The Speckle Toolbox: A Powerful Data Reduction Tool for CCD Astrometry

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Abstract: Recent advances in high-speed low-noise CCD and CMOS cameras, coupled with breakthroughs in data reduction software that runs on desktop PCs, has opened the domain of speckle interferometry and high-accuracy CCD measurements of double stars to amateurs, allowing them to do useful science of high quality. This paper describes how to use a speckle interferometry reduction program, the Speckle Tool Box (STB), to achieve this level of result.

For over a year the author (Harshaw) has been using STB (and its predecessor, Plate Solve 3) to obtain measurements of double stars based on CCD camera technology for pairs that are either too wide (the stars not sharing the same isoplanatic patch, roughly 5 arc-seconds in diameter) or too faint to image in the coherence time required for speckle (usually under 40ms). This same approach - using speckle reduction software to measure CCD pairs with greater accuracy than possible with lucky imaging - has been used, it turns out, for several years by the U. S. Naval Observatory.

1. Introduction

The new generation of low-cost and high-performance CCD and CMOS cameras has revolutionized amateur astro imaging, especially in the area of visual double star astrometry. As far back as the early 1990's, amateurs were using web cams to make measurements of bright double stars with surprising accuracy using the X, Y coordinates of the star image centroids (often chosen manually) and simple Cartesian mathematics.

But the advent and availability of low-cost CCD cameras (and later CMOS cameras) allowed for a complete sea change for this aspect of amateur double-star astronomy, as it was now possible to image truly faint and challenging pairs. When merged with the new data reduction software coming into the market, amateurs had at their disposal powerful tools for the collection of double star data and its accurate reduction to meaningful measurements.

Most recently, advances in software that enable data reduction via Fourier Transforms that run on desktop computers have pushed the limits of where amateurs can do useful research even further out in terms of magnitude and resolution. Prior to this development, measurements of double stars using CCD images (and later CMOS images) had to be done with a process known as "lucky imaging." Lucky imaging is a method that begins with a very large number of frames shot at an integration time (shutter speed) that is as short as possible to help "freeze" the star image during moments of superb seeing. This file of images is then processed by selecting a small percentage of the best frames based on different criteria - best signal-to-noise ratio (where frame selection is based on the ratio of the signal-to-noise versus star density and is best used on noisy frames), or best maximum (where frame selection is based on the strength of the central concentration of light in the star's image, best used with low-noise frames and files with small star images). There may be other options available, depending on the software package used to select the frames used for a lucky image.

Once the frames have been selected, they can be "aligned and stacked", meaning the software will re-center each frame based on the centroid of the primary star. All selected frames are then blended into one final image, which often shows very clean stars that are easy to measure.

However, lucky imaging suffers from the fact that it is very difficult to use with accuracy on very close pairs (closer than about 5 arc seconds) or where one (or both) of the stars is bright, resulting in large star images that may overlap or in which it may be difficult to determine the centroids. Yet this is the domain where most of the interest lies in visual double star astrometry. It also requires fairly bright stars in order to get shutter speeds fast enough to freeze the star images.

This is where speckle data reduction software can be of immense help. Over the last 16 months, I have been gathering data on hundreds of double stars (with these observations being reported in this Journal) using two cameras—a Skyris 618C color CCD, and most recently, the ZWO ASI290 monochrome CMOS camera. I have been reducing my data and making measurements using a speckle reduction program written by David Rowe, chief technical officer at PlainWave Instruments. The original program provided to me by Rowe was called Plate Solve 3, and was a robust multi-purpose program that did many things besides speckle reduction. About six months ago, Rowe released a special sub-set of Plate Solve, called Speckle Tool Box (STB for short in this paper). I will describe in this paper how to use STB to do accurate astrometry on close double stars, whether with speckle interferometry or CCD imaging, and explain how to obtain a free copy for use in your own observing program.

If you have ever requested data from the Washington Double Star Catalog for a particular pair of stars, the reply you got included a text file titled "datarequest_key". If you read that file, you will find a translation key for the methods used to report measurements. Two of those codes are Cu and Su, which are described in the datarequest_key file as "USNO CCD imaging (speckle-style reduction)." (The C and S refer to two different cameras used for the data collection.) Wanting to be sure if this method was like the one I have been using, I wrote Brian Mason at the USNO and asked him about this method. It is, indeed, the method I have been using, in which a CCD image of a double star is analyzed using speckle reduction software in order to obtain more precise measurements than possible with lucky imaging.

Mason (2007) writes, "Most of the systems observed with this camera (the "Cu" camera at the U. S. Naval Observatory in Washington, D. C.) have separations well beyond the regime in which there is any expectation of isoplanicity, so we classify the observing technique for all of these measures as just "CCD astrometry," rather than speckle interferometry. Despite this classification, there is an expectation that the resulting measurements have smaller errors than classical CCD astrometry. Each measurement is the result of many hundreds of correlations per frame, and up to several thousand frames per observation."

2. How Speckle Reduction Software Works

The Speckle Tool Box does speckle reduction by working on a FITS cube. A FITS cube is a set of FITS images bound into a single file. Normally, one should use several hundred to several thousand FITS images and bind them into a FITS cube. Since most camera control software simply captures FITS images and does not bind them into cubes, STB does that for you (I will explain the menu of processes later).

Once the FITS cubes have been compiled, it is best to pre-process the cubes. This is not a requirement in STB, but it does make for much faster solutions when it is time to do the speckle reduction. Pre-processing consists of STB reading each frame in the FITS cube and then computing its power spectrum using a Fourier transform and then taking the squared modulus of each complex pixel value. The frames are then averaged and saved as a file with a special suffix (_PSD) added to the file name.

During speckle reduction, a processed file is loaded into STB and the power spectrum is then graphically displayed on screen as an *autocorellogram*. See Figure 1.

Note that the autocorellogram displays radial symmetry. It is *not* an actual image of the double star, but rather a graphical portrayal of the two-dimensional autocorellation of the averaged power spectrum. The symmetric nature of the display results from the fact that autocorellation of any real function is inherently sym-

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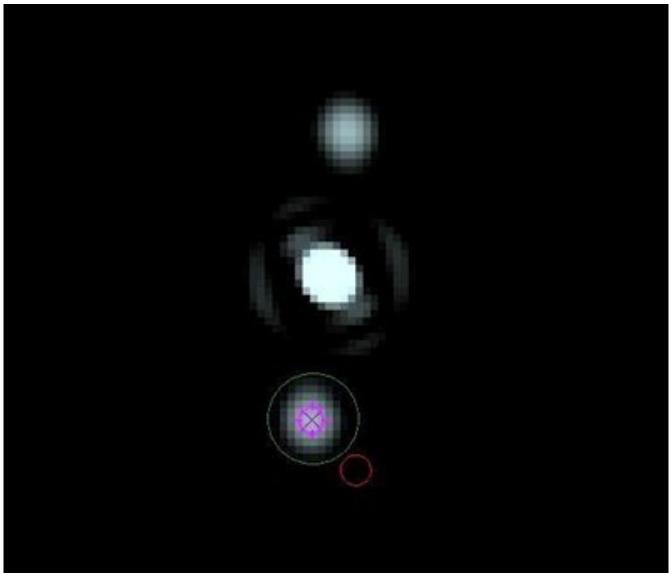

Figure 1. An autocorellogram generated by STB.

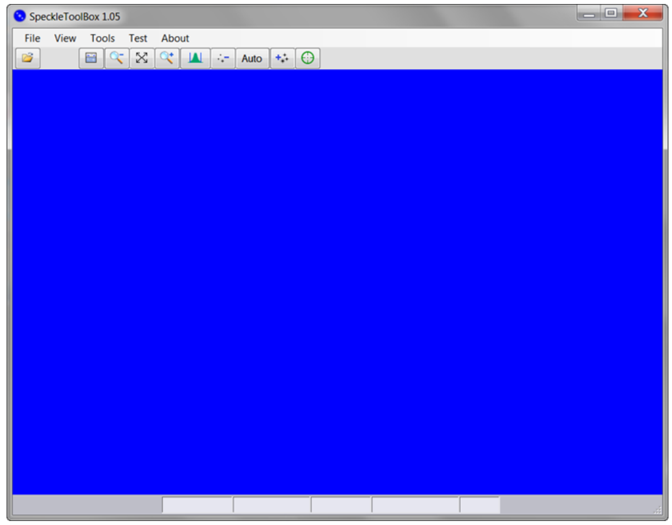

Figure 2: The home screen of The Speckle Toolbox

metrical. Rowe is working on a new feature for STB that can generate a recovered, high-resolution image by a method called Bispectrum analysis, which is extremely demanding on the computer's processor, normally requiring a special co-processor to be installed to allow the program to generate a solution in a reasonable amount of time. (Currently, bispectrum analysis is done mostly on high-speed mainframes, where it is still a time consuming process.)

