Tools and Techniques for Measuring Asteroid Occultations with DSLR and CCD Cameras

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Abstract

Currently most asteroid occultations are measured with video equipment. This technique is limited to stars bright enough to be measured at 30 frames per second and limits participation to observers that have portable low-light video and time standard tagging equipment. This paper presents new observation tools and analysis methods that allow the larger community of astroimagers to make precise occultation measurements with tracking telescopes and DSLR or CCD integrating cameras.

1. Introduction

Occultation events occur when one body, typically non-luminous, passes directly between an observer and a more distant luminous body, completely blocking the distant body's radiation. Occultations are a sub-class of transit events. This special alignment of the observer, distant object, typically a star, and the occulting body provides an opportunity to determine the shape of the occulting body. The most typical forms of occultation measurements are performed on asteroids passing in front of stars and lunar limb features passing in front of stars.

For the case of asteroids, if we know the orbit of the asteroid with sufficient precision to predict the transit, we also know its distance to the observers and its apparent velocity in the plane perpendicular to the observer's line of sight. With this information, simple algebra and multiple observers it is possible to accurately render the cross sectional profile of the asteroid.

With the advances in precision stellar and asteroid astrometry in combination with low cost computing power, it is now possible to predict, with reasonable accuracy, many more occultation events than ever before. For lack of sufficient observers, many of these events are under recorded.

Currently, most occultation observers are diligent shadow chasers. They are typically equipped with telescopes, low light video cameras, a time standard capable of imprinting accurate time codes onto the video, and a video recording system. With this equipment they do fantastic work. This type of equipment is pretty specialized and requires a commitment to this type of observation that not many observers are going to make. At the same time telescopes, DSLR cameras, CCD cameras and computers proliferate.

Drift scan imaging is a known technique for using this most common type of astroimaging of equipment to measure occultation events. The method allows integrating cameras to make accurate occultation observations. Historically, the precision of this method was limited due to time jitter in the observation. This situation has changed with the proliferation of smart-phones, GPS's, computers and wireless networks.

This paper presents an overview of how to make drift scan occultation measurements using modern timing and geodesy technology. It also presents an overview of currently available free computing tools to assist in making these measurements. Finally, it introduces a set of freely distributed tools developed by the author to facilitate occultation planning, observing and data analysis.

We are near a tipping point in occultation astronomy. The correct equipment is in enough hands. Enough events are being predicated with sufficient accuracy that observers may wait for events to come to them. The tools are freely available. The time has come when drift scan occultation observation now belongs in every astroimager's repertoire. And perhaps soon it will become the predominant method for occultation observation.

2. Drift Scan Fundamentals

Traditional video occultation measurement methods point a telescope at the star to be occulted and record the star's image 30 frames or 60 fields per second. To measure an occultation one examines the video frame by frame measuring the star's brightness.

The brightness of the star is plotted against the time coded frames to look for the time and duration of the star's dimming or complete disappearance. This is a mechanization of the visual method of calling out the events seen through the eyepiece, recording the observations on audio tape, while a time signal plays in the background.

Drift scanning uses a different method. One starts to make a traditional long exposure image, but at a precise moment prior to the predicted occultation the user disables, or retards, the clock drive of the telescope. This results in stars being trailed. In some variations of the method, the drive is re-enabled. By measuring the star trail's flux verses position in the image, the precise time and duration of the occultation can be determined.

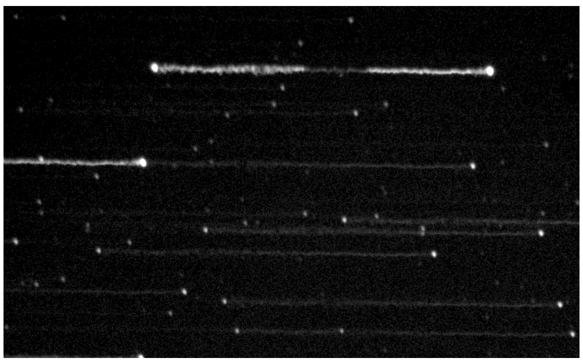

Figure 1. Drift Scan Occultation Observation Example

Figure 1 shows an example of how a drift scan observation appears in an image. In order to determine the precise time and duration of the occultation, the observer needs to know the time that the drifting began, and the rate of drift. Provided the observer knows the rate of drift in pixels/second, reduction becomes a straight forward measurement and calculation.

