Observing the Grazing Occultation of ZC2702 with a USB Video Camera and GPS-Pulsed LED

Frank Freestar8n

This is a report of the October 17-18, 2007 grazing occultation of the 6.8 magnitude star, ZC2702. This observation is unusual because I did it with a USB video camera recording directly to the PC hard disk at approximately 57 fps. Since timestamps are unreliable when recorded by the PC, a GPS-synchronized pulsing LED provided a high accuracy 20ms flash every 1s. A central part of this document is the analysis of the pulses so that I can interpolate the time of each frame precisely, and estimate the reliability of the timing based on the jitter in the frames themselves. I found that the USB camera worked quite well despite a small fraction of dropped frames, and the combination with an accurately pulsed LED provided frame timings at the millisecond scale.

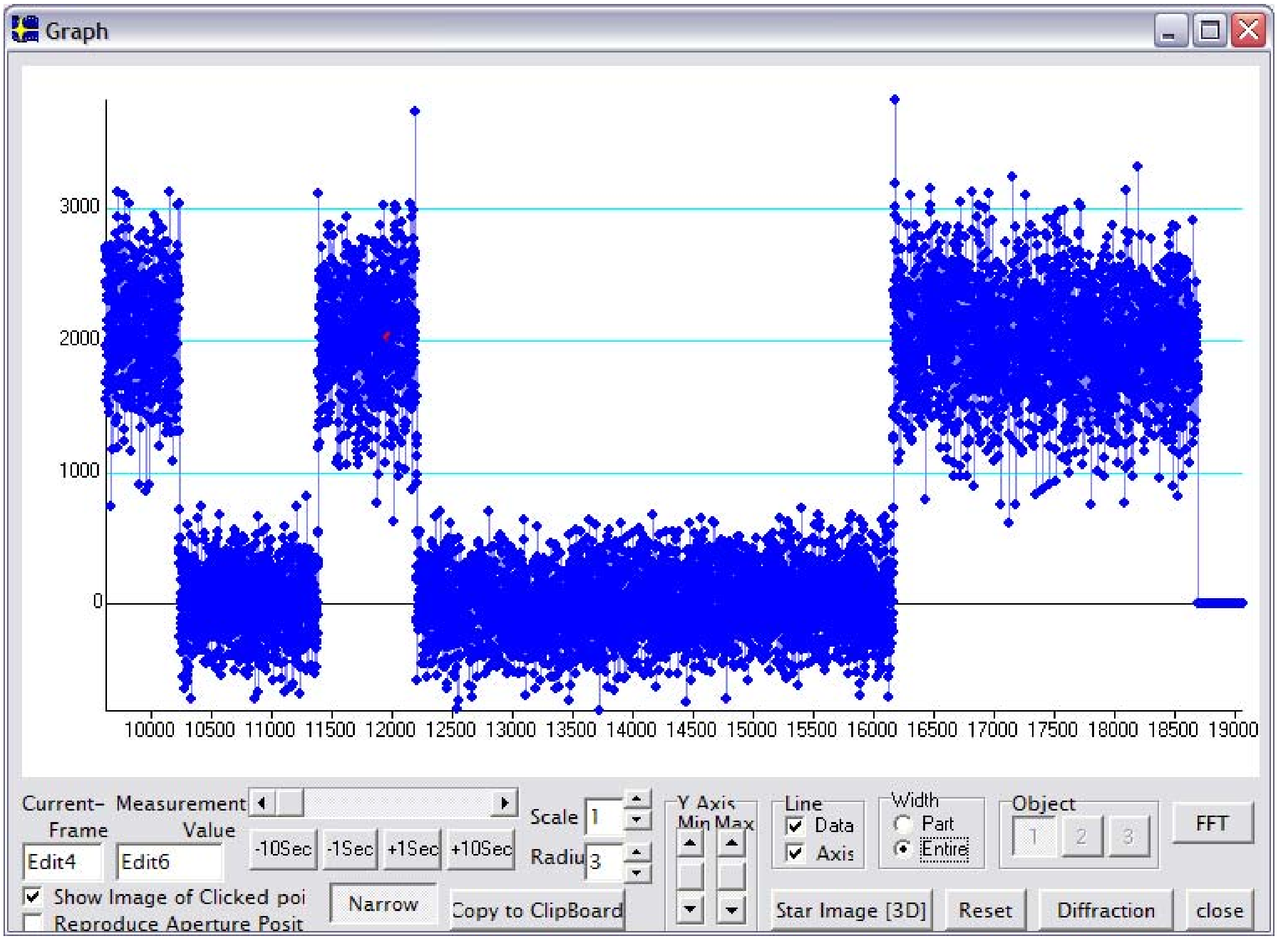
Outline

1. Summary of occultation observation, equipment, and software
2. Why a USB camera: Advantages and disadvantages
3. Details of pulse timing behavior in video
4. Interpolation of frame timing and resulting accuracy based on jitter
5. Diffraction observations
6. Future work