So how does one use STB to generate autocorellograms that can then be measured with higher precision that lucky imaging?

3. Using The Speckle Tool Box to Make FITS Cubes

The Speckle Tool Box home screen is shown in Figure 2.

At the top of the screen is a list of commands and below that, a palette of tool icons. I will explain each part of STB in detail and show how each part contributes to an astrometric solution.

To make FITS cubes, click on TOOLS, then from the drop-down menu, select "Make FITS cube(s)…" A dialog box will appear, as shown in Figure 3.

The instructions in the "Operation" window detail how to select files for binding into Cubes. STB allows you to specify whether the original files are monochrome or color and even allow the user to crop the files to a uniform size. Since STB works best on images that have dimensions that are a power of two (256 x 256 and 512 x 512 being the norms), this is an important feature.

4. Doing a Drift Calibration with STB

A drift calibration is done by clicking on TOOLS and selecting "Drift Calibration Analysis…" This opens a powerful feature of STB: a simple way to determine the camera's angle with reference to true north as well as the pixel scale for the camera (how many arc seconds each pixel spans).

To obtain drift files for analysis, you must select a bright star near the meridian and at a medium declina-

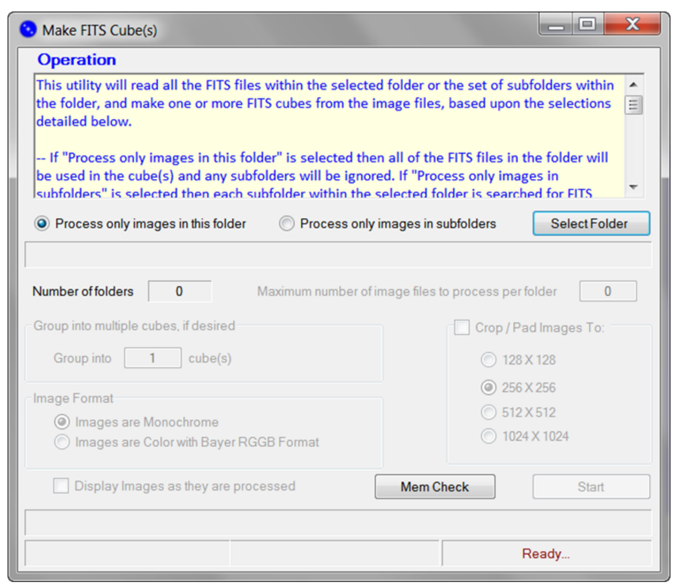

Figure 3: Dialog box to make FITS cubes

tion (between 30° and 60° works best, but any declination will work). Jot down the declination of the star for use later.

Use the telescope's slow motion controls to nudge the star just off the east edge of the camera chip (you may have to temporarily cut power to the polar axis drive motor to see which way the star drifts). Then (1) start recording the file and (2) kill power to the drive motor. When the star drifts off the west end of the chip, (3) stop the recording and (4) re-power the drive motor.

Use the slow motion controls to return the star to just off the east edge of the chip and repeat the process. I suggest you do at least 12 drifts, and more is even better. (I normally use 20 drifts when calibrating my system.)

Figure 4 shows the dialog box that starts the drift analysis process.

This window is very important and requires considerable user input, so I will cover it step by step and illustrate with an actual drift analysis.

The area tagged "1" in the red circle (Callout 1) is where you enter the maximum number of frames to use for the analysis. The default is 1,000 but you may specify any number you wish. For instance, if you have a camera chip whose long axis is east-to-west and you are shooting at very short integration times (which I recommend), you may well have over 1,000 frames in the drift file, so feel free to set the maximum at whatever level you think is best. STB will use only as many frames as the file contains, so if you set the value high, no harm is done.

Step 2 is indicated by Callout 2 and it and is where you select the drift file you wish to analyze. In my practice, I use an external USB hard disk drive on my observatory's computer and save my drift files to it. Once my observing session is finished, I power the computer down and take the USB drive into the house for analysis the next morning.

Callout 3 allows you to tell STB to not start analyzing the frames until some length of time into the file. I usually enter 0.2 seconds in this window in case my camera control software has a stutter when it starts capturing frames.

At Callout 4, you enter the declination of the drift star, leaving spaces between the degrees, minutes and seconds (dd mm ss).

We suggest you check the box by Callout 5, Reject Outliers, and set the rejection at 2 sigmas. This makes for a very tight band of acceptance of data points and improves the accuracy. (With a value of 2, all centroid positions more than 2 standard deviations from the RMS line of the drift are ignored in the calculation.)

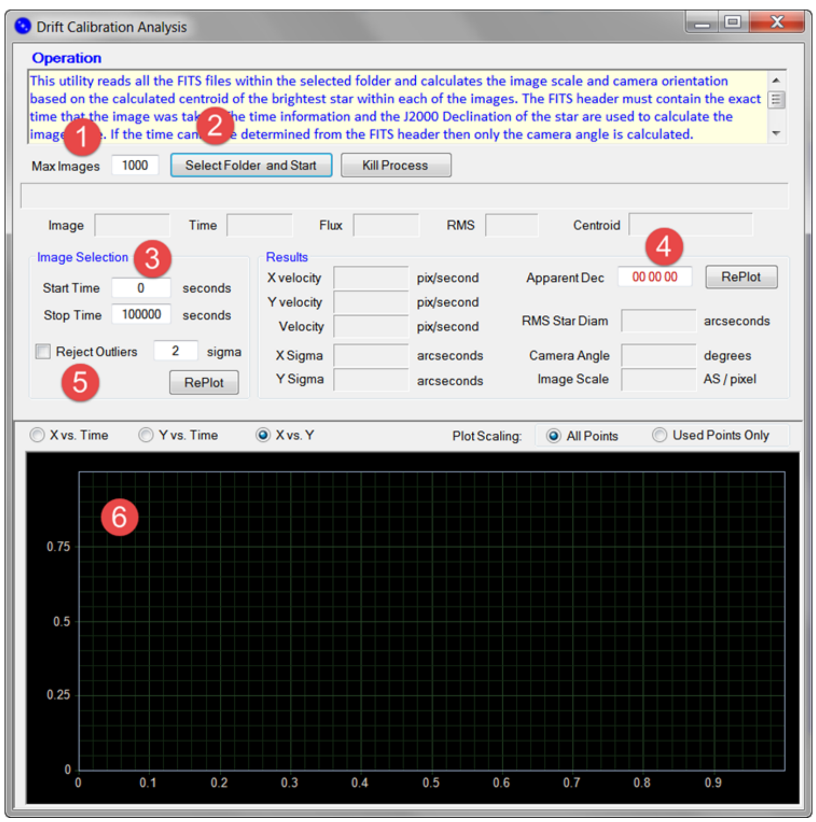

Figure 4: The Drift Analysis dialog window

Callout 6 is where STB displays its results and the final drift line.

Figure 5 shows the Drift Analysis window active with a drift file we captured of the star Regulus:

The numbered callouts in the window show (1) the maximum number of frames I used, (2) the start time of 0.2 seconds into the file, (3) the declination of Regulus, (4) rejection of outliers more than 2 sigmas from the mean, (5) the RMS diameter of Regulus in arc seconds, (6) the camera angle (with respect to true north), and (7), the pixel scale in arc seconds per pixel.

Since we did this drift with Regulus just west of the meridian (and the OTA on the east side of the mount), the camera angle shows -176.73°. Its actual orientation must be set by adding 180° to this to obtain 3.27°. With the OTA on the west side of the mount, the camera angle given by STB is the camera angle to use for measurements. But note that if you cross the meridian with your OTA (doing the notorious meridian flip), you'll need to add (or subtract) 180° to the camera angle for stars measured on the opposite side of the mount as the side on which you captured the drifts.

An Excel spreadsheet lets us input the results of each drift analysis to compute the mean, standard deviation, and standard error. (We find that beyond 25 drifts, the mean, standard deviation and standard error change very little, which is why we normally do 20 or so drift files for calibration purposes.)