3. Drift Scanning vs. Video

Drift scanning has both disadvantages and advantages when contrasted with video measurements. The greatest strength of the drift scan method is that integrating cameras, particularly in the case of CCD cameras, have better signal to noise ratios than video cameras. Video signals rarely approach 10 bits signal to noise ratios. DSLR cameras typically have 12 to 14 bits S/N ratios, and cooled CCD's can have 14 to 16 bits S/N ratios. Additionally, since you read out your imager only once, you have only one unit of readout noise per pixel, as opposed to 60 per second. This latter advantage is only significant if your drift rate is less than 60 pixels/second. The other strength of this method is that by varying your plate scale or drive speed, you have complete control over the drift rate. This allows you trade off timing accuracy for improved signal to noise ratios by lowering your drift speed.

These two advantages provide the ability to measure events, albeit to lower resolution, than are simply inaccessible to video, for a given aperture of telescope.

The method's greatest weaknesses is that time jitter in the triggering of the drift tends to be larger than in video measurements. Even if the power to the telescope drive is interrupted, flywheeling of the motors and energy stored in the scope power supply capacitors will cause the drifting to begin some time later than when it is triggered. In the case where the drive servos are commanded to stop or retard, the delay in the servo motor loop will cause the drifting to be delayed by the servo latency.

4. Drift Scan Planning

The first step in making an occultation observation is to locate events proximate to you. IOTA, the *International Occultation Timing Association,* has a wonderful web site that will show you predicted events in your vicinity. I am particularly fond of Steve Preston's *Worldwide Occultation Prediction Page.* It provides a concise summary of upcoming events with a notation of the broad geographical regions from which the event is expected to be visible. If an event is going to be visible in your broad geographical region, you can then link to a more detailed map of the shadow's path across the Earth. If this looks like something accessible to you, you can then download a summary of the occultation event and the visible path with 1 sigma error margins.

Upcoming Events:

April 2012

Event Date/Time	Rank	Asteroid	Star	Visibility	dM D A	Details
07 Apr , 12:40 UT	53	(161) Athor mag 12.8	UCAC2 21109150 mag 10.9	W Mexico, New Zealand	2.1m 8.3s 81°	[Mar 31 23:05]
07 Apr , 12:54 UT	45	(778) Theobalda mag 15.5	UCAC2 15772636 mag 10.9	Australia	4.6m 7.1s 74°	[Feb 09 08:07]
08 Apr , 03:38 UT	99	(165) Loreley mag 13.7	2UCAC 38785762 mag 13.2	SW USA, Mexico, Venezuela	1.0m 18.2s 68°	[Mar 31 23:07]
08 Apr , 05:02 UT	10	(3346) Gerla mag 16.4	2UCAC 11856157 mag 9.5	Brazil, Argentina	6.9m 2.6s 56°	[Jan 10 11:46]
08 Apr , 06:49 UT	42	(341) California mag 13.3	TYC 5545-00242-1 mag 10.0	N Canada	3.4m 1.5s 25°	[Mar 31 23:09]
08 Apr , 07:41 UT	0	(120061) 2003 CO1 mag 20.3	UCAC2 23171710 mag 13.2	South America	7.1m 8.5s 88°	[Mar 10 09:44]
08 Apr , 08:07 UT	67	(196) Philomela mag 12.1	2UCAC 22091680 mag 12.5	SE USA	0.6m 11.1s 52°	[Feb 11 01:32]
08 Apr , 13:18 UT	16	(2288) Karolinum mag 16.0	HIP 91652 mag 10.1	S Pacific	5.9m 1.5s 54°	[Jan 10 11:49]
08 Apr , 15:36 UT	99	(702) Alauda mag 12.8	TYC 7890-01339-1 mag 12.0	Antarctica, SW Australia	1.2m 39.8s 50°	[Feb 11 01:33]

Figure 2. Occultation Event Summaries

Once you have located an event, you need to pick a site from which it will be observed. If you are fortunate, the site may be your own back yard, or your observatory site. More likely you will need to travel some distance, so prior planning is key. To facilitate this effort the author has developed a utility that converts occultation event summaries to ".kml" files that load as overlays to Google Earth's application.

The application is titled *Occultation Maps*. When run from a PC it presents a screen as shown in Figure 3.