Summary of occultation observation, equipment, and software

I observed the graze of 6.8m ZC2702 from southern New York, USA, at a spot 2.91 km south of the southern limit graze line, based on Brad Timerson's maps at http://www.fingerlakessynthetics.com/occultations/GrazeMaps.html. The moon was at 36% phase and 14 degrees altitude under clear skies with high humidity at roughly 8pm EDT October 17, 2007. I observed with a Celestron C11 on CGE mount, with focal reducer, providing 279mm aperture, f/5, or 1400mm f.l. The camera was a Lumenera SKYnyx 2-0m USB video camera recording direct to disk with the program LucamRecorder, http://www.astrofactum.de/Astrofactum/LucamRecorder/index.htm. This program created a cropped, 240x240x8bit lossless AVI at 57 fps, with a log of timestamps based on the PC clock. To improve the accuracy of these timestamps, I placed an LED pulsing in synch with GPS time in front of the telescope. The LED was driven by a 20ms pulse on each second from a Garmin 18 LVC unit, http://www8.garmin.com/products/gps18oem/spec.html, which has stated accuracy of 1 microsecond.

I recorded four events: D R D R, and all peaks show diffraction effects easily resolved at 57 fps due to the graze angle, as shown below. I then used the LED flashes to interpolate the times of each frame, and fit the resulting events to a diffraction model in LiMovie, http://www005.upp.so-net.ne.jp/k_miyash/occ02/limovie0925.html, to determine their times and graze angles.



Edit4

Edit6

Scale 1

Radiu 3

☑ Data

☑ Axis

○ Part

● Entire

☑ Show Image of Clicked poi

☐ Reproduce Aperture Posit

Why a USB camera: Advantages and disadvantages

Video cameras and camcorders are commonly used for occultation timing because they are inexpensive, compact, reliable, and allow streaming many minutes onto a tape or other medium. They have a disadvantage in that they are designed for everyday, rather than scientific use, and may have compression or other routines that work fine for typical recreational videos, but could produce artifacts on an object such as a star. One commonly used detector for occultations is the PC164C, which is an analog camera that outputs video format in NTSC or PAL. In typical usage, this output is fed into a portable camcorder that records in its own particular format (codec), which is later converted to AVI or similar format for analysis on a computer. Although the final result is binary, there are intermediate stages of analog conversion to digital, followed by compression via a lossy algorithm.