The RMS diameter of the star (Callout 5) is a rough indication of the quality of the seeing for the drift observation, as the poorer the seeing, the larger the star's image. However, this value is also very dependent on the star's magnitude and the camera integration time. It is therefore a relative indicator of seeing, and experience will let you determine what sort of seeing you will have for the night based on the RMS diameter of the star.

This method is fast and accurate, normally only taking the first 20 or 25 minutes of an observing session (unless the camera was not moved from the last session, in which case you do not bother doing a drift).

5. Processing FITS Cubes

From the TOOLS menu, select "Process FITS Cubes…" to pre-process the data. This results in smaller file size and faster processing during speckle reduction of the images. The Process FITS Cubes dialog window is shown in Figure 6.

Begin by clicking the button by Callout 1. Clicking this button opens the computer's file directory from

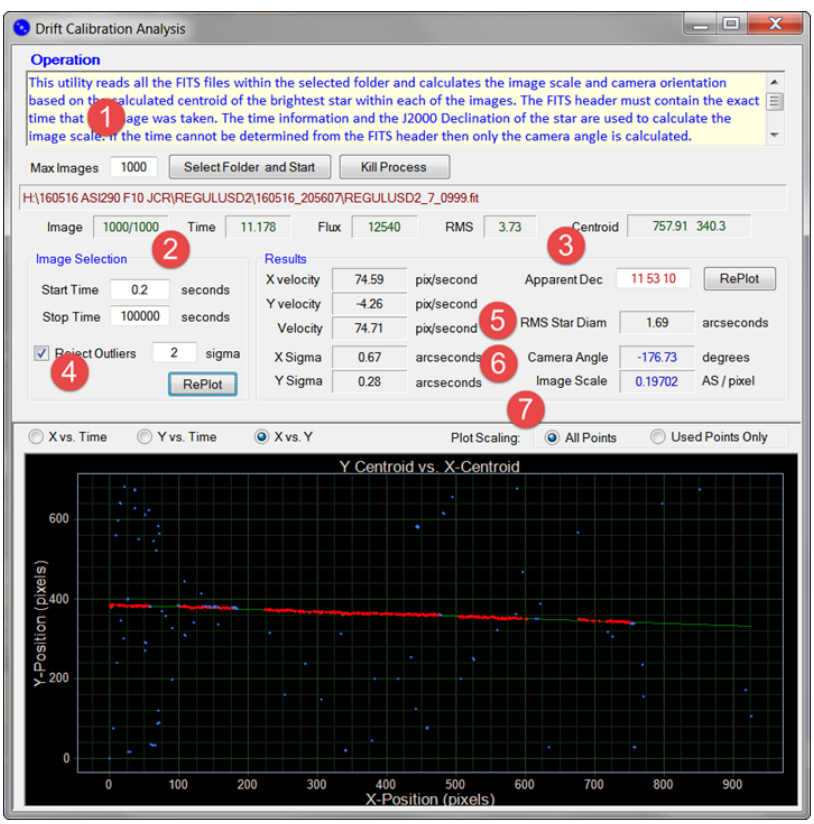

Figure 5: Drift Analysis using Regulus at f/10

which you may navigate to where you have stored the FITS cubes you wish to analyze. You may process one cube at a time or do a batch process on as many cubes as you wish.

If you want the processed cubes to be saved in a separate folder (which I always do, as I found that it makes it easier to locate them later), click the box next to Callout 2 and then use the browse button (Callout 3) to locate the folder you want the processed files to be stored in. If needed, create the folder.

You are then ready to begin processing. Click the Process button (Callout 4) to begin. STB will then display its progress as it opens, reads, and processes each FITS cube you have selected. Depending on the size of your files and your computer's processor speed, this normally takes between five and 10 minutes per 1000-frame cube.

When finished, you may close the Processing dialogue window. If you wish to check that your processed files went to the correct folder, use the Windows Explorer to find the folder you specified and be certain that your processed files are there.

6. Speckle Reduction with STB

Now that you have determined the camera's angle and pixel scale, and have built your FITS cubes and processed them, you are ready to start doing speckle reduction. To do so, use the TOOLS menu and select "Speckle Reduction…". The dialog window shown in Figure 7 will open.

This dialog window is the heart of STB. I will explain its use by first explaining how to generate an autocorrelogram (Callouts 1 and 2). Later, I will explain how to tweak the autocorrelogram using the options under Callout 3.

Figure 8 is the autocorrelogram generated for ARG 24 with no Reference-Star FITS Cube or PSD File selected. (We' ll explain that more in a moment.)

We need to work on this autocorrelogram before we do the measurement. First, it will help to enlarge the image. This can be done using the mouse wheel or by clicking the Enlarge button. The result is shown in Figure 9.

Next, we want to clean up some of the background noise and make the star images a little smaller. This is done by using two different buttons — levels and dimmer.

By clicking on the levels button, the dialog window shown in Figure 10 appears.

Note the slider near Callout 1. We must click the slider and drag it to the right about to the point where the intensity graph flattens out (Callout 2). Figure 11 is how the autocorrelogram looks after doing this.

Notice how the background is now much darker and "cleaner." But we still need to make the star images a bit smaller, so we click on the Dimmer button and end up with an autocorrelogram that looks like that shown in Figure 12.

We are now ready to perform the astrometry functions. We click the astrometry button which brings up the dialog window shown in Figure 13.

We have not actually measured anything yet, but I

(Continued on page 59)

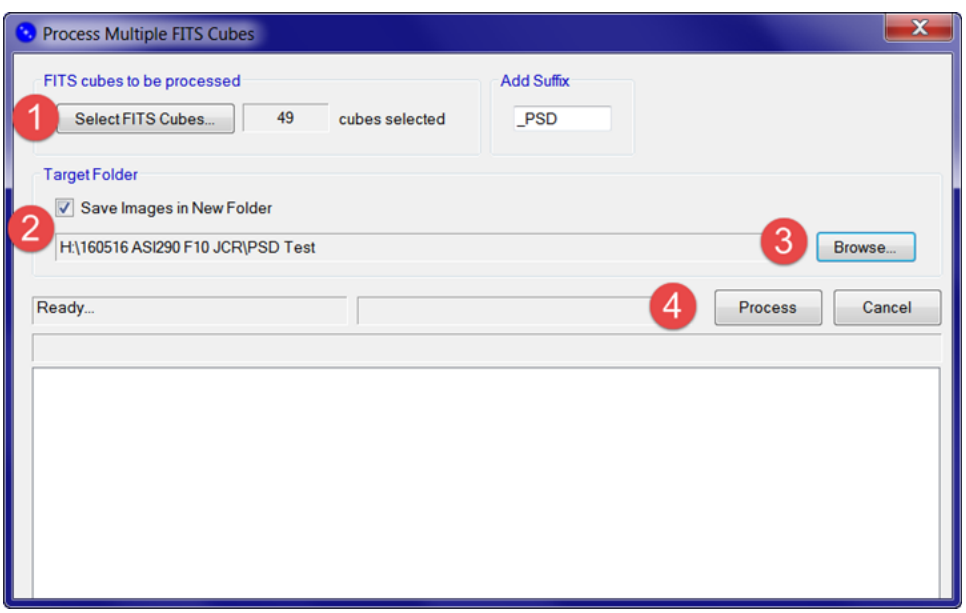

Figure 6: The Process FITS Cubes dialog window.

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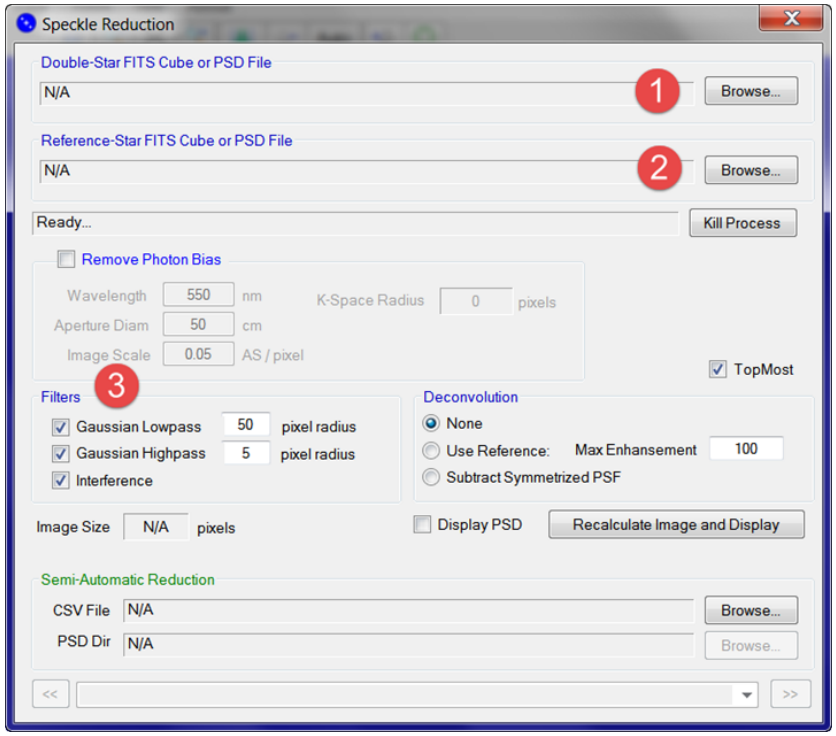

Figure 7: The Speckle Reduction dialog window.