Once you have loaded an event, the header summary of the event shall appear in the dialog's main window. Assuming you already *have Google Earth* on your computer, simply click on the "Convert and View" button. Shortly, the globe will be displayed with the shadow path and 1 sigma error estimate imposed over it

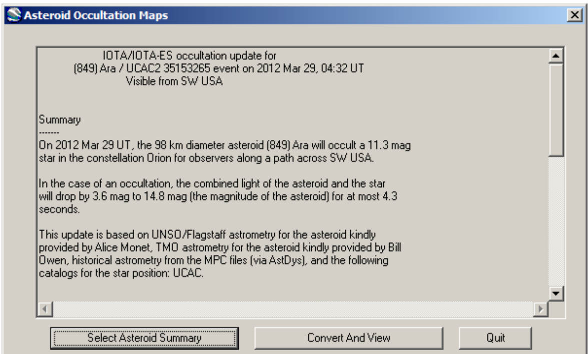

Figure 3. Google Earth Map Generator

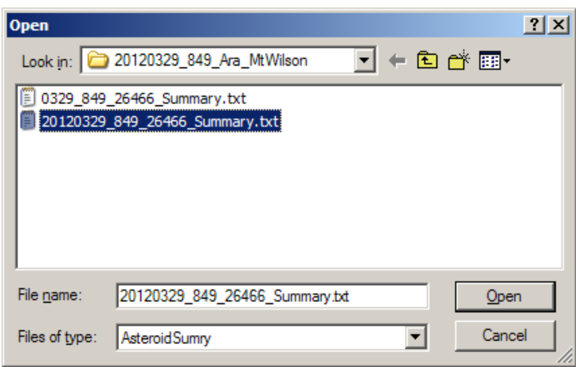

Figure 4. Loading An Event

Once you have the path in *Google Earth*, it is easy to use the interactive controls and overlays to locate an observing site that provides you with convenient access and infrastructure. For the event pictured in Figure 5, it was fortunate that the path of expected visibility passed directly over the Mount Wilson Observatory.

With the permission of the facility superintendent, I was able to set up in their 16-inch dome to attempt to view this event.

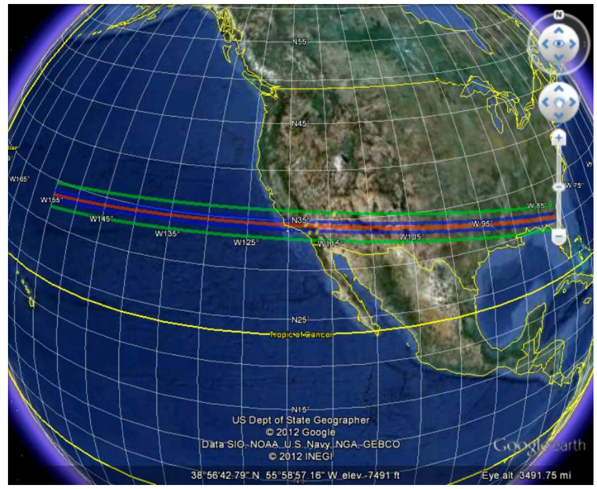

Figure 5. Shadow Path In Google Earth

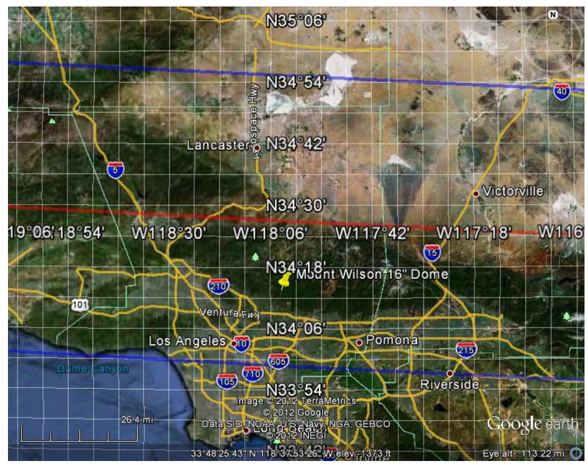

Figure 6. Site Selection

5. Making The Observation

Since you should have selected your opportunity well in advance, best practice is to setup and configure your gear a week or so ahead of time and rehearse. This will prevent nasty surprises, such as overcrowded star fields, poor signal to noise ratios, faulty cables, missing software, over filled disk drives, etc.

