Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

Rick Wasson

Sunset Hills Observatory, Murrieta, California
ricksshobs@verizon.net

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Abstract: Equipment, observing procedures, data reduction techniques, and software used to measure double stars with a Dobsonian telescope by the Video Drift Method are described in detail. Challenges encountered with an Alt-Az telescope and data reduction, such as calibration, a continuously rotating field, and digital video pitfalls - along with ways to overcome them - are discussed. Early measures from 2011 are reported and compared with measures of well-established sources, validating the use of a Dobsonian telescope to measure double stars by the Video Drift Method.

Introduction

The author has been an amateur astronomer for nearly 60 years, having a particular interest in areas where amateurs can make scientifically useful observations. Past observations included AAVSO variable stars and BVRI photometry of variables and eclipsing binaries, with several published papers, e.g. Wasson, Hall et al. (1994).

In 2008 a video camera and a GPS time-inserter were purchased for the purpose of observing occultations of stars by asteroids, in support of the IOTA ongoing program to measure asteroid sizes, shapes, and precise positions for improved orbits. After moving to Murrieta, CA in 2010, a 12-inch "Go-To" Dobsonian telescope was added to reach fainter occultation targets.

With a long-time interest in double stars, the author noticed an article by Nugent and Iverson (2011), also occultation observers, describing a method for measuring double stars using the same equipment already at hand. He had to give it a try!

While an alt-az telescope is certainly capable of observing double stars visually, it is not the usual instrument for *measuring* double stars. The challenges imposed by an alt-az mount, and ways to overcome them, are recurring topics here.

The purposes of this paper are:

To describe the Video Drift Method as adapted by the author, using a Dobsonian telescope.

To give details of the techniques, tools, and procedures used.

To present the first results of double star measures made in 2011.

To assess the quality of the measures by providing statistical data and example comparisons with presumably higher-quality observations.

To discuss error sources and evaluate the impact on quality of the measures.

Equipment

The author's telescope is a portable Orion 12-inch (304 mm) f/4.9 "Go-To" Dobsonian, with a focal length of 1500 mm.

The camera, used at the Newtonian focus in place of a 1¼" eyepiece, is a PC-164c low-light surveillance video camera, incorporating a Sony EXview HAD CCD black & white sensor, providing standard NTSC analog video at 29.97 frames/sec.

The CCD detector contains 510(H) x 492(V) pixels. Each pixel is rectangular 9.6μ(H) x 7.5μ(V) for an overall detector size of 4.9mm(H) x 3.7mm(V). The field of view, for the 1500 mm focal length, is approxi-

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

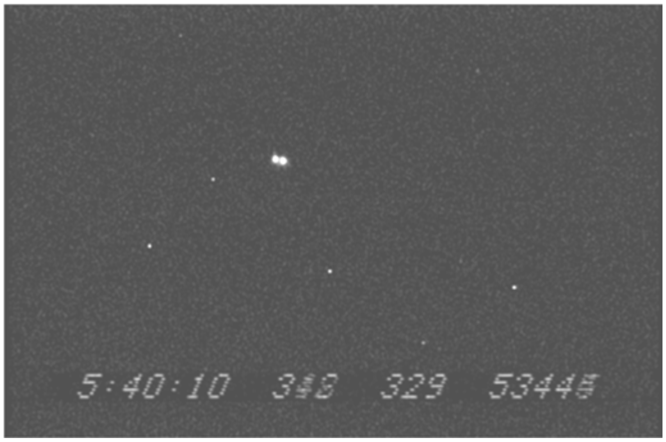

Figure 1. A single frame of video showing the GPS time display at bottom.

Figure 2. The author with 12-inch Dobsonian "Go-To" telescope and support equipment.

mately 11 x 8 arc minutes.

A "Kiwi" GPS time inserter, originally purchased for accurate timing of asteroid occultations, adds a GPS time display at the bottom of each video frame.

Analog video from the camera is digitized at 8 bits in real time by a Canon ZR-200 camcorder and written to MiniDV cassette tape. No color filters have been used for observations, so far.

Some observations have been made with a Barlow lens for higher magnification of close doubles. Figure 1 is a single full-frame image from a drift video, showing the GPS (UT) time display at the bottom. In this case a 3x Barlow was used, for an effective focal length of 4.5 meters and a field size less than 4'x3'.

The permanent "bow-tie" pattern of 5 hot pixels below center shows up in videos on warm summer evenings, because the camera has no cooling. The double star is the eastern pair of the famous "double-double" Epsilon Lyrae (STF 2383CD), whose separation is 2.3 arc seconds.

Each video "frame" actually consists of two line-scanned "fields" of half the lines (the odd or the even pixel rows) of the CCD chip. The two fields are alternately read out at slightly different times, and are interlaced together to create a frame. Therefore, there are two GPS time values for fractional seconds imprinted, while the hour, minute, and second values are common to both fields. Although GPS time may be more accurate, 3 decimal places (i.e., rounded to the nearest millisecond) are imprinted by the KIWI; one msec is adequate for both occultation timing and double star measurement.

In Figure 1, the first three numbers are UT hour, minute, and second, followed by the millisecond times of the two fields. The number at right is a continuous running field count since the last KIWI GPS satellite initialization.

The author's portable observing setup for recording drift videos of double stars is shown in Figure 2. On the table are the camcorder, KIWI GPS time inserter, finding charts, and numerous connecting cables. The video camera is mounted in a Baader 1¼ inch Q-Turret, together with low- and medium-power eyepieces to help find and center objects.

Observing Procedure

All observations were made using the Video Drift Method described by Nugent and Iverson (2011). When using an alt-az mount, the field continuously rotates during the observing session at a variable rate depending on declination, latitude and hour angle.

The east-to-west drift direction of stars, assumed to be a straight line over the small field of the video camera, is used as an absolute reference to measure the video frame orientation to the sky. The known sidereal drift rate, together with accurate (GPS) timing of the drift across many pixels, is used to measure the "plate scale" (a term from the days of photographic plates) in arc-sec/pixel.

The video frame is first roughly aligned with the sky by rotating the camera in the eyepiece holder until stars drift left-to-right (east-to-west), horizontally on the camcorder monitor, with the drive turned off.

To make an observation, the target stars are moved slightly out of the field eastward, the telescope drive is turned off, and a video recording is made as the stars drift across the field – on the true east-west path. The recording is stopped once the stars drift out of the field,

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

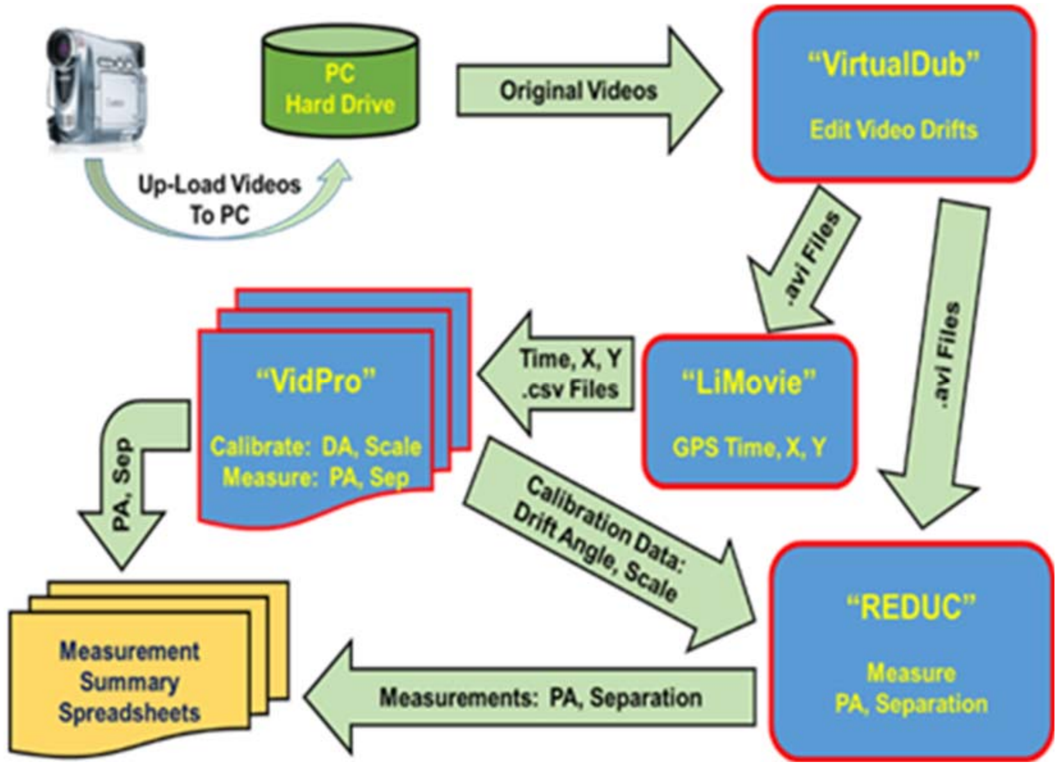

Figure 3. Data reduction process, showing the four primary software tools and data flow among them.

and the tracking motors are turned back on to avoid losing the stars. Current practice is to repeat this process for 3 or 4 "drifts" for each target double star, although for the early observations shown later, only one or two drifts were recorded.