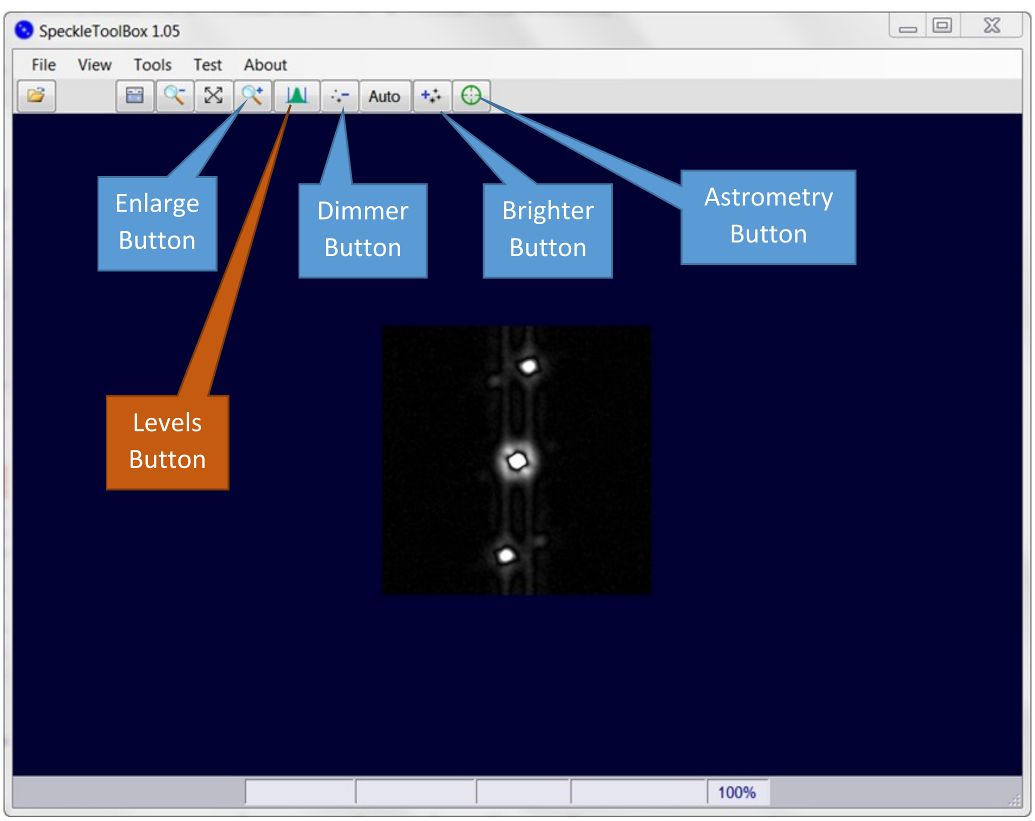

Figure 8: Autocorrelogram for ARG 24, unprocessed.

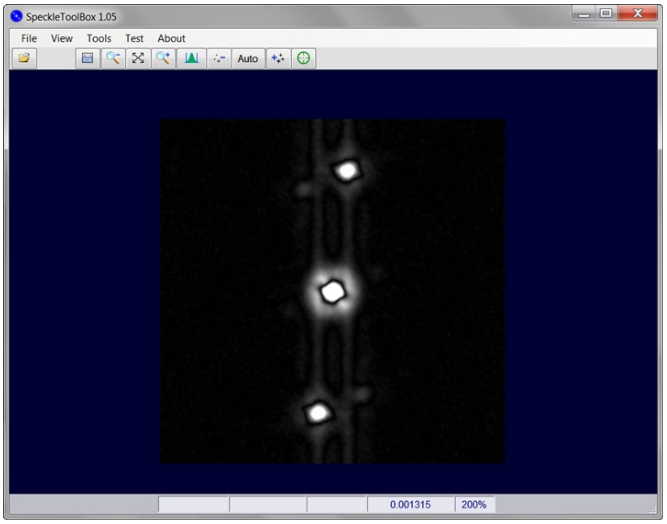

Figure 9: ARG 24 zoomed in.

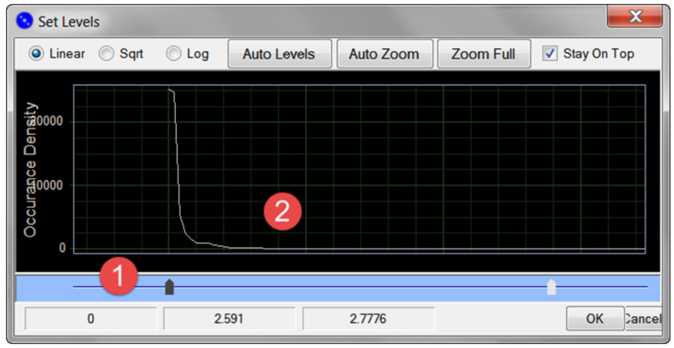

Figure 10: The Levels Button dialog window.

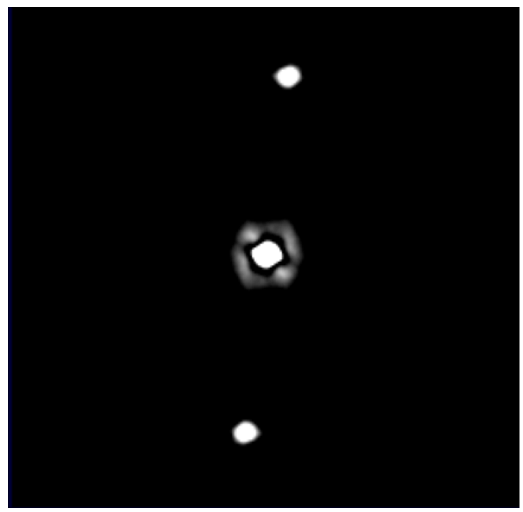

Figure 11: The "improved" autocorrelogram.

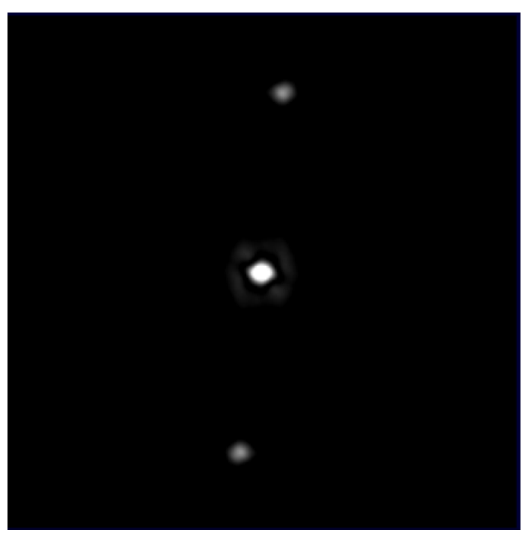

Figure 12: The autocorrelogram after dimming the stars 3x

(Continued from page 57)

did enter the camera angle and pixel scale from the night that I imaged ARG 24 (Callouts 1 and 2) . (We'll explain all of the features on this window but for now let us just focus on making the measurement.)

To obtain the measurement, click the button labeled "Auto Detect". When you do, the autocorellogram will change and look as shown in Figure 14.

It might be hard to see, but there is a small pink colored "ship's wheel" around the star at the top of the frame. Checking the bottom of the astrometry dialog window, we see the measurement made by STB as shown in Figure 15.