The keys to making a good observation are being on target, getting a good exposure, accurate timing, and precise geodesy. All of these can be practiced in your backyard BEFORE you go, should travel be required. Once you can do it perfectly in your yard, you can pack everything that is there and know you will have all the tools required when you get to your site. Even if the site is your own yard, you will have worked out all the kinks when you are not under the gun.

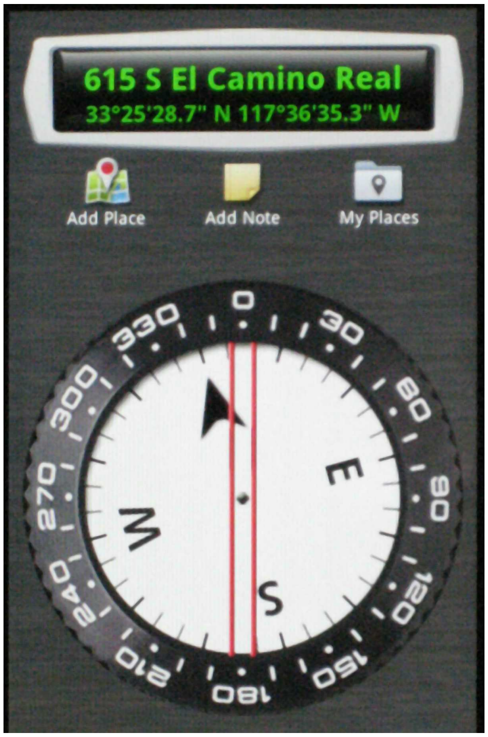

Figure 7. Cell phone GPS/Compass

First, work out the exact location from which you will observe. This is easy if you are already using Google Earth. Just put a pushpin on your site and read out the latitude and longitude. Alternatively, if you must change locations at the last minute, you can retroactively locate the site in Google Earth, or often smart cell phones now contain GPSs that can give your exact location.

Next, select your drift method. The two primary choices are "Drive Off" or "Drive Guided". The "Drive Off" method simply removes power from your telescope and lets the Earth's rotation move the stars across your image frame. This is absolutely the simplest method. It can be as simple as:

1. Centering Your Star
2. Starting Your Exposure
3. Punching off the power switch on your telescope as you listen to WWV on a shortwave radio.
4. Waiting for your exposure to finish.

A more complicated method may use a computer triggered switch or relay to interrupt the power to your scope. This approach takes human reaction times out of the equation and does not impart motion to the scope. Regardless of the method used to perform a "Drive Off" observation, the drift rate will be a function of your plate scale and the declination of the target star.

The formula to convert pixels to time for "Drive Off" observations is:

$$\frac{PS \times Length}{15.041 \times Cos(Dec)} = T$$

Where:
PS = Plate Scale (arc sec/pix)
Dec = Declination of Target Star
T = Duration of Event
$Length$ = Length of Event In Pixel

While this method is easy, it does mean that you will need to employ focal reducers and/or binning of your images to adjust the plate scale to fit the brightness and duration of your event.

The other observing method, that I call "Guided Drift", requires you to have a telescope with either an autoguider port, computer commanded tracking rates or slewing. In this method you command the telescopes servo system to alter its drive rate by initiating a guiding command, or altering the drive rate for a fixed amount of time, starting before the event and ending after the event. This method requires a computer with a connection to your telescope, but has the advantage that you can precisely tailor the drift rate to suit your instrument's sensitivity. Additionally, data reduction does not require any astrometry to solve plate scales on your images.

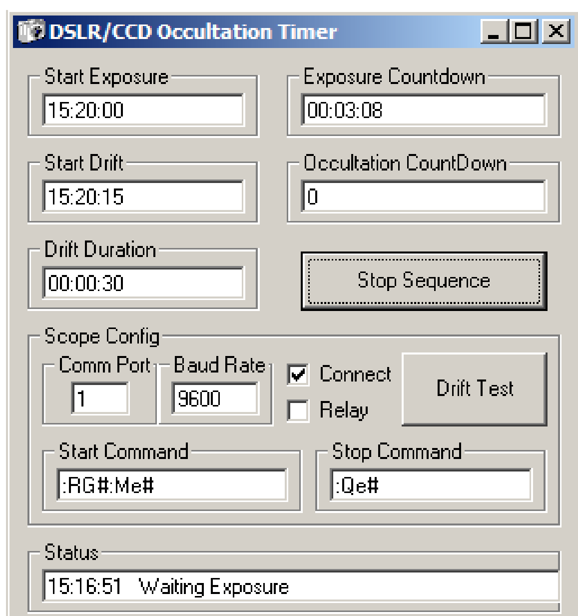

Figure 8. Drift Scan Trigger Screen Shot

The author has developed a PC application that controls this process. Once you have entered your event parameters, the software alerts you as to when to start your exposure. After that, all the key timing events are triggered automatically. The application is titled *Drift Scan Trigger.* Figure 8 shows a screen shot of the application.