After the first drift, an alternative and more efficient method is to manually drive the stars back off the left (east) edge of the field, then let them drift across again; this is repeated for as many drifts as desired, recording continuously all the while with the sidereal drive turned off.

For equatorially-mounted telescopes, the drift method is commonly employed for "calibration runs" to determine camera orientation, then applied to all observations for the same fixed camera position.

For alt-az-mounted scopes, however, the drift method must be used to calibrate *every* individual observation, because no two drifts have the same orientation and because the camera is frequently adjusted to keep it roughly aligned with the sky. This definitely makes measuring double stars with a Dobsonian telescope more challenging!

In the video drift method, each drift sequence is a stand-alone package of information containing data for calibration of both pixel scale and sky orientation, by using the known sidereal drift direction and rate, coupled with accurate GPS time for each frame. No other calibration observations are necessary. Of course, the video sequence also contains many short-exposure image samples (frames) used for double star measurement.

To insure that target stars or drifts are not confused later during data reduction, the drift files are appended a, b, c, etc. and the approximate time of each drift is noted by hand on the observing log sheet.

With a telescope focal length of 1500 mm, the field of view is small - about 11 x 8 arc minutes. However, at the equator, the time for a star to drift across the field is still about 45 seconds, giving over 1300 video frame samples. Of course, at higher declination the drift times are longer, giving more samples. With a 3x Barlow, typical drift times near the equator are about 15 seconds, providing nearly 500 video frames for each drift.

Data Reduction Overview

Data reduction of the digital video recordings of double star drifts is accomplished in several steps; the flow sequence is shown in Figure 3. The recordings are first uploaded from the camcorder to a computer; then the drifts are final-edited in the "VirtualDub" program (Lee, 2010) and saved as .avi (audio video interleaved) files.

Analysis begins with processing each drift in the "Li Movie" program (Miyashita, 2008); GPS time and the central pixel (X, Y) of the double stars are saved in a .csv (comma separated values) file, which is like a long spreadsheet list where each row contains the information extracted from one frame. The .csv file from LiMovie is pasted into a "VidPro" spreadsheet (Nugent & Iverson, 2011), which calculates the two calibration parameters, Drift Angle (DA), and Plate Scale, and also measures the double star Position Angle (PA) and Separation.

The two calibration values are entered into the "REDUC" program (Losse, 2011), which can measure the double star PA and Separation in several ways. Finally, the measures of all drifts and methods are summarized in a spreadsheet, where the average and standard deviation are calculated. In the following sections, each step in the data reduction process is discussed in detail.

Video Data Handling

Video Upload to PC

The IEEE 1394 serial bus interface standard was developed in the 1990s for Apple computers (called "Firewire" by Apple) for high-speed continuous data streaming, and works well with Digital Video (DV). USB was designed at about the same time for PCs to carry a large number of small data packets; it was originally much slower, but is now comparable in speed. Each is a serial communication protocol between electronic devices, but they are neither interchangeable nor compatible with each other.

Digital video from the camcorder was originally imported through a firewire cable and card installed in a PC. An alternative method is now used: a "Movie Box" high speed translator by Pinnacle, which is capable of capturing several different communication formats, including firewire DV and HD, and provides output to a USB 2.0 or 3.0 port, now standard on most PCs and laptops.

Some preliminary editing (shortening) of the video drifts may be done during upload, to reduce hard drive storage a little. Roughly 200 MB of storage space is required for each minute of digital video.

Dropped Frames

During upload of video files from the camcorder cassette to the computer there is the danger of dropping individual video frames, if any supporting link in the transfer chain (electronics, cables, processors, software, etc.) cannot keep up with the frame rate of the other links. Dropped frames may compromise the calibration method based on GPS time, discussed below.

To verify that no frames are dropped during upload, columns to calculate GPS time increments between frames are added to the LiMovie output .csv file. Inspection of these values, which should always be 0.033 or 0.034 seconds (about 1/30 second for NTSC video) verifies that no frames are missing.

"VirtualDub" Editing Program

The uploaded video clips are edited in the freeware program "VirtualDub" (Lee, 2010). Each drift is "trimmed" to begin just after the double star enters the field from the east and end just before it exits the field. VirtualDub then saves the edited version as a new .avi file, which in turn is read by the analysis programs "LiMovie" or "REDUC."

The author has had difficulty with the originally-uploaded .avi files not being readable by either LiMovie or REDUC. However, after editing and re-saving by VirtualDub, the problem disappears. It may be that Virtual Dub uses a variation of .avi files with a more commonly-accepted format or header. See the "Video Issues" section for further discussion of related issues.

"LiMovie" Program

"LiMovie" (Miyashita, 2008) is a freeware program which was developed for precise timing analysis of video recordings of lunar and asteroid occultations. For application to double star measurement, the three essential tasks which LiMovie performs are:

1. Photometric measurement of star images in a video sequence, even for quite faint stars;
2. Tracking the movement of stars from frame to frame;
3. Extraction of the GPS time of each interlaced video field from the pixel-pattern characters imprinted by the GPS time-inserter.

LiMovie produces an output file containing, frame-by-frame, the GPS times of the two fields and the brightness and central pixel location (X, Y or row, column) of one to three selected stars, as well as a number of other parameters used for occultation purposes. This file, in .csv format, is readable by Excel spreadsheets, and is used as the primary input for follow-on VidPro astrometry analysis.

Figure 4 shows an example of a "3D" graphic display available in LiMovie, where the grid represents pixels and the "height" of the star is the pixel brightness. This view is useful for monitoring the progress of LiMovie analysis in near-real-time. The red and blue rings at the base of the star are used for photometric analysis. Although documentation states that the star centroid of pixels within the photometric aperture is found during photometric analysis, this information does

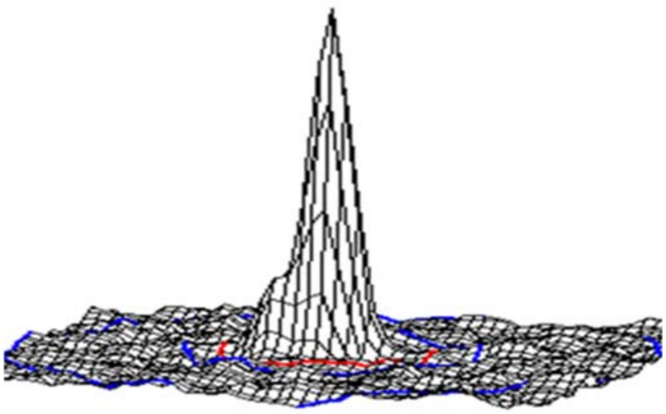

Figure 4. LiMovie 3-D view of a close double.

not seem to be available in the .csv file for astrometry analysis – the data are rounded to the nearest (brightest) whole pixel.

If the stars have no clear space between them, or if one is much fainter and close to the other, LiMovie may lose track of the faint star or jump to the brighter one, defeating the double star measurement capability. This is the case in the example of Figure 4, where the faint companion is only a small bump on the left side of the bright primary star. However, LiMovie can still be used to track the primary star (or any other star in the field) and produce data suitable for calibration, even when the pair itself can't be measured.

"VidPro" Workbook

The "VidPro" Excel workbook was developed by Nugent and Iverson (2011) to measure double stars using the Video Drift Method. The VidPro workbook consists of three spreadsheets:

Sheet1: A general sheet with star identification and measure results;

Sheet2: A detailed calculation sheet into which the LiMovie output .csv data file is pasted;

Sheet3: An instruction sheet.

VidPro Measurement

Once the data are entered into the few designated cells of Sheet1 and the .csv file from LiMovie is pasted into Sheet2, the measurement cells are automatically updated. All frames in the drift are measured; average values and standard deviations of PA and separation are presented.

VidPro is intended for measurement of doubles having moderate to wide separation, because: (1) LiMovie must be able to faithfully track both stars in every frame, and (2) LiMovie provides only the location of the central (brightest) pixel of each star image in the output .csv file. Of course, higher magnification can be used to spread the stars apart, but the spread-out star images may become more difficult for LiMovie to track.

Although VidPro is intended for use on doubles where the individual stars can be followed by LiMovie, the author created a "single star" version of VidPro, which he routinely uses for drift calibration of close pairs. This version simply eliminates those cells which use the 2nd star data as well as the averaging calculations in the spreadsheets, to avoid undefined calculations.

VidPro Drift Angle Calibration

VidPro uses a linear regression of the drifting locations of a star's brightest pixel (CCD row and column, or X, Y) in all frames to calculate the frame orientation or Drift Angle (degrees), which defines the video frame orientation to the sky. If both stars can be tracked by LiMovie, a regression for each component is calculated and the two Drift Angles are averaged.