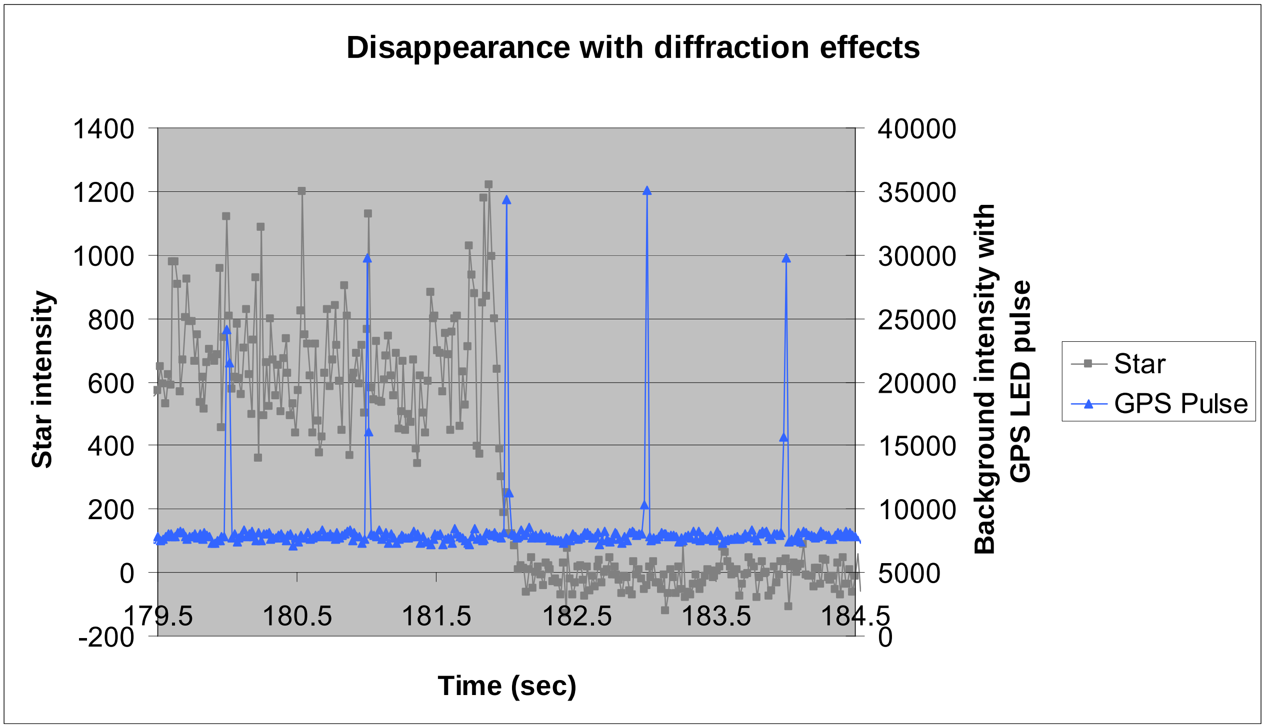
Video astronomy has grown over the years due to increased success of planetary imaging by amateurs with modest equipment. As a result, both software and video hardware have improved, including cooled cameras with croppable output, high frame rates, and lossless storage via either USB or Firewire connections to a PC. With the increased power and offerings in this realm, it becomes attractive to use such a camera for video recording of occultations, particularly since there is no conversion from analog, no loss or corruption of data, and the ability to set frame rates above and below NTSC/PAL.

There are many disadvantages to USB cameras, mainly due to their reliance on a PC to store the data in a real-time application, but also to their lower sensitivity. It's not clear that there should be any fundamental difference in sensitivity, but there may be differences in available cameras due to different chips offered in analog vs. digital video cameras. In addition, since PC's are not primarily designed for real-time usage, there may be dropped frames and misleading timings. Analog cameras have a further advantage that there are conventional means for inserting a video timestamp into the analog stream without perturbing the timing or dropping frames. This is much less straightforward with a USB camera. Furthermore, the need for a PC during video capture may make a setup less robust since camcorders are more designed for operation in the field. Finally, for standalone and remote occultation observations, a PC would have to be hidden and have adequate power to work reliably.

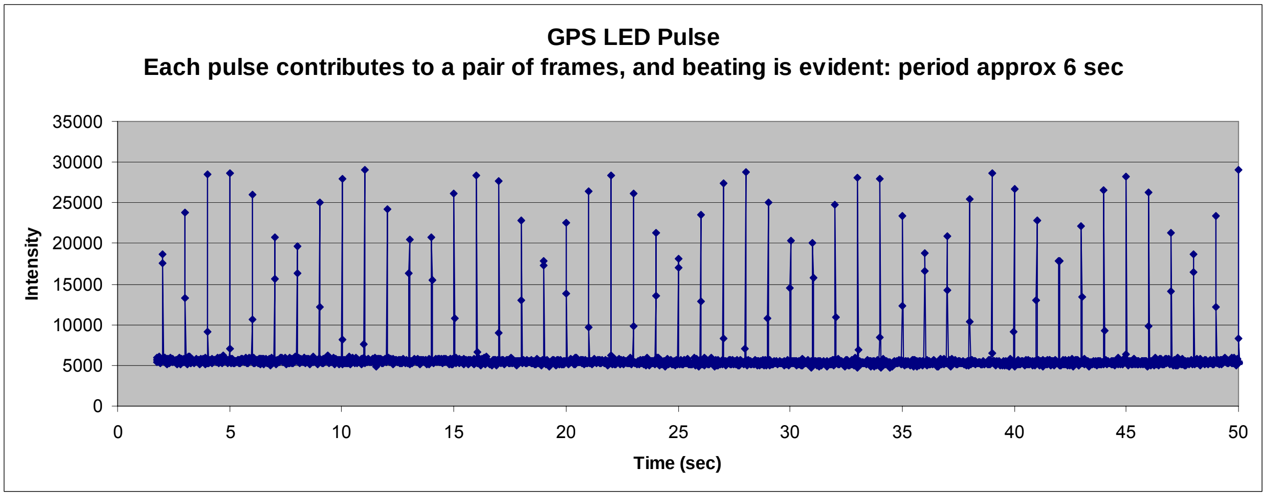
Nonetheless, conveniences such as pure digital capture and the ability to operate at high frame rates and trade off frame rate with exposure time make USB cameras a potentially beneficial alternative.