Notice that STB found the companion star to lie at a position of Theta = 170.07° and Rho = 17.7113". If we check the Washington Double Star Catalog we will find that the last measure (as of this date) was made in 2012 and had Theta = 350.2° and Rho = 17.57". STB appears to be about 180° off for Theta. This is easy to correct.

At the bottom of the astrometry dialog window is a button labeled "Remove Target". Clicking that removes the pink icon around the companion star. We must now manually indicate the companion star with the mouse. As we move the mouse cursor over the autocorello-gram, we notice that it appears as a small green circle.

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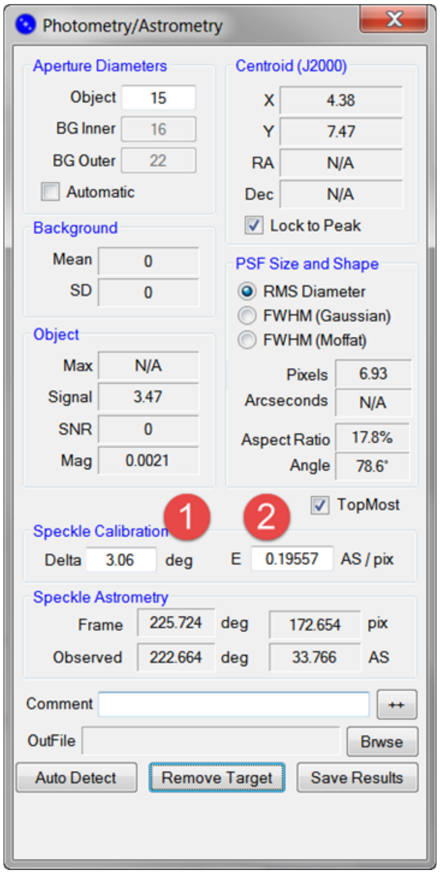

Figure 13: The Astrometry dialog window

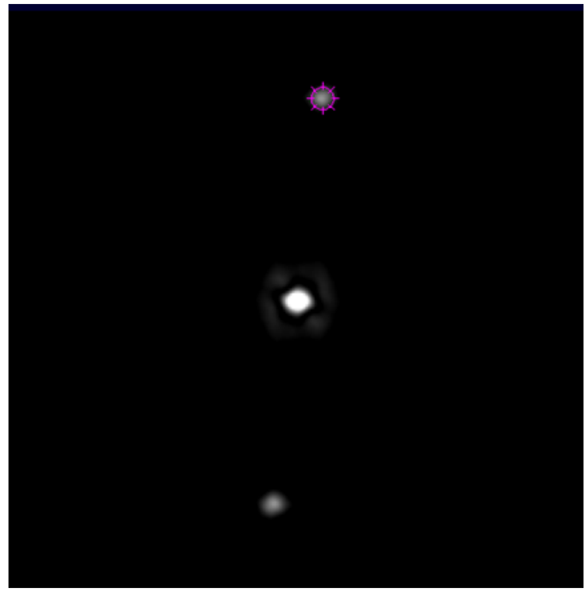

Figure 14: Results of the Auto Detect option.

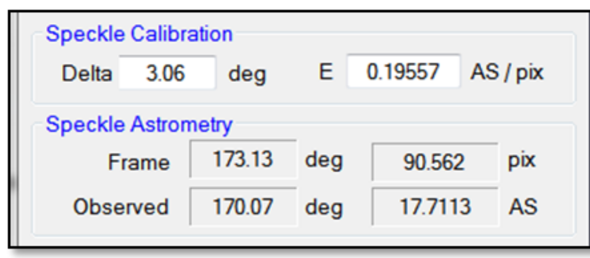

Figure 15: Astrometry results.

When we place the circle over the companion star at the bottom of the frame, the screen will look as shown in Figure 16.

By right clicking at this point a menu will fly out to the right of the mouse with several options as shown in Figure 17.

We want to select the last option on the menu, “Set Target Location.” When we do, the astrometry window will update to the new numbers as shown in Figure 18. These numbers are in close agreement to the 2012 measure and show that over four years, ARG 24 has moved about 0.14° clockwise in Theta and reduced Rho by about 0.1405".

Any time the companion star is at a value of Theta of 180° or less, STB will correctly identify it when the Auto Detect button is clicked. If the companion has a value of greater than 180° for Theta, the companion star will have to be manually selected.

Manual selection can be a tricky process. Figure 19 shows the settings for the Object Aperture used for the solution just derived. The setting for the Object Aper-

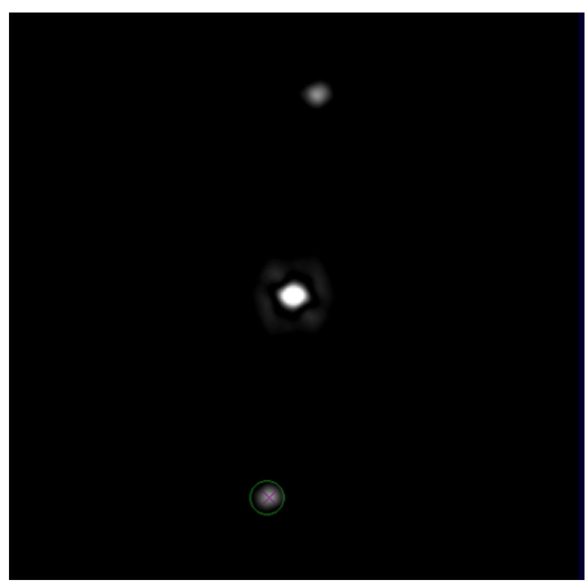

Figure 16: A manually-selected companion star.

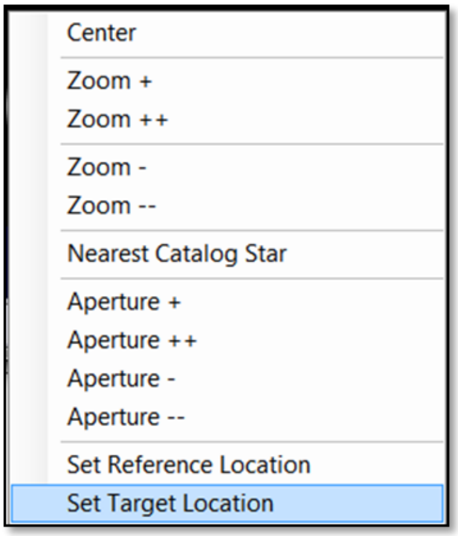

Figure 17: The manual selection fly-out menu.

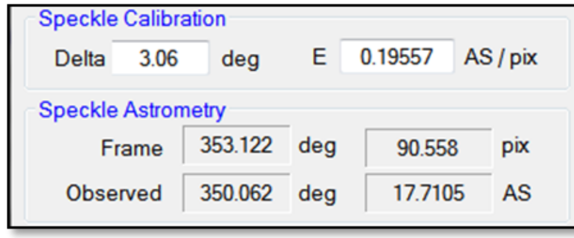

Figure 18: The updated astrometry window.

ture is critical for a good manual solution as well as having as clean an autocorrelogram as possible with star images that are smaller than the Object Aperture.

Note how the setting of 15 creates a selection circle that is larger than the companion star (Callout 2). Figure 20 shows the effect of making the Object Aperture larger while Figure 21 shows the effect of making it smaller.

Note how large the green circle is in Figure 20 — far larger than the companion star image — while in Figure 21 it is much smaller than the companion star. When the Object Aperture diameter is too large, STB may pick up background noise from the autocorrelogram and lead to a faulty solution. Conversely, when the Object Aperture is too small, important information about the precise location of the companion star may be truncated by the selection radius.

Also note that the checkbox “Lock To Peak” is checked. When this is the case, if the Object Aperture is large enough, centering the location circle over the companion star will place an X on its centroid, leading

Figure 19: Effect of Object Aperture on a manual solution (part 1)

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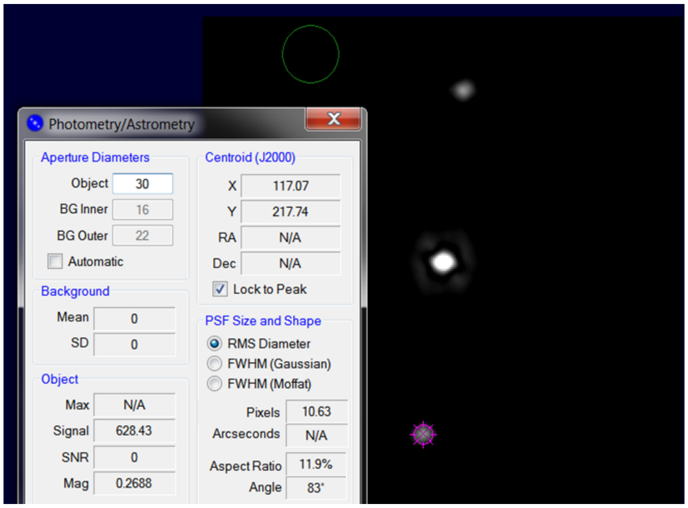

Figure 20: The Object Aperture is too large.