VidPro "Plate Scale" Calibration

VidPro uses the GPS time increment (Δt, minutes) between last and first frames, and the star declination (δ), to calculate the actual angular distance (arc-sec) traveled by the star at the sidereal rate during the drift. It divides this result by the hypotenuse of the pixel rows and columns (ΔX and ΔY) traveled during the drift, to get the "plate scale" (arc-sec/pixel), Equation (1). The author's plate scale is typically about 1.0 arc-sec/pixel when no additional magnification is used.

$$Scale = \frac{\Delta t}{\sqrt{\Delta x^2 + \Delta y^2}} \bullet 60 \bullet 15.041068 \bullet \cos(\delta) \qquad (1)$$

"REDUC" Analysis & Measurement

REDUC is a powerful program written expressly for double star analysis and measurement. It is provided free by e-mail request from the talented and productive French amateur Florent Losse (2011). A comprehensive on-line tutorial is handy to refer to and very helpful while learning the program.

REDUC does not operate on video files directly, but rather on a sequence of fits or bitmap files. But it has the very convenient capability to read a video (.avi) file and convert it to a set of bitmaps.

An alt-az telescope is not the usual instrument for observing double stars, and the limitations imposed by the mount - continuously rotating field, the need to frequently re-align the camera approximately east-west, and the requirement to calibrate each drift uniquely - can

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

cause difficulty because the program is used in ways for which it was not designed, particularly in calibration.

REDUC Drift Angle Calibration

REDUC offers several modes of drift angle calibration, including drift videos, for which it performs a linear regression of the long track of star centroid positions. An example is shown in Figure 5, where each "+" symbol marks the centroid of the brightest star in one frame. The wiggles are due to seeing and a moderate wind bouncing the telescope slightly.

REDUC analysis automatically begins by finding the brightest star in each frame, and calculating the centroid of that star image to a small fraction of a pixel. This works very well for steady tracking.

But for video drifts, the brightest star in one frame may not be the same star in the next frame, if the star drifts out of the field or if a brighter star enters the field. If REDUC doesn't track the same star during the entire drift, more than one track appears, through which a mathematically correct, but meaningless linear fit is made.

A particular problem for faint fields is that the brightest "star" may actually be a hot pixel or even part of the GPS time display! These errors can be overcome by de-selecting the frames that cause problems, but that is a lot of extra work.

REDUC "Plate Scale" Calibration

For "plate scale" calibration, REDUC again has several methods for calibration. For any camera, pixel size is a REDUC input and may be used in calculating scale factor. However, the focal length and any magnification used in the optical path (e.g., a Barlow or eyepiece projection) must also be known accurately. The actual magnification factor is generally not exactly the same as the nominal value (for example, the magnification of a 3x Barlow is almost never precisely 3.00).

Calibration requirements are often fulfilled with an equatorial mount by measuring standard "fixed" stars, and leaving the camera and focus untouched for long periods. But this approach is impractical with an alt-az scope, because the camera needs to be adjusted and may be re-focused much more often; a slight change in focus also makes a slight change in plate scale. The advantage of using GPS timing for each frame is not available in REDUC.

For these reasons, and to make the data reduction process as consistent as possible, VidPro calibration results are always used by the author as input for REDUC analysis. It should be noted that VidPro and REDUC assume opposite signs for Drift Angle. Therefore, the sign of Drift Angle from VidPro must be reversed when used as input to REDUC.

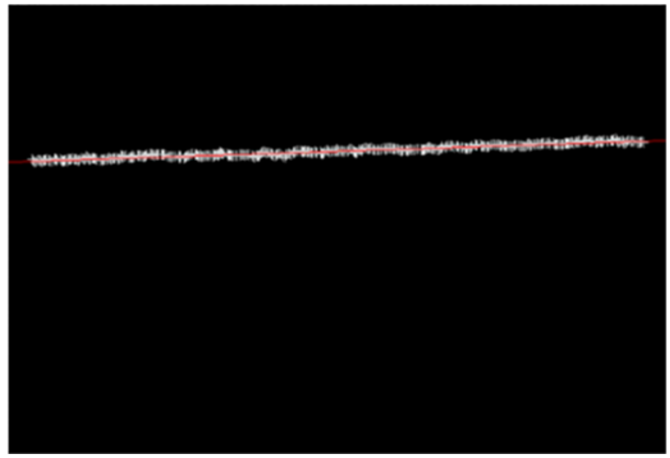

Figure 5. REDUC trace of the brightest star's centroid in a video drift, and best linear fit.

Benefits of Many Video Samples

For any given video frame, the seeing causes large random uncertainties in the measures of position angle and separation. Integration over time with any camera can produce clean star images which may be measured accurately. However, time exposures produce star images roughly the size of the "seeing disk" (typically several arc-seconds across), larger than the diffraction-limited Airy disk, which is less than one arc-second. The seeing disk is larger because the seeing distorts not only the shape of the stars, but continually moves them around in the field as well.

The trade-off for video double star observations is that brighter stars must be observed because of short exposures, but measurement uncertainties are reduced dramatically by the large number of video frame samples taken in a single drift. Several drifts in succession further defeat the seeing, reducing uncertainties of the overall average PA and Separation measures.

When the seeing is reasonably good, the unique advantage of the video drift method is the chance to obtain a few "lucky" images (Anton, 2012) that approach the theoretical resolution of the telescope by capturing a rare, fleeting moment of very good seeing.

REDUC Image Sorting

A powerful tool in REDUC is the capability to sort a large number of images to find the "best" frames. Three criteria are available for deciding what "best" means: (1) maximum brightness, (2) maximum signal/noise ratio, and (3) visibility. The author usually uses the "Best of (Max)" option, but "Best of (S/N)" is also useful for bright stars having plenty of signal. The visibility option presents the user with the task of choosing the best-

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

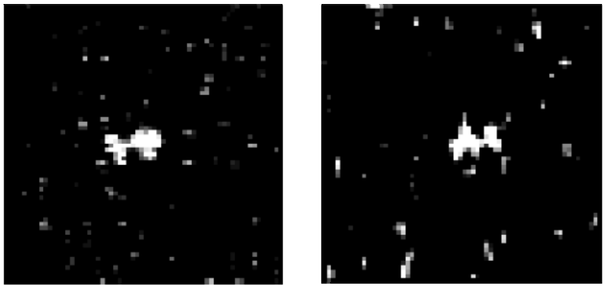

Figure 6. ES1630. Distorted images from single frames in "good" seeing.

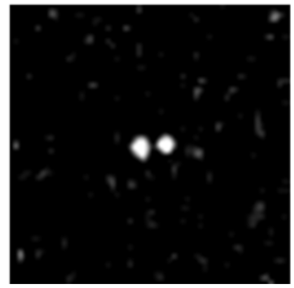

Figure 7. ES1630, separation 5.3". A "lucky" image caught in a moment of excellent seeing.

appearing frames, impractical for the hundreds of frames in a typical video drift.

After sorting, the bitmap image names are arranged in a new list, re-ordered from best at top to worst at bottom. Near the top of the sorted list, one or a few exceptionally crisp "lucky" images may be found. These few images can be measured directly, if desired. Figure 6 shows two typically-distorted images of ES1630, taken on a night of good seeing. Figure 7 shows a "lucky" image from the same drift. The images are 64 pixels square, and the separation is 5.2 arc-seconds.

When the "best" sort is completed, any desired portion of frames may be selected for further analysis. The author usually analyzes the best 25% and the best 10% of frames in each drift. Not all the images in such an arbitrarily-selected group are as sharp as one would like, but the significant number of samples still remaining serves to average out the random seeing distortion.

REDUC Measurement

Once the frames are ready for measurement, multiple methods are available. The direct measure of each frame is easily accomplished with two or three mouse clicks. But this can become tedious for many frames. Again, REDUC has a convenient "Auto" shortcut, where the program quickly and automatically measures the double star PA and separation in each of the many selected frames.

For each drift, the author typically measures the double star first in the "Auto" mode. Enough images are measured (at least a few dozen) to yield reasonable standard deviation statistical data, an indication of internal variability of the measures. Methods for identifying and dealing with out-lying individual measures are also provided.

REDUC Shift & Add Mode

Perhaps the most powerful tool in the REDUC analysis arsenal is the "Shift & Add" mode. First, the centroid of the brightest star of each selected frame is calculated (to a small fraction of a pixel) and then all the frames are "aligned" (shifted) to the common primary centroid. New shifted images are created and the bitmap copies that REDUC had been operating on are discarded (not the original bitmaps). The new frames are then stacked (added together).

The shift-and-add process creates a single synthetic frame in which the true star images tend to be reinforced, while the random seeing distortions and sky background variations tend to cancel out. The double star components typically become crisp, well-shaped and clearly separated. The shifted-and-added frame can be measured, but no statistics are available because now only a single image is measured. Figure 8 is a Shift-and -Add image of ES1630. The primary is the star on the right, which appears slightly fainter in the un-filtered CCD image, perhaps because it is bluer, where the CCD is less sensitive.