To use the "drift scan trigger" program with telescopes that accept guiding and tracking commands directly from their serial ports, simply connect your PC to you telescope. The command sequences to start and stop drifting can be entered in the "Start Command" and "Stop Command" windows.

In the example in Figure 8, the program is configured to command a generic Meade telescope to apply east guiding for the drift duration. Since my Meade telescope hand controller lets me specify a guide rate from 1 to 100 percent of sidereal rates, I can pre-configure my scope with a tracking rate appropriate to my target. A guide speed setting of 100% effectively halts the drive system on my scope.

If your scope lacks the ability to serially command the drive system, it may still be equipped with an auto guiding port. Typically, these are presented as modular phone connectors where the grounding individual pins cause the scope to slowly guide east and west in RA and north and south in DEC. In these systems, you can build a simple serial port controlled switch to interface with the scope's guider port. A schematic for a simple control is shown in *Figure 9.*

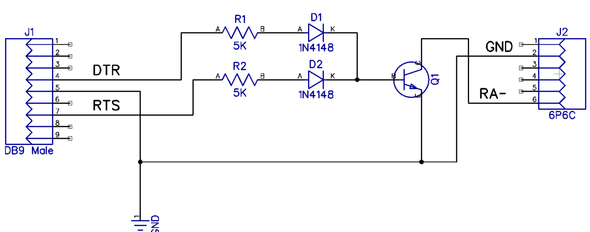

Figure 9: Guider Input Interface

Finally, you can modify the circuit in *Figure 9* to activate a relay interrupting power to your telescope.

If you are using the guider interface or a relay, you need to check the relay box in the program to change the way the serial port is commanded. Otherwise, uncheck the relay box if you are serially commanding your telescope.

To use the Drift Scan Trigger program, synchronize your computer's time with a standard time signal (see section 6). Next determine how long you want to drift. Your drift time should be longer than the expected occultation duration plus 2-sigma of the expected time and an additional margin for trigger.

Configure the start time to be at least 15 second prior to the start of the drift timing, and be sure your total exposure time leaves some additional time at the end of the drift sequence. This will cause you to have two bright images of your target star in your exposure with a thread of light between recording the target star's flux during the drift interval.

There is a Drift Test button that allows you to simulate the event instantly. This allows you to frame your target. Start your exposure and click on "Drift Test". The program will command your telescope through the same sequence of commands that will be sent during the event. It allows you to inspect your result and if necessary adjust the position of the target star in the frame or modify your drift rate or plate scale to optimally capture the event.

When your occultation event time nears, click the "Start" button. The status line will count down the time until the start of the exposure. Starting 6 seconds before the exposure, the computer will start beeping at one pulse per second to prepare you to start the exposure. As the program counts to 0, start your exposure. From here on, all the critical actions will be triggered under computer control.

6. Precise Computer Time

The key to success with drift scan method is having the computer clock maintain as precise a time as possible. If you computer has a broadband Internet connection, keeping precise time is easy. There are a number of excellent programs that will synchronize your computer's clock with the National Institute of Standards and Technology's atomic clock. My personal favorite is *Dimension 4*. Once loaded, it runs in the background, waking up at programmable intervals, pinging the Atomic clock and updating your PC's clock.