Figure 21: The Object Aperture is too small.

to a more accurate solution.

Sometimes it is not possible to get the background of the autocorellogram totally dark and noise free. (This will be particularly the case for close stars of unequal magnitude.) When that is the case, even with a properly sized Object Aperture, the Lock to Peak function will not work as designed. The noise around the companion star will pull the centroid selection off-center. When that happens, your only option is to clear the Lock to Peak box and manually center the X over the companion star. You will get a solution, but with a trade-off in some accuracy.

Figure 22 shows a pair of stars (STF 233) where the area around the companion is not free of noise.

In a case like this, STB would not be able to lock onto the companion (the star to the left of the primary) because there is too much competing noise. You would have to manually place the selection aperture over the companion with Lock to Peak unchecked, then right-click and select Set Target Location.

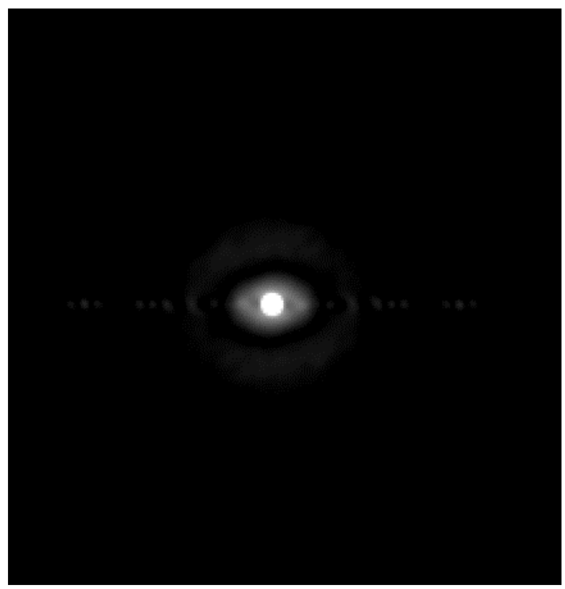

Figure 22: Autocorrelogram for STF 233 with the companion embedded in noise.

7. The Gaussian Filters

If we return to the Speckle dialog window, we notice that the bottom half has several options (shown in Figure 23).

Callout 1 is where we can adjust STB's filter settings. Callout 2 is where we set up the deconvolution star parameters. And Callout 3 is a checkbox that allows us to display the power spectral density as an image. We will now cover each of these functions in detail using material generously supplied by STB's author, David Rowe and his collaborator, Russ Genet.

Gaussian Lowpass Filter (Callout 1)

For a run on a specific telescope, the Filters can often be set once (perhaps after some experimentation) and then left alone for the reduction of an entire run. Proper setting of the two Gaussian filters should optimize the detection and measurement of the double.

A telescope's optical system is a spatial low pass filter where the low pass cutoff frequency (in pixels) is a function of the wavelength, the f/ratio of the telescope, and the size of the pixels. Recall that the Airy disk radius, R, is given by

$$R = 1.22\lambda\left(\frac{F}{D}\right)$$

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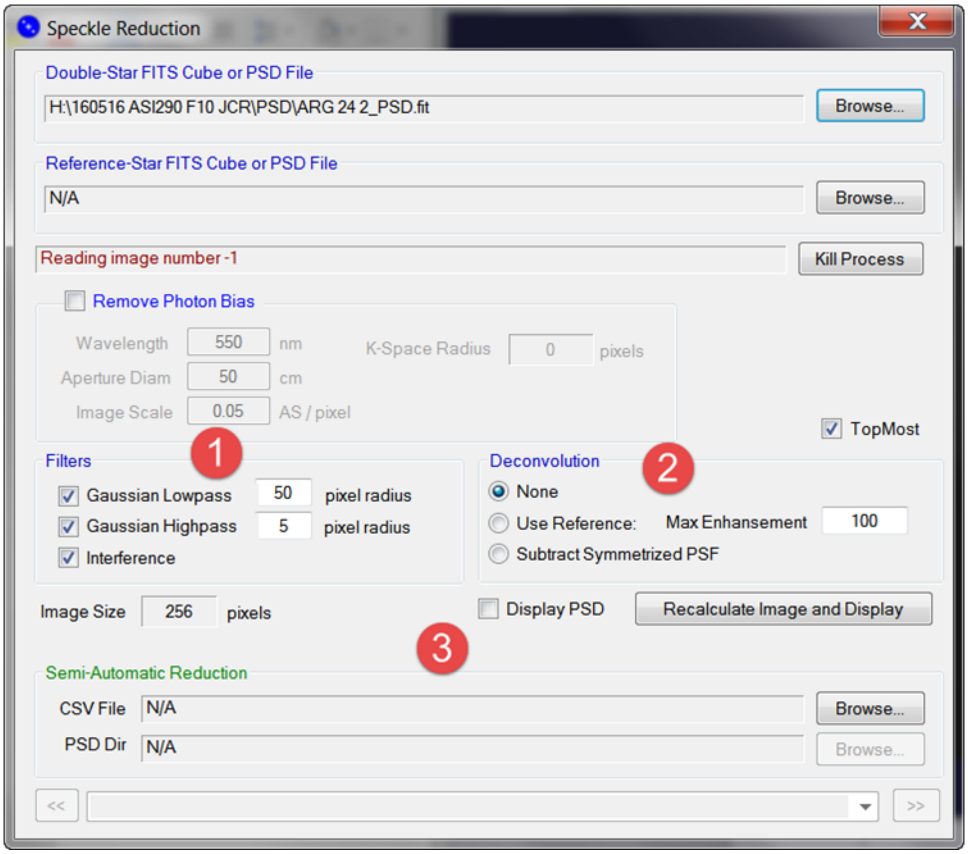

Figure 23: The Filters section of the Speckle dialog window.

where λ is the wavelength and *F/D* is the focal ratio of optical system. In pixels, this is given by

$$R(\text{pixels}) = 1.22\lambda\left(\frac{F}{D}\right)h$$

where *h* is the pixel dimension.

As an example, take the pixel dimension to be 10 microns, the wavelength to be 0.8 microns, and the focal ratio to be 50. The Airy disk radius will be approximately 5 pixels. The Fourier transform of the Airy disk will have most of its energy within a spatial frequency, fc, given by

$$f_c = \frac{N}{2R}$$

where *N* is the size of the image and *R* is the radius of the Airy disk, all values being in pixels.

In the spatial frequency domain, there is very little signal higher than this frequency. However, beyond this frequency there is considerable noise from the electronics, from the sky background, and from photon shot noise from the object. Therefore, to improve the signal-to-noise ratio and to reduce unwanted interference from the electronics, it is wise to apply a low pass filter with a cutoff proportional to this spatial frequency. Thus, the cutoff frequency, *fc* (pixel radius), should be approximately:

$$fc = \frac{hN}{2.44\lambda\,\mathrm{F/\,D}}$$

Taking an example from a speckle interferometry run at Pinto Valley Observatory, λ = 0.8 microns, *h* = 10 microns, *F/D* = 50, *N* = 256, yields *fc* = 26 pixels. For my C-11 and ASI290 camera (2.9 micron pixels at *F/D* of 11 and 15), the value of *fc* is 35 for the f11 optical train, and 25 for the f15 train. In practice, it is a good idea to make the low pass filter somewhat wider than this so that most of the signal information is allowed through the filter. For that reason, I usually set the low pass filter at about 40 for my setup. You will obviously need to calculate the settings for your particular optical setup when using STB.

This only provides a good starting point. In fact, the auto-correlation has noise and signal statistics that are more complicated than the above simplified argument would suggest. For PVO II, experimentation suggested that an *fc* of about 50 pixel radius worked best, although the solutions were not overly sensitive to this setting. I often find that running the low pass filter up to 50 or 60 improves the autocorellogram noticeably over my "standard" setting of 40.