Because Figure 8 is a stack of many frames, each containing different random seeing distortions, the two stars appear somewhat bloated compared with the single -frame "lucky" image of Figure 7. However, the signal/noise is better, because the star "signal" is reinforced and the seeing "noise" is reduced by canceling in many samples. While the single-frame image appears to be better, it is still subject to shifts and rotations. Therefore, the Shift & Add image should yield more accurate measures, and the measure of only one lucky image may not be reliable by itself.

For a very faint pair, the centroid of a brighter star in the field may be used as the point to which all images are shifted, while moving and shrinking the new shifted set of images to include just the faint pair (usually 64 pixels square). After shifting, the field usually contains only the double star of interest. The new small frames are again shifted, this time to the centroid of the primary star, which is now likely to be the brightest star in the tiny field. After the second shift, the images are stacked into a single crisp image of the faint pair. It is amazing to watch faint stars, all but invisible in individual frames, suddenly pop out in the new stacked image!

If a double star is very close (or even overlapping!),

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

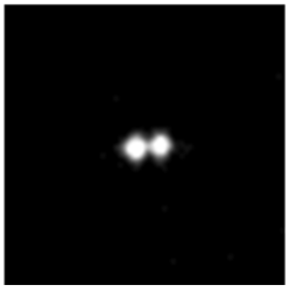

Figure 8. ES1630 Shift & Add image, 64 x 64 pixels. Best 109 (10%) of 1128 frames in a drift.

a second method for measuring the shifted-and-added image is provided: the Model mode. A mathematical model of two stars whose point spread functions may overlap, is compared iteratively with the clean image until an adequate match is achieved. The converged model is then used to measure PA and separation.

Alt-Az Mount Difficulties

Limitations for High Magnification

For close doubles, high magnification is required, but the limitations of a Dobsonian alt-az mount impose a number of serious problems:

1. Uncertainties in the location of each star's "brightest" pixel are magnified, along with the star images, separation, and seeing distortion. Calibration uncertainties grow, because pixel uncertainties of the first and last frames affect the ΔX and ΔY terms in equation (1).

2. Drift times become shorter and star movements get faster as the field shrinks, making it more difficult to keep from losing the stars while the drive is turned off. The camera field is aligned with altitude and azimuth movement only near the meridian, so coordination of the two controls is usually required.

3. As the stars move across the field faster, sidereal smearing of each image will begin to limit accuracy of the video drift method, when the frame rate can no longer freeze sidereal motion within one or two pixels.

4. Star light smeared across more pixels by faster movement will limit access to faint stars.

Guidelines for sidereal rate smearing, which depend only on effective focal length, pixel size, and declination, are shown in Figure 9. It should be noted that such limitations apply to drift calibration runs for equatorial telescopes as well as to normal drifts for alt-az scopes. The new generation of astronomical video cameras having capabilities for very short exposures can overcome this problem for bright stars.

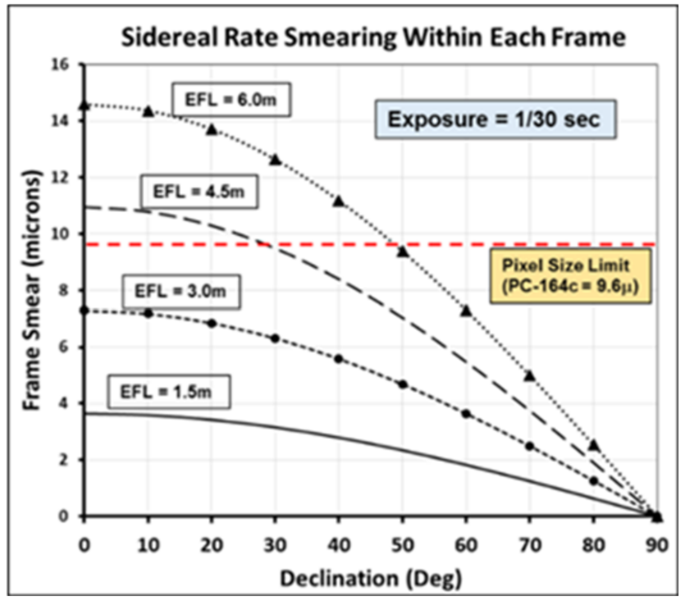

Figure 9. Sidereal rate smearing for a range of Effective Focal Length (EFL) and declination.

Steady Tracking

A good way to deal with high magnification and short drift times is the "Drift-Steady-Drift" method: taking a few minutes of video (several thousand frames) with the telescope tracking the stars, sandwiched between several short sidereal drifts before and after. The double star measures are made using the steady tracking data, to avoid sidereal rate smearing. The steady video is edited using VirtualDub into multiple clips of perhaps 30 seconds each, short enough that the drift angle of the slowly rotating field can be assumed constant. In this method, a high-quality steady sequence is used to create several measurement samples, while multiple drift samples are available for calibration and interpolation, to minimize the impact of larger calibration errors occurring in any single drift.

Steady Tracking Interpolation

The drift videos are analyzed in VidPro as usual for calibration, and then are used to interpolate for drift angle at any desired steady-tracking time, according to the mathematical model for alt-az field rotation given by Burnett (2000). Equations (2) through (5) summarize the method, with variables defined below.

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

$$\sin(Alt) = \sin\delta\sin\phi + \sin\delta\sin\phi\cos H \quad (2)$$

$$\cos(Az) = \frac{[\sin\delta - \sin(Alt)\sin\phi)]}{[\cos(Alt)\cos\phi]} \quad (3)$$

$$RR = \frac{W[\cos\phi\cos(Alt)]}{\cos(Alt)} \quad (4)$$

$$DA(t_2) = DA(t_1) + \frac{1}{2}[RR(t_1) + RR(t_2)](t_2 - t_1) \quad (5)$$

Where
α is the star Right Ascension
δ is the star Declination
ϕ is the observer's Latitude
H is Hour Angle ($H = LST - \alpha$)
LST is Local Sidereal Time
Alt is the star Altitude
Az is the star Azimuth
RR is the field Rotation Rate
W is the sidereal rate (0.250684 deg / minute)
DA is Drift Angle
t_1 is a time for which Drift Angle is known
t_2 is a time for which Drift Angle is being interpolated (e.g., the current and next mid-times of any two successive video clips).

Interpolation for drift angle at the mid-time of each of the steady tracking video clips is done in a spreadsheet which is normally used to summarize the measured results; but the interpolated drift angle and average plate scale are first plugged into REDUC, *before* analyzing the steady videos. Although more drifts may be required for VidPro calibration analysis (a few drifts before and a few more after steady tracking), REDUC analysis is usually easier and faster for steady videos than for drifts.

Sidereal smearing should have less impact if the drifts are used only for calibration, rather than also for measures. This is because the camera detector rows are aligned approximately east-west, so smearing is generally along rows. Uncertainties caused by smearing across more than one pixel affect the ΔX term of equation (1), but not the ΔY term, reducing the error in scale factor. There may also be improvement in drift angle uncertainty, since for small drift angles, the ΔY term has a greater effect than the ΔX term, but is less affected by smearing.

The scale factor of equation (1) is the average value

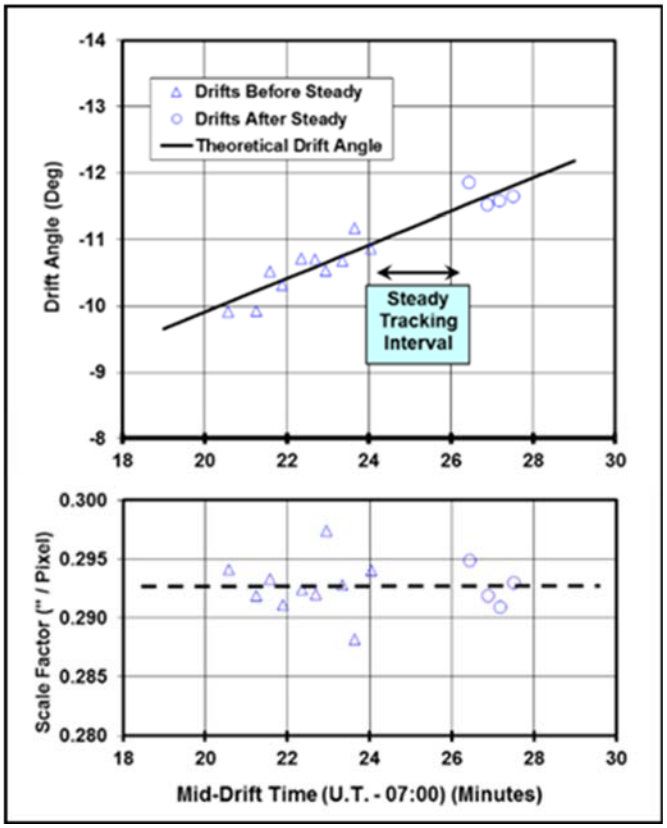

Figure 10. Drift-Steady-Drift method calibration.

of all the drifts. Of course, it applies to steady tracking also. An example of calibration data for the drift-steady-drift technique is shown in Figure 10. The dashed line indicates the average plate scale factor, which is used to analyze the steady tracking videos.