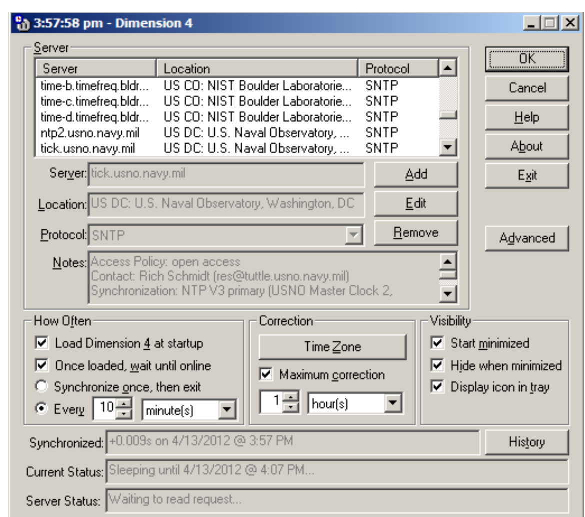

Figure 10. Dimension 4 Screen Shot

One of its excellent features is keeping a running history of its corrections so you can get an estimate of the drift rate and the statistical accuracy you may expect from your observations.

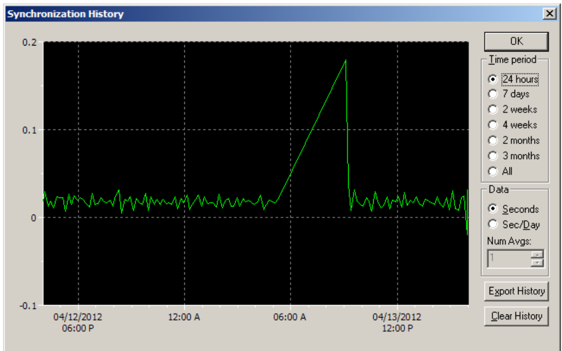

Figure 11. Time Correction History.

Figure 11 indicates that my machine tends to stay within 10 msecs of standard time as long as I maintain an Internet connection. Left on its own, it drifts at a rate of 180 msec in 3 hours, or 60 msec per hour.

This tool is even useful in the field. As long as your observing location has 3G or 4G cell phone service, you can tether your phone to your computer, run *Dimension 4* and have time accurate to 10 msec.

Figure 12. USB GPS Receiver

In the event you do not have network connectivity, there are two other methods that are very reliable. First is WWV and WWVB, the NIST radio stations that transmit time signals on 2.5MHz, 5MHz, 10 MHz and 15MHz. When using these sources, I turn on only the computer and radio and keep them as far apart as I can and still hear the radio. My experience is that these signals can be difficult to use near computers, telescopes and cameras that all emit radio interference. But if you use WWV to sync your clock shortly before observing and have characterized the clock drift with Dimension 4 previously, you can still get pretty accurate results.

NEMA GPS signals are the final option. An inexpensive USB GPS module runs about $25 from various Internet vendors. It looks to the computer just like a serial port connected to a GPS receiver.

Several years ago the author developed a utility to capture locations information and synchronize computer clocks from GPS serial data streams.

One of the well known problems with GPS/NEAM data streams is that they show a delay between the correct time and the output of the time string that is device dependent. However it is the author's experience that while these delays differ from device to device. For a given device the delays are relatively constant. For that reason, the *GPS Geodesy* program includes a "Delay" parameter field. It contains a static correction to be applied to the GPS time standard prior to its being applied to the PC clock.