Clicking Display PSD (Callout 3) will toggle from the normal autocorrelogram solution image to the PSD (Power Spectral Density) fringe pattern display. If, as shown in Figure 24, the Gaussian Lowpass is set too wide, noise beyond the telescope cutoff will be seen, suggesting that the setting should be reduced to a smaller pixel radius. On the other hand, if there is no signal at all beyond the telescope cutoff, then the filter is set too narrow and should be widened.

Gaussian Highpass Filter (Callout 1)

The Power spectral density (PSD) is the Fourier transform of the image. The purpose of the Gaussian Highpass Filter is to remove, as much as possible with a simple filter, the broad tail of the point spread function (PSF) that is due to seeing and optics. This filter removes the lowest-frequency information in the image and is typically set between a 2 to 5 pixel radius. It is set empirically to give the best auto-correlation.

A useful way to set the filter is to look at the PSD, which can be done by toggling Display PSD to bring up the fringe pattern. As shown in Figure 25, set the pixel radius to remove the bright spot in the zero-order PSD fringe pattern without hurting the rest of the fringe pattern. The Gaussian high pass is usually not needed when single star reference deconvolution is used.

Interference Filter (Callout 2)

In certain situations we have encountered significant interference, possibly due to the interaction of the camera with the main 120V AC power source at remote locations. Much of the unwanted interference was found to lie along the lines fx = 0 and fy = 0 in the spatial frequency domain. If the Interference filter is checked, the values along the fx = 0 and fy = 0 axes in Fourier space are replaced by the average values of their neighboring pixels. This filter is quite specific to the type of interference produced by the camera.

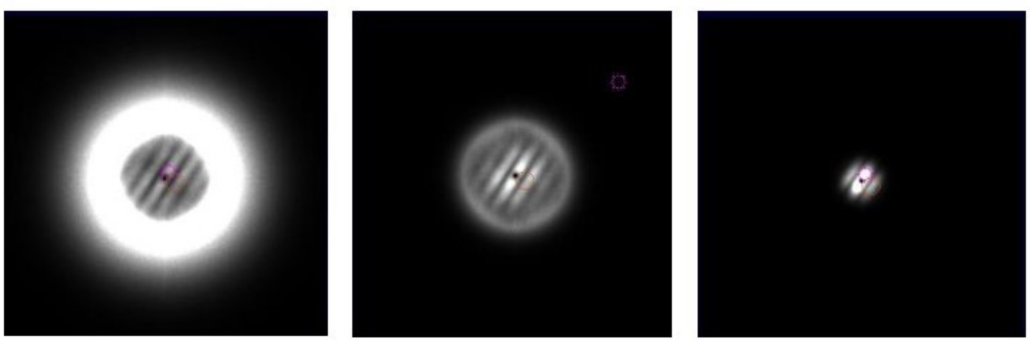

Figure 24: On the left, the Gaussian Lowpass filter was set too wide (70 pixels), allowing high frequency noise to be included. On the right, it was set too narrow, cutting off useful information. In the middle it was set just slightly larger than the spatial cutoff frequency imposed by the telescope's aperture.

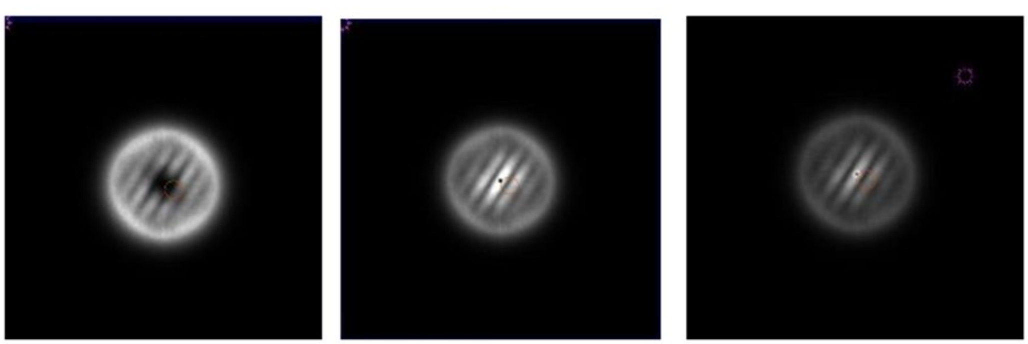

Figure 25: On the left, the Gaussian Highpass filter was set to wide, not only cutting out the bright central peak, but also much of the fringe pattern. On the right the filter was set too narrow, allowing the bright central peak to shine through. The center is set correctly.

Deconvolution (Callout 2)

There are three Deconvolution options: None, Use Reference PSD, and Subtract Symmetrized PSF. Each is discussed below.

None Although not recommended, speckle interferometry reduction can be accomplished without the use of single reference stars for deconvolution. For this option, simply select None under Deconvolution. It can be quite helpful to apply a Gaussian high pass filter when not using deconvolution. This is especially the case when using STB to analyze pairs too wide or faint for speckle but for which you want the accuracy of an STB solution compared to lucky imaging.

Use Reference PSD The use of deconvolution reference stars is highly recommended. Not only will it sharpen the double star image, it will also remove much of the telescope's optical aberrations, including the effect of the central obstruction. In addition, if the reference star was taken close in time and located near the double star, deconvolution will remove much of the atmospheric dispersion and broad tail due to the effects of seeing. Deconvolution will help in almost all instances. If the reference star is a poor match for the double star, there are cases where a false detection can occur for doubles with dim, close companions.

Deconvolution is based on the following mathematical properties: (1) the recorded image of a very short exposure is the convolution of the "perfect" image of the object with the PSF of the telescope plus the instantaneous atmosphere, and (2) the convolution operation can be implemented by taking the inverse Fourier transform of the product of the Fourier transforms of the "perfect" image and the point spread function (PSF) of the telescope plus instantaneous atmosphere. Symbolically:

$$F(I) = F(O) * F(T)$$

where $F(\,)$ denotes the Fourier transform, I is the actual image recorded, O is the "perfect" image of the object, and T is the PSF of the telescope plus instantaneous atmosphere. Speckle interferometry is based on averaging a large number of very short exposures which "freeze" the atmospheric seeing, allowing us to take the average of the above equation in transform space. If we let <*I*>, <*O*>, and <*T*> denote the averages of the Fourier transforms of I, O, and T, as defined above, then we can calculate an approximation for the Fourier transform of the object's power spectral density (PSD) as:

Taking the inverse Fourier transform of <*O*> yields an approximation to the object's autocorrelation, with the telescope and atmosphere removed. This process is called deconvolution.

To perform this operation, we need an estimate of <*T*>, the autocorrelation of the telescope plus atmosphere. A convenient way to find this estimate is to obtain a speckle cube of a nearby single star. The most effective deconvolution will be based on single star speckle observations that are very near the object from the point of view of the atmospheric conditions and telescope pointing. We feel that it is good practice to observe a single reference star that is as near as possible to the double star in both time and space. The reference star must, of course, be bright enough to show excellent

$$\langle O \rangle = \frac{\langle I \rangle}{\langle T \rangle}$$

SNR after speckle preprocessing.

To use a reference star for deconvolution, check Use Reference PSD and set it to 100 percent. The percentage option was included so one can experiment with the strength of the deconvolution when using non-ideal reference PSDs.

Subtract Symmetrized PSF This option was developed for close, dim double stars without good reference stars. A symmetrized PSF is made from the image and is subtracted from it, yielding only the non-symmetrical part. This can highlight an otherwise difficult-to-detect companion. This technique should be used with caution, since non-rotationally symmetric telescope aberrations can mimic a close, dim double.

Display PSD (Callout 3)

Toggling Display PSD will move back and forth between the autocorrelogram solution and the power spectral density fringe pattern.

Kill Process (Callout 3)

Kill Process simply stops the FITS cube speckle preprocessing.

8. Creating an OutFile Using the Astrometry Dialog Window

Near the bottom of the astrometry dialog window are prompts for creating an OutFile. See Callouts 1, 2, and 3 in Figure 26.

After a star has been measured, STB allows you to generate a CSV file which can be read by Excel (or most other spreadsheet programs) so you may collect data and mathematically analyze it later, computing means, standard deviations, and standard errors. To do so, you need to specify a name and location for your OutFile. Click the "Brwse" button to the right of the OutFile name window and navigate to a folder (or create one) where you want STB to save the results. After the folder is selected, type a name for the file in the OutFile window.

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If you wish to add any comments to the measurement, type them in the window indicated by Callout 2.