In Figure 10 the theoretical Drift Angle (solid line) has been shifted to force the sum of the residuals of the drift data points to zero. The theoretical Drift Angle line happens to appear straight because of the location of the double star in the sky (near the meridian, but not near the zenith) and the fairly short observing time interval (less than 8 minutes). Although the line is actually slightly curved, simple linear interpolation would have caused minimal error in this case. However, when observing high overhead, the curvature is much more apparent; at the zenith the alt-az field rotation rate is infinite.

Stars Observed

Double Star Selection

Most of the early target double stars were selected because they were in the nearby field of a star which was to be occulted by an asteroid, and were usually observed the same night, before or after the occultation

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

event. Therefore, the selection of target stars was essentially random, the "seeing" was not always the best, and the fields were not always near the meridian. But this approach served to enable the author to gain experience with suitability of targets, observing methods, data reduction software, and generally gain confidence that the Video Drift Method produced reasonable double star measures.

To locate an asteroid occultation target star, charts are customarily produced from Megastar (2003) and printed for use at the telescope. Adding double stars located within the chart is simply a matter of turning on the label feature to show the double star symbol, discovery designation and separation for all doubles in the field. Those having suitable separation and magnitude are then looked up in the on-line Washington Double Star Catalog, and the WDS entries are copied into a spreadsheet. Space is added to note conditions, equipment, time, etc., and the spreadsheet is printed to become a reference and observing log at the telescope.

Locating faint stars in a small field is challenging; but once the target field is acquired in the camcorder monitor, having the WDS information at hand makes it easy to verify the double star identity by rough comparison with the catalog separation, Position Angle and magnitudes.

As an introductory group of first measures with the Video Drift Method and the 0.3m telescope, Table 1 lists twenty-three double stars, each observed on one of three nights late in 2011, providing the following information: WDS Catalog identifier, discovery designation, WDS primary and secondary magnitudes, date observed, Position Angle (deg), ±standard deviation of PA, Separation (arc-sec), ±standard deviation of Separation, number of video drifts, and total number of video frames recorded. No filters, Barlow lens, or eyepiece projection were used for these measures.

Measurement Techniques

The measurement techniques used by the author typically include both VidPro (one measure of PA and Separation for well-separated stars) and REDUC (multiple measures for all stars). In REDUC, three methods have been used, as appropriate: Auto, Shift & Add / Auto, and Shift & Add / Model (see the REDUC Shift & Add Mode section above). For each recorded drift, the group of REDUC measures typically followed this pattern:

1. Select best 25% of all frames in the drift.

Make Auto mode measure (average of individually-measured frames).

2. Shift & Add all selected frames. Make Auto

Table 1. Early Measures with a 0.3m Dobsonian Telescope and the Video Drift Method

WDS	Discovery	WDS Mags	Date	PA	+- σ(PA)	Sep	+- σ(Sep)	# Drifts	Frames
01171+5631	BU 3	8.1 10.5	2011.8712	24.5	0.6	4.43	0.07	2	4032
01214+5656	STI 1578	10.93 10.9	2011.8712	8.9	0.6	6.48	0.17	1	915
01221+5627	STI 1585	8.87 12.7	2011.8712	221.5	0.3	9.61	0.07	2	3942
01222+5628	STI 1586	11.12 12.1	2011.8712	245.4	2.2	7.00	0.19	2	3100
01224+5624	STI 1587	11.21 12.7	2011.8712	144.5	0.3	13.05	0.03	2	2916
01233+5634	STI 1594	11.18 11.56	2011.8712	306.1	0.2	15.59	0.15	2	3577
01238+5633	STI 1597	11.47 11.5	2011.8712	345.7	1.2	6.99	0.12	2	3577
01239+5626	STI 1598	11.6 11.6	2011.8712	52.4	2.6	3.94	0.24	1	1657
05173+0557	J 241	11.20 11.5	2011.9781	166.9	0.7	4.81	0.08	1	1285
05268+0437	BAL 2634AB	11.2 11.4	2011.9781	201.6	0.3	17.18	0.10	2	2194
05268+0437	BKO 15AC	11.2 12.0	2011.9781	176.8	0.4	13.28	0.13	2	2194
05282+0442	BAL 2635AB	11.28 12.1	2011.9781	210.4	0.3	6.12	0.03	1	320
05282+0442	BKO 16AC	11.28 12.8	2011.9781	276.4	0.2	30.20	0.08	1	320
05314+0450	BAL 2637	11.03 11.71	2011.9781	292.9	0.2	14.79	0.06	1	1260
05315+0438	BAL 2638AB	12.00 12.1	2011.9781	113.0	0.1	18.47	0.13	1	1776
05315+0438	BKO 18AC	12.00 12.0	2011.9781	85.7	0.3	17.75	0.11	1	1776
05324+0502	BAL 2639	10.5 11.0	2011.9781	72.6	0.4	6.69	0.10	1	970
05328+0436	BAL 2640	11.2 11.4	2011.9781	60.4	0.1	9.61	0.03	1	1282
06256+4323	ES 1534	10.65 11.33	2011.9753	95.2	0.9	2.01	0.02	1	1687
06285+4304	J 910AB	9.94 10.59	2011.9753	338.5	0.5	2.22	0.04	1	1650
06285+4304	J 910AC	9.94 10.62	2011.9753	33.0	0.1	45.95	0.06	1	1650
06291+4240	A 2449	10.30 10.52	2011.9753	244.3	0.3	1.88	0.05	1	1575
06311+4253	ES 1630	11.88 12.0	2011.9753	92.4	0.9	5.18	0.14	2	3155

mode measure (single measure of stacked image).

3. Make Model mode measure of stacked image for close pairs.

This approach was followed two or three times, each time selecting fewer but higher-quality frames (e.g., best 20% and 10%, or best 25%, 15%, 5%).The overall result is typically one VidPro measure and six to nine REDUC measures for each drift. While all the measures are not rigorously independent, because they use some of the same data and the same repeated methods, this approach does give an opportunity for scattered results to appear if large variations are contained in the data.

Uncertainty Statistics

In Table 1, the position angle and separation values are averages of the whole group of individual measures made from all drifts, both VidPro and REDUC programs, and all techniques and samples used within REDUC. Likewise, the σ(PA) and σ(Sep) values are standard deviations of the same entire group of measures. In this way - by taking large samples [multiple drifts (current practice) with many frames in each], by sorting the samples to reduce seeing effects, and by measuring the samples in several ways - it is expected that the statistics and repeated sampling produce improved accuracy and reduce the random errors lurking within individual frames.

In cases where the star components are very faint, very different in magnitude, or very close, the REDUC Auto mode may have difficulty tracking the secondary star reliably. In extreme cases, it was possible to get reasonable results only from the Shift & Add / Model mode.

Comparison with Other Measures

The U.S. Naval Observatory (USNO) maintains the database of all published double star measures summarized in the Washington Double Star (WDS) Catalog. One of the main database benefits is to provide the data from which binary star orbits can be modeled, leading to improved estimates of stellar masses. When used for calculating orbits, measures are given weighting factors based on their quality. Weighting criteria include telescope aperture, observing method (visual, photographic, CCD camera, speckle interferometry, etc.), and other factors.

One way measures are evaluated by USNO is to compare them with well-defined binary orbits in normalized plots similar to Figures 11 and 12 (Hartkopf et al., 2013). Although the author has not yet observed enough well-studied binaries to make definitive comparisons, most of the stars of Table 1 were measured since 1990 by well-established observers or surveys with aperture equal or greater than the author's (0.3m). These sources, which are assumed to be more accurate than the author's, are noted in the legends. Each increment, ΔSep or ΔPA, is the measure of Table 1 minus the measure of the more accurate source. "USNO Speckle" indicates speckle interferometry measures of Mason et al., (2001 and 2012), aperture 0.7m; "Tycho/Hipparcos" is the well-known astrometry satellite, aperture 0.3m; "2MASS" is the Two Micron All Sky Survey, aperture 1.3m; and "BKO CCD" indicates the measures of Ladanyi & Berko (2002), aperture 0.4m with a CCD camera.