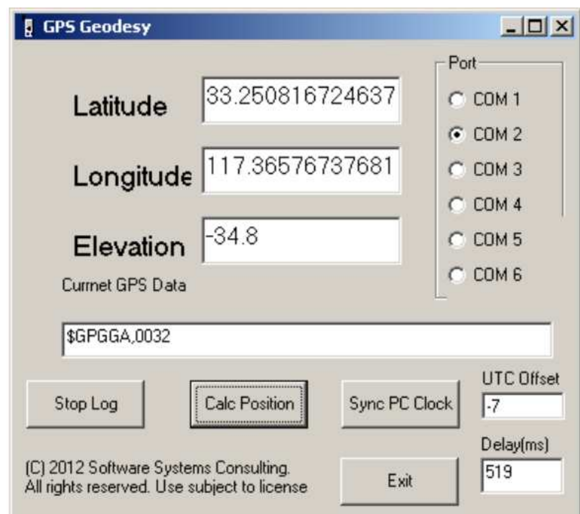

Figure 13. GPS Geodesy Screen Shot

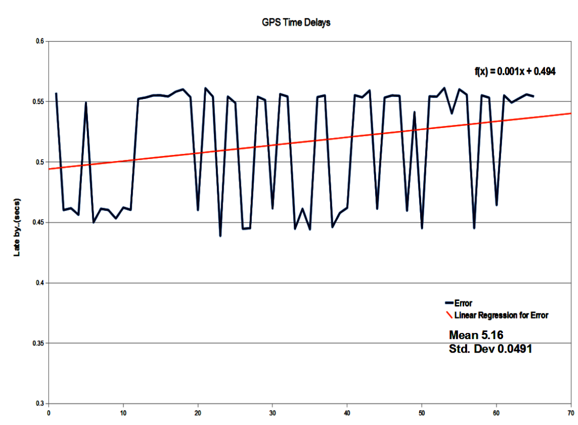

Figure 14. GPS-NEMA Jitter

Figure 14 shows the results of 60 trials of applying GPS serial time corrections verses Dimension 4 network time standards. It demonstrated that GPS serial data streams provide accurate timing to ±50 milliseconds, 1/20th of a second accuracy from virtually any location.

To characterize a new device, simply connect yourself to the Internet and put the GPS where it can get enough satellites to get a fix. Often you can obtain a fix in a wood frame structure. Then bring up both *Dimension 4* and *GPS Geodesy* on your system. Set the GPS delay to 0 and alternate between synchronizing to network time and GPS time. About 50 or so tries will get you a statistically useful sample population. Now go to *Dimension 4's* history window and export the history file as a CSV file and use your favorite spreadsheet to analyze the results. Take the simple mean and plug it into the *GPS Geodesy* program's delay parameter and you are ready to go into the field.

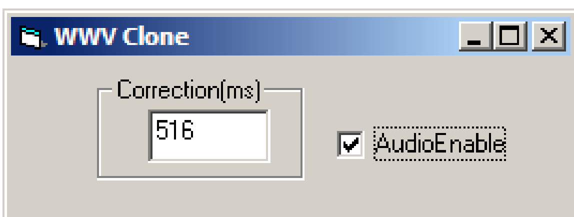

Figure 15. Virtual GPS

The final time tool, developed by the author, is titled virtual *WWV Clone.* It uses the PC's clock and the audio system in a computer, to create a fake WWV audio stream. It assumes the computer has been synchronized with some time standard. The PC itself has some delay inherent in the multimedia system, so the best way to calibrate a computer is to set the computer time via your preferred method and then tune WWV in on a good radio. You can then adjust your correction factor so that your computer's time signals sync with WWV's. The human sense of rhythm is accurate to better than 10 milliseconds. So, when it sounds good, it is good.

With a PC and a WWV clone, you can make drift scan observations by simply watching the PC's clock. Open the shutter on your camera and pull the plug on the right WWV time tick.

Regardless of the drift scan exposure method you employ, the duration of the occultation will be measured very precisely. The primary error will be the time displacement of the observation related to the jitter in the drift triggering mechanism.

7. Data Reduction

The ultimate product of your observation will be the duration and start time of the occultation at your observing location, or lack thereof. Data reduction is the process of extracting that information from your drift scan image.

The steps in data reduction of a drift scan CCD image start out as in any other CCD image, by calibrating for bias, dark current and potentially flat fielding the optics.

To facilitate the easy extraction of the event data, the next step is to rotate the image such that the star trails are precisely horizontal. The tool used to do this should be flux conserving, so as not to corrupt the photometric information in your image.

Next you want to extract the brightness history versus position in your image. Most astronomical image processing tools provide a method for this process.

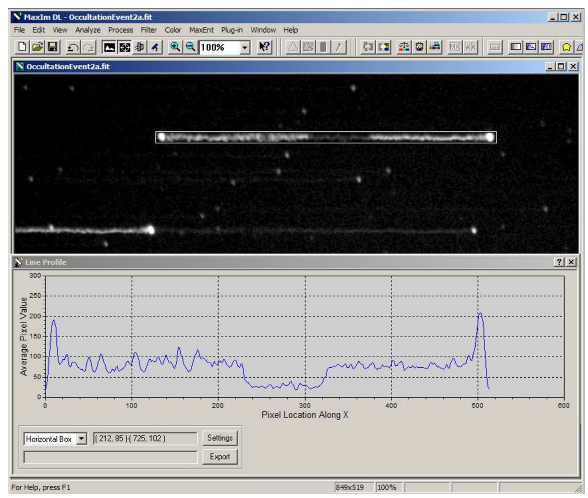

Figure 16. Line Profile Extraction

Figure 16 shows how to accomplish this in Maxim/DL. Using the cursor, box the target star's trail including both the start and end points. From within the "View" menu, select "Line Profile". Finally, within the line profile dialog box, select "Horizontal box".