When you are ready to save the measurement, click the button titled “Save Results”.

Once the OutFile has been created and the first record saved, all subsequent measurements you make during that run of STB will be appended to the OutFile as new records.

When you have completed your measurements, you may exit STB and open the OutFile CSV in your spreadsheet program. If you are using Excel, I suggest that you save the file immediately as an Excel file rather than the CSV file that STB generates.

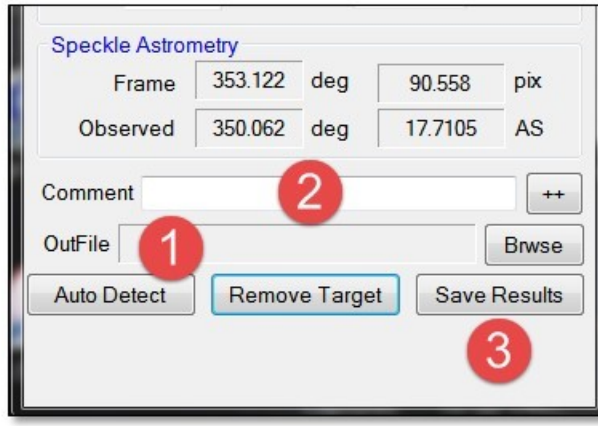

Figure 26: The OutFile options

9. Structure of the OutFile

As shown in Figure 27, the OutFile is comma delimited, one row per output record. The top row provides column content abbreviations. These abbreviations are provided below, followed by a short description.

Num This is the object sequence number from the input CSV file directory, when used. If an input CSV file is not used, this entry will be blank.

Target This is the target (double star) identification. Usually it is the Washington Double Star (WDS) catalog name, such as 09345+0723, but it can be some other identifier, such as GJ3579.

ThetaC This is the last catalog or predicted (input) double star position angle (PA, θ, and Theta are all abbreviations for position angles). This calculated (prediction) may be the last reported position angle, but could be an interpolated value from an orbit ephemeris, or even a maximum likelihood prediction. *ThetaC* is used by PS3 to place a small red circle on the autocorrelogram, where the secondary is expected.

ThetaO The observed position angle. This only has meaning when the user provides the camera angle, *Delta,* from some calibration external to the reduction. If not available, the user can enter any number and ignore the results, or enter a camera angle of “0” and the output would be the “uncorrected” camera angle.

ThetaO-C PS3 simply calculates this as *ThetaO* minus *ThetaC.* This is the difference between the observed position and the calculated (i.e. predicted or expected) position angle; the classic O -C.

RhoC This is the last catalog or predicted (input) double star separation (Sep, ρ, and Rho are all abbreviations for separation). This calculated (predicted) separation may be the last reported separation, but could be an interpolated value from an orbit ephemeris, or even a maximum likelihood prediction. *RhoC* is also used by PS3 to place the

Num	Target	ThetaO	ThetaC	ThetaO-C	RhoO	RhoC	RhoO-C	ThetaF	RhoF	ApD	RelInt	DMag	Comm
24	00283+6344	111.831	91	20.831	0.3857	0.4	-0.0143	100.531	33.251	12	0.2216		
76	01036+6341	4.098	19	-14.902	0.2226	0.3	-0.0774	352.798	19.192	12	0.2312		
1	00022+2705	228.354	273	-44.646	0.166	0.8	-0.634	217.054	14.312	12	0.0571		Close one!
2	00024+1047	69.213	73	-3.787	0.2468	0.2	0.0468	57.913	21.273	12	0.0535		Prediction close.
3	00029+4715	294.729	295	-0.271	1.5947	1.6	-0.0053	283.429	137.47	12	0.155		Wide and easy. Prediction right on.
4	00046+4206	105.922	95	10.922	0.1304	0.1	0.0304	94.622	11.244	5	0.0486		Very close but good solution.
5	00055+3406	307.239	304	3.239	0.15	0.2	-0.05	295.939	12.933	5	0.0675		Also close. Prediction off a bit.
6	00073+0742	321.309	323	-1.691	0.3515	0.4	-0.0485	310.009	30.3	11	0.2919		Easy. 2nd & 3rd order images.
7	00085+3456	52.817	79	-26.183	0.1383	0.1	0.0383	41.517	11.922	5	0.1508		Close. Solution not stable.
13	00118+2825	67.367	69	-1.633	0.4474	0.5	-0.0526	56.067	38.571	11	0.1454		Easy. Prediction close.
14	00121+5337	317.605	313	4.605	0.3344	0.3	0.0344	306.305	28.827	11	0.1709		Very easy.
18	00174+0853	305.499	307	-1.501	0.1556	0.2	-0.0444	294.199	13.417	5	0.0411		Difficult. Not quite stable.
19	00174+0853	303.657	307	-3.343	0.1553	0.2	-0.0447	292.357	13.386	11	0.1254		Easy and stable.
20	00205+4531	96.724	102	-5.276	0.656	0.7	-0.044	85.424	56.553	11	0.0896		Verey easy. Clean!
21	00209+1059	118.746	117	1.746	0.7557	0.7	0.0557	107.446	65.145	11	0.1286		Very easy. Clean.
23	00251+4803	273.507	242	31.507	0.3186	0.3	0.0186	262.207	27.464	11	0.0335		Prediction off, but not too far.

Figure 27: The OutFile structure.

small red circle on the autocorrelogram where the secondary is expected.

RhoO The observed separation angle. This only has meaning when the user provides the plate scale (arc seconds per pixel), *E,* from some calibration external to the reduction. If not available, the user can enter any number and ignore the results, or enter a plate scale of "1" and the output will be the "uncorrected" frame pixel separation.

RhoO-C PS3 simply calculates this as *RhoO* minus *RhoC*. This is the difference between the observed position and the calculated (i.e. predicted or expected) separation; the classic O-C.

ThetaF Position Angle in the Frame. *ThetaF* is calculated by PS3, using simple trigonometry, from the centroid pixel locations.

RhoF Separation in the Frame. *RhoF* is calculated, using simple trigonometry, by PS3 from the centroid pixel locations.

ApD Aperture Diameter (radius in pixels).

RelInt This is the total (integrated) intensity of the companion divided by the integrated intensity of the primary. This will eventually be used to form an estimate of the differential magnitude of the double star.

DMag This will be calculated in a future version of the program. At this time the entry is blank.

Comm User comment added during reduction.

DSFN Double star (FITS cube) file name.

RSFN Reference star (FITS) cube file name.

AR Elongation Aspect Ratio (degrees).

AA Elongation Angle (degrees). The angle that corresponds to the elongation aspect ratio.

Delta Camera Angle (degrees). Camera orientation angle with respect to the sky.

E Plate scale (arc seconds/pixel).

GLP Lowpass Radius (pixels). Settings for Gaussian lowpass filter.

GLPen Lowpass used (True/False).

GHP Highpass Radius (pixels). Setting for Gaussian highpass filter.

GHPen Highpass used (True/False).

IFen Interference Filter used (True/False).

DCon *Deconvolution* Type: *None*=0, *Use Reference PSD*=1, *Subtract Symmetrized PSF=2*.

DConP *Deconvolution percent,* usually set at 100%.

LTPen *Lock to Peak* (True/False).

JPEGFN Filename of the solution image.

DaT Date and time output created.

10. Computer Requirements for STB and Obtaining a Free Copy

STB has been designed to run on a Windows only platform (Windows 7 or later) and requires a 64-bit processor. Since the processing of fits cubes can be a very intensive operation, obviously the faster your computer's chip, the better.

If you would like a free copy of STB, please send an email to the author and indicate in your message that you would like a copy of the program. I will reply to your email and attach a zip folder to my reply. The zip folder it will be named STB.ZZZ, the ZZZ file extension being a fictitious one that lets an attachment slip past email servers that automatically block ZIP files. Once you receive the file, save it to a folder on your computer (a name like STB would work well). Navigate to the new folder and rename the file from STB.ZZZ to STB.ZIP and then extract it. Be sure to let the extraction process extract all files to the same folder.

Once the extraction is complete, find the file named SpeckleToolBox.exe and send it to your desktop as a shortcut.

11. Conclusion

The Speckle Tool Box has proved to be a very powerful and easy to use analytical tool for doing speckle interferometry and highly precise measurement of the CCD images. Those who are currently engaged in CCD measurements of double stars may very well wish to investigate this program.

12. Acknowledgements

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13. References

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