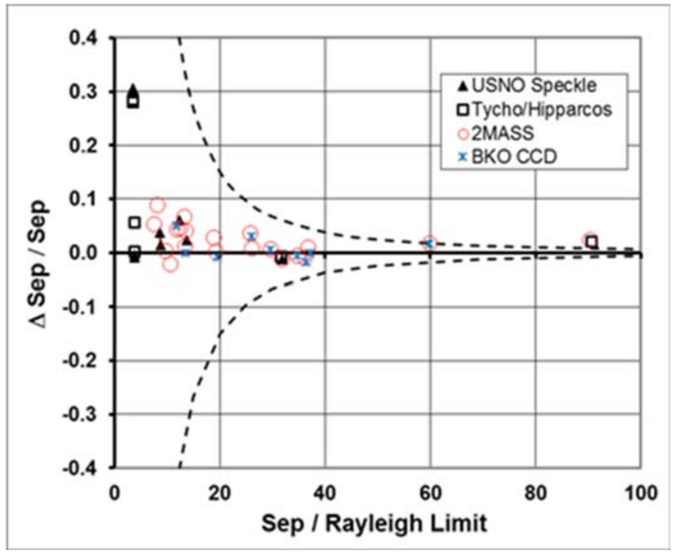

Figure 11. Separation accuracy comparison.

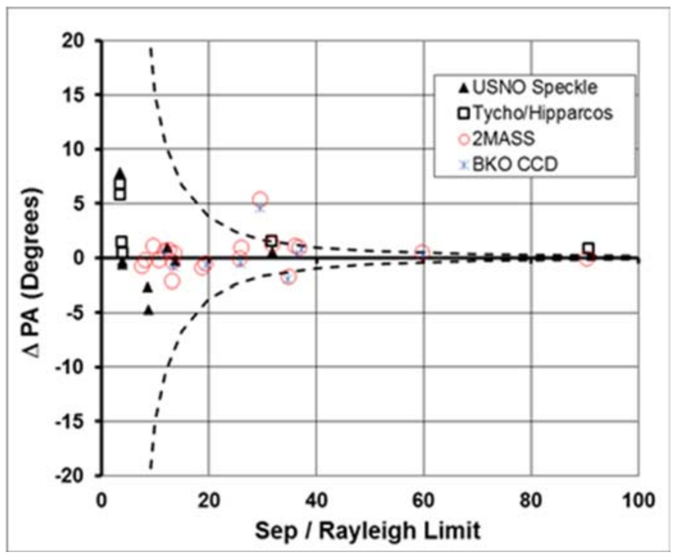

Figure 12. Position Angle accuracy comparison.

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

The dashed lines, which are inverse square functions of the normalized separation (X-axis), correspond approximately to boundaries of the O-C data shown in the USNO Sixth Orbit Catalog for all measures of binaries having well-defined orbits; thus they represent the uncertainty envelope of many measures, many observers, and virtually all methods. The Rayleigh Limit is about 0.5 arc second for the 0.3 meter aperture if the peak sensitivity of the CCD video detector is assumed to be at a wavelength of 600 nm.

For the small data sample available, most of the separation increments fall well within the dashed bounds in Figure 11, as expected. The PA increments of Figure 12 are more scattered, with one point far above the dashed boundary line. This point is for the pair BAL2637, discussed below.

It must be noted that all the measures of Table 1 were originally reduced with a systematic error which effectively stretched the frames horizontally. This error was not discovered until revealed in comparisons similar to Figures 11 and 12. This issue is discussed in the section on Error Sources below, and may be the topic of a separate paper (Wasson & Nelson 2015).

It should be possible to improve the quality of future measures by recording more drifts and by using higher magnification for close pairs. Nevertheless, the comparisons of Figures 11 and 12 generally validate the Video Drift Method as applied to measuring double stars with a Dobsonian telescope.

Individual Star Notes

STI 1578

Both stars appeared very faint in the unfiltered CCD video, with the secondary (northern component) appearing slightly brighter (probably redder), as seen in Figure 13 (96 x 96 pixels). The pair was not visible in the video until after the REDUC Shift & Add technique was applied, based on the brighter star approximately 2' north. This measure was made 100 years after the first measure of 1911, but several other measures have also been made recently. North is up and East is left in Figures 13 through 17 and Figure 19.

STI 1586

Based on WDS magnitudes (11.12, 12.1), the secondary seemed quite faint and the primary much brighter. As shown in Table 1, the PA uncertainties were unusually high (±2.2°). Because of the faintness of the secondary, all measures used the Shift & Add mode, but the primary star shape was odd, and a faint artifact appeared between the stars, perhaps caused by telescope collimation errors.

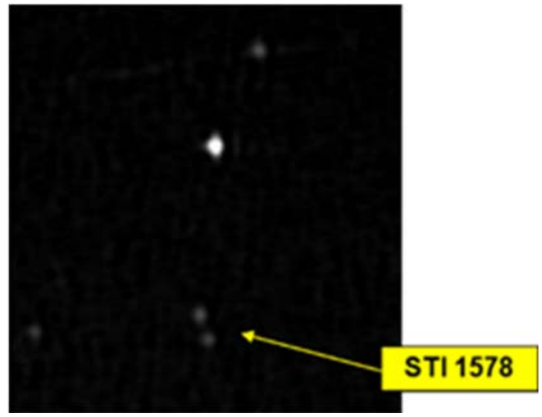

Figure 13. The field of STI 1578.

STI 1597

The PA of the original measure (167°) has been flipped 180° in more recent measures based on the southern star being brighter. The WDS gives virtually the same magnitudes for both components (11.47 and 11.5), but the secondary component appears considerably fainter in the unfiltered CCD Shift & Add frame of Figure 14 (64x64 pixels).

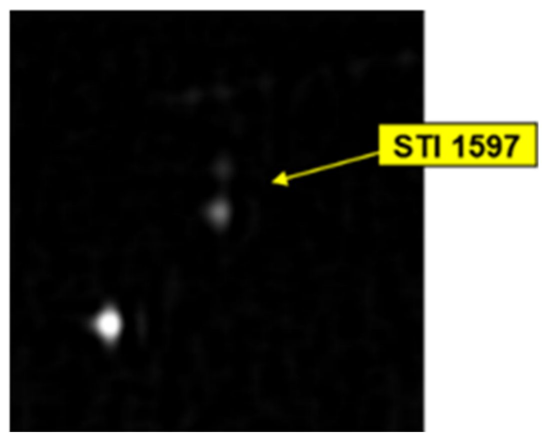

Figure 14. The field of STI 1597.

BAL 2634AB, BKO 15AC, AD

The AB components were discovered in 1910 by Baillaud; C and D were identified by Ladanyi and Berko (2002). WDS lists both C and D as magnitude 12.0, but D appears much fainter than C in the unfiltered CCD video, as seen in Figure 15, a Shift & Add image of the best 130 of 907 total frames.

BAL 2635AB and BKO 16AC

Unfortunately, the field was not centered well, and only one drift was taken, so only 320 frames near the western edge of the field were available for analysis.

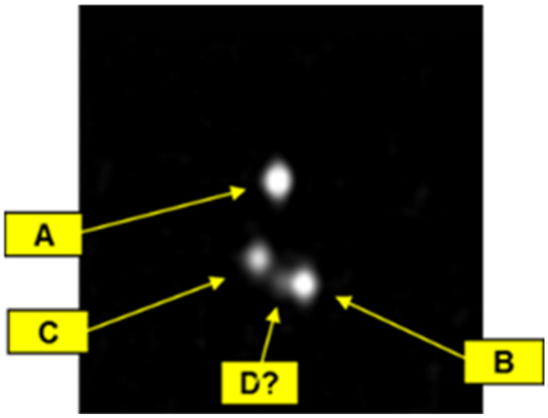

Figure 15. BAL 2634AB and BKO 15AC, AD.

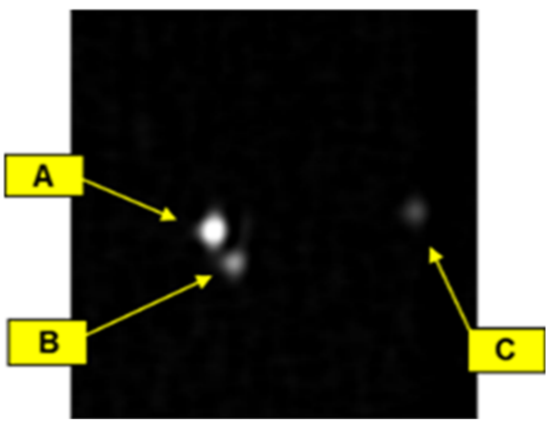

Figure 16. BAL 2635AB and BKO 16AC.

BAL 2637

A Shift & Add image of this pair is shown in Figure 17 (64x64 pixels). The PA measure apparently has a large error, but the Sep error is small. Upon plotting all the historical measures, which have a large gap from 1895 and 1910 until the Hipparcos satellite in 1991, a pattern emerged in both PA and Sep which may indicate significant orbital motion, as seen in Figure 18. Therefore, the PA difference from the three most recent measures, which were clustered in 1999 to 2001, does not seem quite as bad.

J910

The AB pair has a separation of only 1.7" (Mason et al., 2001) and was not intended for measurement. However, it appeared elongated, as shown in Figure 19 (64x64 pixels), and was measured "for practice" with

Figure 17. BAL 2637.

