deviations and standard errors and led to the conclusion that the best method to calibrate a CCD for astrometry is to use a transmission diffraction grating and a narrow band-pass filter (such as an H-Alpha) or green laser (532nm). Due to the inconsistent output of most red lasers, it was decided to avoid a red laser test for the same reason the O-III filter was rejected.

Acknowledgments

This research has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory. The author wishes to thank Russell Genet, David Rowe, and Vera Wallen for editorial assistance and review of the manuscript; Mike Collins of Phoenix, Arizona for procurement of the aluminum gratings; David Douglass of Tempe, Arizona for use of his H-Alpha filter; Ethan and Randall Wuthrich, Kyle Dolbear, and Gary Mason for their assistance with the green laser tests in the desert; Jack Drummond for his Orbit Prediction spreadsheet; and Bob Buchheim for his assistance in preparing an Excel spreadsheet for the analysis of the data generated by the transmission grating tests.

References

Genet, R. M. 2013. High speed astrometry of STF 2848 with a Luminera camera and REDUC software. *Journal of Double Star Observations*, 9, 2, 124-129.

Iverson, E. & Nugent, R. 2015. Reaching magnitude +16 with the modified video drift method. *Journal of Double Star Observations*, 11, 2, 128-134.

Laberyie, A. 1970. Attainment of diffraction limited resolution in large telescopes by Fourier analysing speckle patterns in star images. *Astronomy and Astrophysics*, 6, 85-87.

Losse, F. April 2015. REDUC data reduction software. Downloaded via http://www.astrosurf.com/hfosaf/uk/tdownload.htm.

Rowe, D. Plate Solve 3.33 speckle analysis software. Downloaded from author.

Teiche, A., Genet, R. M., Rowe, D., Hovey, K., & Gardner, M. 2014. Automated speckle interferometry of double stars. *Journal of Double Star Observations*, 10, 4, 342-245.

Tokovinin, A. April 2013. Speckle calibration with laser. Private correspondence.

Wiley, E. O. 2013. A pixel correlation technique for smaller telescopes to measure doubles. *Journal of Double Star Observations*, 9, 2, 142-152.