At this point you have a graph of the sum of the columns within the box plotted against the row pixels. To maximize signal to noise ratios you want to box the star trail while encapsulating as few of the background pixels as possible.

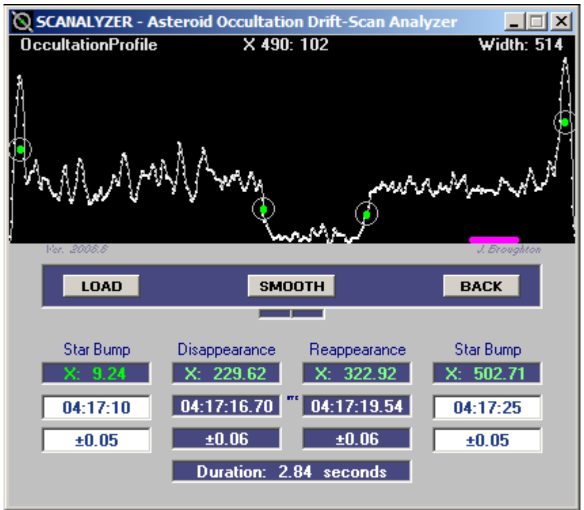

Figure 17. Scanalyzer Screen Shot

Similar graphs can be extracted by IRAF and IRIS. Both are free image analysis software.

At this point there a couple of different ways to go. Easiest in Maxim/DL is to move the over the graph, reading out values. Locate the center of the star before and after the drift. The drfit time divided by the difference in pixels between the two star images is your *SecondsPerPixel* coefficient. Now measure the pixels between start of drift and the midpoint of the occultation ingress. Next measure the duration of the occultation in pixels. Multiplying both values by the *SecondsPerPixel* coefficient to get the timing of the events.

Alternatively, you can export the data to a ".CSV" file and perform similar computations in your favorite spreadsheet.

Finally, John Broughton has developed an easy interactive drift scan analysis tool called *Scanalyzer* that he distributes for free from his website. It takes exported profile drift scan text or .CSV files as input and provides an interactive means to calculate the occultation timing and the error bars associated with the observation. It also has advanced features including time corrections for non linear plate scale distortions.

8. Tool Links

John Broughton. Drift scan tools: Scanalyzer & ScanTracker
http://www.asteroidoccultation.com/observations/DriftScan/Index.htm

Christian Buil. Iris CCD and DSLR image processing and analysis software
http://www.astrosurf.com/buil/us/iris/iris.htm

Cyanogen Systems. Maxim/DL Image Reduction and Analysis Software
http://www.cyanogen.com/

Google. Google Earth Download
http://www.google.com/earth/index.html

Meade Instrument. Planetarium and Image Processing: AutostarSuite 5.5
http://meade.com/software-manuals

NOAO. IRAF- Imaage Reduction and Analysis Facility
http://iraf.noao.edu/
http://acs.pha.jhu.edu/~shy/x-iraf-windows/

Steve Preston. Worldwide Occultation Prediction Site
http://www.asteroidoccultation.com/

Space Telescope Science Intitite. STSCI Data Analysis System - IRAF Extensions
http://www.stsci.edu/institute/software_hardware/stsdas

SSC. Occultation Tools: GPS Geodesy, Asteroid Occultation Maps, Drift Scan Trigger
http://www.ssccorp.com/Observatory

Thinking Man's Software. Dimension 4 - Network Time Synchronizer
http://www.thinkman.com/dimension4/

Do not forget to report your observations. There is strength in your numbers, but only if you share them. For full instructions on reporting your observations see:

http://www.asteroidoccultation.com/observations/

9. Conclusion

The odds are that if you are reading this article, you have all the necessary equipment and expertise to observe an occultation. Give it a try. You may not always see the occultation, but that is where the asteroid isn't and that fact is worth reporting. And you may find that measuring an asteroid's cross section is exciting. You and a handful of collaborates can solve the cross section of an asteroid with observations that span a handful of seconds. Shape modelers spend a lot more time for their results!

10. Acknowledgements

The author would like to thank the Mount Wilson Institute for the use of its facilities while developing and testing the tools referenced in this paper.

11. References

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