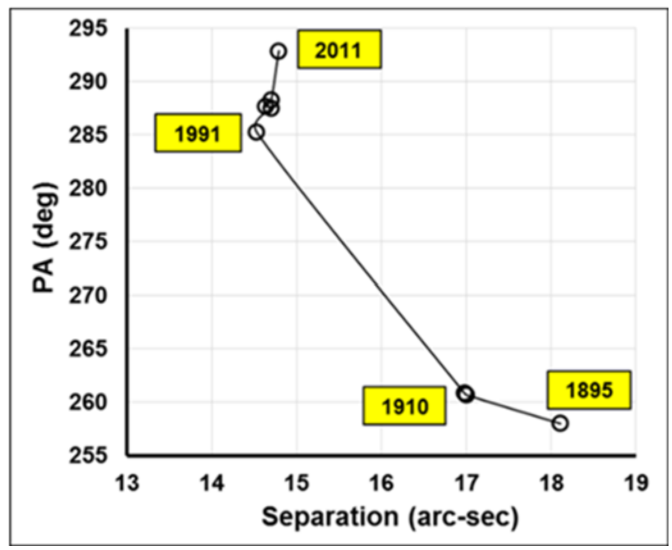

Figure 18. All historical measures of BAL2637.

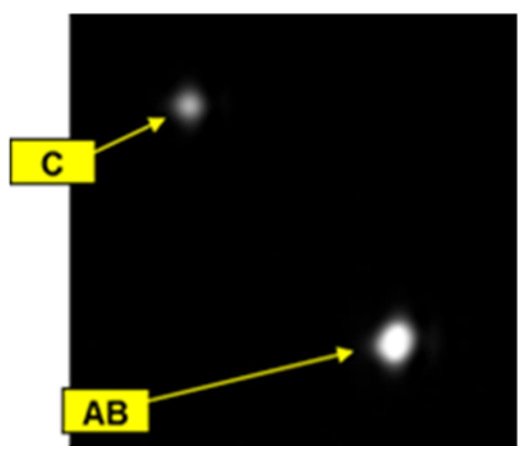

Figure 19. J910 with elongated image of AB.

the REDUC Shift & Add / Model technique. The large errors in both Sep and PA (Figures 11 and 12) indicate that AB is not an appropriate target for a focal length of only 1.5m. However, it is probably bright enough to measure much more accurately with a 3x Barlow. The historical measures are rather scattered, but indicate there may be some orbital motion, so this pair deserves closer observation.

The pair AC was the original target. Although the widest separation presented here, it still shows slightly higher errors than expected in Figures 11 and 12, perhaps influenced by the elongated primary.

Video Issues

Rectangular Camera Pixels

The Sony EXview HAD CCD detector, which was designed specifically for low-light video surveillance applications, has rectangular 9.6μ (horizontal) x 7.5μ (vertical) pixels. In ordinary CCD cameras, digitization takes place as each pixel is read out. However, a video camera operates as an analog device, producing a voltage as its output. Each CCD row corresponds to a video line scan; the pixels of that row produce changes in the voltage as they are clocked out at a specific frequency.

In digital video, the camcorder samples and digitizes the voltage signal, writes the digital data to cassette tape or memory card, and displays it on its own monitor. Sampling and digitization of the analog voltage occur at a frequency within each row (line scan), according to NTSC standards, that gives 720 samples per line. This standard timing coordination within each line scan creates a correct image for each video frame, *regardless of the original shape of the CCD detector pixels*. Rectangular pixels have the effect of under-sampling horizontally, compared with vertically. However, correct (undistorted) digital images *should* be presented for calibration and measurement. Details of video operation and standards may be found in on-line articles, such as Matrox (2003) and National Instruments (2011).

The Video Stretch Problem

As astronomers, we are used to CCD cameras, where the pixels forming an image are fundamentally important. But video transformation from analog to digital is not as straightforward as one would like to assume. In the analog video world, with a heritage set in stone decades before the digital age, the essentials are line-scan voltage, frequencies of line scan voltage and line shift, and *all* the lines (some for image, some for timing pulses and some blank); these analog elements play together nicely to provide a TV picture. Pixels are an artificial afterthought!

As Pirazzi (2011) puts it, on his humorous and extraordinarily educational web site, “We blissfully assume that the image size of the picture is totally standardized and represents the ‘complete’ picture. And, we assume that the pixels are square: that 100 vertical pixels is the same distance on the display monitor as 100 horizontal pixels. Unfortunately, we're in for a rude awakening, because in many important cases that we must handle in video software today, *some or all of these assumptions are wrong.”*

Pirazzi’s words came true for the author; when comparing his measures with the recent better-quality measures of other observers, discussed above - *stars with large separation also had large* <u>*differences*</u> *in separation*. While in search of the reason, he discovered that the effective pixels he was measuring had been *stretched horizontally 12.5%!* This is not noticeable in frames displayed on the computer screen, but it is as though the sky had been stretched wider than the view originally seen by the camera – fatal for double star measurement.

Based on key information from the .avi file headers, provided by Nelson (2014) for files before and after processing by VirtualDub, it was verified that the program had effectively stretched the pixels horizontally, distorting the physical shape of each frame. It happened when the input .avi video file *Aspect Ratio* (original video display AR = width/height = 4/3 = 1.333) was changed in writing the output .avi file (AR = 3/2 = 1.5) for display on the computer. Virtual Dub stretched the pixels inadvertently (by 1.5/1.333 = 112.5%), without even dealing with them directly!

The author’s unfortunate experience is one of the hidden pitfalls of “standard” digital video. Users of other cameras, camcorders, or software may encounter similar problems, but with a different amount of stretch. The best way to avoid problems is to understand the video history, digitization, and display processes by taking a “crash course” (Pirazzi, 2011), enabling one to be on the lookout. If issues are encountered, there are ways to correct for them *before* data reduction (Nugent and Iverson 2014).

Improved standards of High Definition video (1080 HD) should reduce similar problems for HD, but have probably not eliminated them completely.

Correction of Measures

Since all calibration and measurement starts with the output .avi video files from VirtualDub, all the essential quantities were distorted: Drift Angle, Plate Scale, Position Angle, and Separation. But all was not lost - the author derived equations for the geometry of true vs measured quantities by starting with the fundamental stretch problem, summarized in equations (6) and (7).

$$\Delta X_{True} = \frac{\Delta X_{Measured}}{1.125} \quad (6)$$

$$\Delta Y_{True} = \Delta Y_{Measured} \quad (7)$$

Since the data reduction process had consumed several weeks of spare time, the data were not re-reduced, but were corrected to the "true" values in a spreadsheet. The corrected measures are presented in Table 1 above. The corrections are not described further here – details and insight into the pitfalls of standard DV may be the topic of another paper (Wasson & Nelson, 2015). Ironically, Richard Nugent (2014) had notified the author about the same problem just a few weeks before he discovered it for himself, but he did not yet appreciate its significance.

How to Avoid the Stretch Problem

After further investigation, a very simple way to avoid the "stretch" problem was found within the VirtualDub program itself: the capability to override the defaults in order to maintain the Display Aspect Ratio (i.e., the picture shape) of the output .avi file the same as the Aspect Ratio of the original video camera analog picture [DAR = 4(H)/3(V) = 1.333]. This will be easily accomplished as a routine part of the first video editing step in future data reduction, using existing VirtualDub standard video "filters" to re-sample (interpolate) the horizontal line scans properly to maintain Aspect Ratio.

The potential for picture stretching is believed to be a danger for all combinations of video cameras, digital recorders, and computer upload software, but can also be easily avoided by the simple solution available within VirtualDub. Details are planned for a future paper, but the author can provide an outline of the process by email, for anyone interested.

Initial verification of the VirtualDub process to maintain Display Aspect Ratio has been completed satisfactorily. Several of the widest doubles in Table 1, chosen because they had the largest errors due to the stretch problem, were re-reduced completely, in both VidPro and REDUC. The residuals were similar to those of Figures 11 and 12, but in all cases were even smaller, averaging about 40% of the "corrected" values shown in those plots. This initially validates both the corrections used for the measures presented in Table 1, and the new VirtualDub process to avoid the stretch problem in the future.

Other Possible Error Sources

Random vs Systematic Errors

Random errors occur in all measurements, but tend to cancel out as the number of samples gets larger.

Systematic errors are a major recurring problem in scientific measurement, because they do not randomly cancel, but tend to bias the results. Even when they are identified, they may be difficult to correct.

"Unknown unknowns" may be the worst type of errors, because we don't know their size or direction, and we don't even know their identity! The "stretch" problem described above was a prime example of an unknown-unknown-systematic error.

Several identifiable error sources, most of which are unique to the Video Drift Method as used by the author, are discussed below. However, the list is never complete.

Calibration Error Estimates

The VidPro .csv files give the brightest pixel of star images as the location of the star, so there is always some uncertainty due to seeing or telescope movement (wind, vibration, etc.) which affect calibration results.

Model Assumptions: In order to estimate the approximate size of Drift Angle and Plate Scale uncertainties, let's make the following assumptions for a simple drift model:

1. The central pixel location of any star image may be off by +-1 to +-4 pixels randomly in both X (row) and Y (column) position, for the author's nominal focal length of 1.5 meters; since the plate scale is approximately 1"/pixel, this assumption corresponds to an 8" "seeing disk," which may include some telescope movement.
2. For a poorly-aligned frame, the drift covers 470 of the 510 horizontal pixels and 100 of the 492 vertical pixels - a large 12^{o} Drift Angle.
3. The GPS time of any frame may be off by 1 millisecond. Frame intervals are about 0.033 second, but the GPS time of each frame is more accurate.
4. The star declination is zero (fastest drift).
5. Drift time is 30 seconds.

Drift Angle Calibration: For Drift Angle, the pixel location error of any given frame (a few pixels) will be largely offset, during the linear regression fit, by similar random errors in other frames. When taken over hundreds of pixels across the chip, the Drift Angle calibration uncertainty should be very small, probably a small fraction of a degree.

When optical magnification is used, the pixel uncertainty is also magnified, but the chip size and number of pixels do not change. Therefore, the Drift Angle calibration uncertainty should grow roughly with the magni-

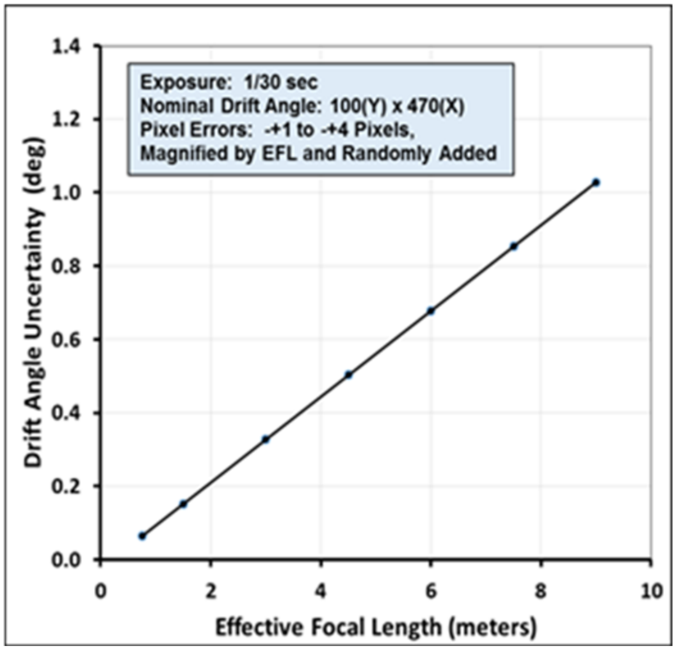

Figure 20. The effect of random pixel location errors on Drift Angle calibration.

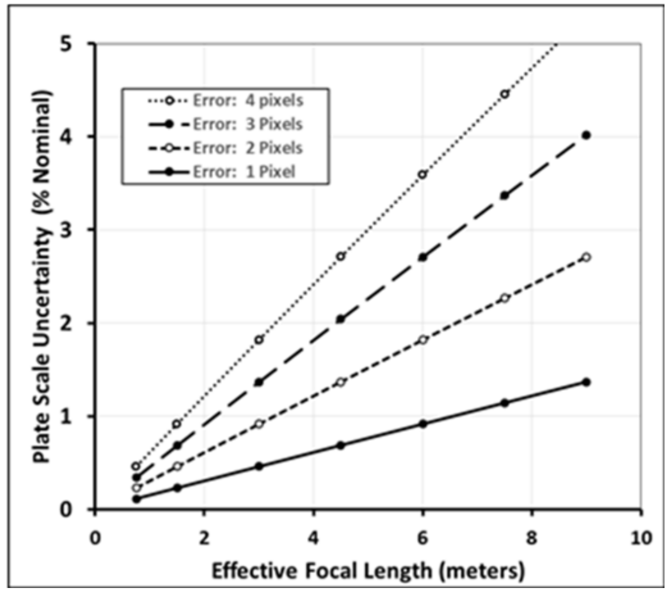

Figure 21. Effect of pixel location errors on Plate Scale calibration.

fication (i.e., effective focal length), as shown in Figure 20. To generate this plot, the linear regression was resolved for each EFL, after adding the magnified pixel errors, and the nominal Drift Angle was then subtracted to get the uncertainty.

Since each new drift has unique errors, randomly different from those of other drifts, the errors of multiple drifts should tend to cancel. Therefore, as effective focal length increases, it becomes more important to record extra drifts, to mitigate the growing Drift Angle calibration errors of Figure 20.

Plate Scale Calibration - Time: Substituting the GPS time error (2 x 0.001 second) into equation (1) and normalizing by the nominal plate scale (about 1”/pixel), we have the estimated plate scale calibration error of equation (8), which is very small. Even if magnification of several times were used, and normalized by a nominal scale several times smaller, the GPS time error would still be small.

$$\Delta Scale(t) \approx \frac{(0.002/481)\bullet 1}{1} \approx 0.006\% \qquad (8)$$

Plate Scale Calibration - Location: The plate scale calculation of equation (1) depends on the brightest pixel locations in the first and last frames only. Figure 21 shows the impact of pixel location uncertainty on plate scale calibration, which directly affects the measured separation. Plate scale uncertainty is fairly small at the prime focal length of 1.5 meters; even adding 4-pixel errors in both the first and last frames produces an error less than 1%. However, the uncertainty grows linearly with higher magnification (effective focal length), and becomes large at longer focal length if 4-pixel errors occur.

A way to reduce the impact of plate scale calibration errors is to record and analyze more than one drift, just as discussed above for drift angle errors. Of course, this requires more time and more data reduction work, but the overall quality of the measures may be significantly improved by averaging out some of the errors of those few key first and last frames.

As a compromise between quality and practicality, the author’s current typical practice is to make three drifts with no added magnification, but adds more when higher magnification is used.

The estimated errors discussed above are representative of the author’s telescope and camera. Reduced errors may be achieved with a camera that has more pixels, making longer drifts possible. But more pixels may also mean smaller pixels, so the brightest pixel location uncertainty would increase again. Generally, using a Barlow or eyepiece projection to better separate close doubles will increase the errors, because the star images, seeing distortion (and resulting brightest pixel uncertainties) are magnified.

Optics of Fast Reflectors

Double stars have traditionally been measured with

Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

telescopes of moderate to long focal length, such as refractors and Cassegrain reflectors, with good reason. According to Taylor (2012), the "fast" mirrors (f/6 or less) of most modern Newtonian reflectors, especially Dobsonians, are at a great disadvantage when attempting to resolve double stars approaching the theoretical resolution of the primary aperture, e.g. the Rayleigh criterion.

Fast Newtonian primaries require a larger secondary mirror obstruction, displacing more light from the Airy disk into the diffraction rings. Coma begins to expand the Airy disk quite close to the optical axis; although not noticeable visually, it nevertheless degrades the image. Collimation errors displace the optical axis away from the center of the field of view, increasing the coma at the center. Short focal length also makes focus more critical and more difficult.

The combination of poor collimation plus coma produces asymmetric star images, even for a perfectly-figured mirror; the Airy disk is expanded and the centroid is biased radially – a classic systematic error!

The small size of the video camera detector generally forces the drift to be near the center of the field. But Taylor (2012) shows how very small the "critical" field is, for coma to be smaller than the Dawes Limit (roughly 20% smaller than the Rayleigh criterion). The critical size of the field for the author's 12-inch f/4.9 (EFL =1500mm) Newtonian, when perfectly collimated, is only about 2 arc minutes across, smaller than the field of view of the CCD chip! It is easy to keep a star from drifting along the top or bottom edge of the field, but some degradation of the Airy disk seems unavoidable with Dobsonian telescopes during the eastern and western portions of the video drift - exactly where the plate scale calibration frames used in equation (1) come from!

For perfect collimation, longer focal length generally expands the size of the "critical" field as the square of the f/ratio. For a 12-inch at f/7, the field in which theoretical resolution can be achieved approximately doubles to 4 arc-minutes. A Barlow or eyepiece projection must be used to increase the effective focal ratio, for measuring separations approaching the Rayleigh criterion, but coma may still be present if poor collimation displaces the optical axis away from the center of the magnified field of view.

Special effort is required to collimate fast reflectors; methods typically used for visual observing are probably inadequate, leaving the optical axis still somewhat displaced from the center of the field. The best collimation method, but also perhaps the most difficult, is the star test. The goal is to intermittently see segments of diffraction rings distributed *concentrically* around the Airy disk of a star at the center of a small, high-power field, even while the rings are continuously fragmented and scattered by the seeing – easier said than done! But useful measures of slightly wider doubles are still practical, as demonstrated herein.

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Measuring Double Stars with a Dobsonian Telescope by the Video Drift Method

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Rick Wasson, Sunset Hills Observatory, Murrieta, CA, is a retired Aeronautical Engineer, and has been an amateur astronomer for about 60 years. His main interests are double stars, asteroid occultations, photometry, and spectroscopy.