Details of pulse timing behavior in video.

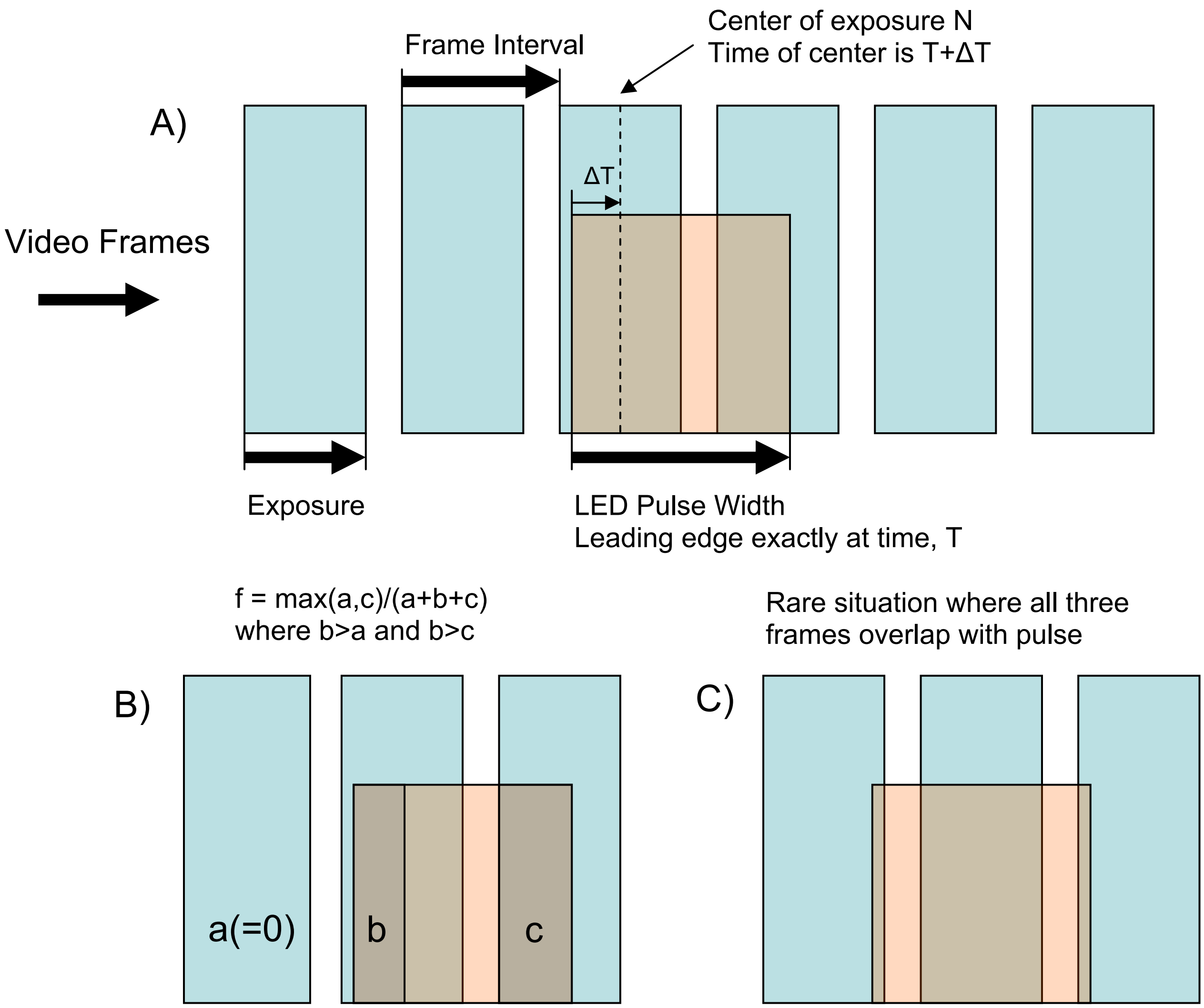
Below is a close up of the first disappearance event on the video. The blue curve shows the background value as it is pulsed by the LED on each second. The gray curve is the star intensity as deduced by LiMovie after background subtracting to remove the pulsing background. The disappearance shows clear diffraction effects, and the pulses themselves show a "beating" behavior since each 20ms pulse touches two adjacent video frames.



The figure below shows the beating more clearly, with just the background plotted.

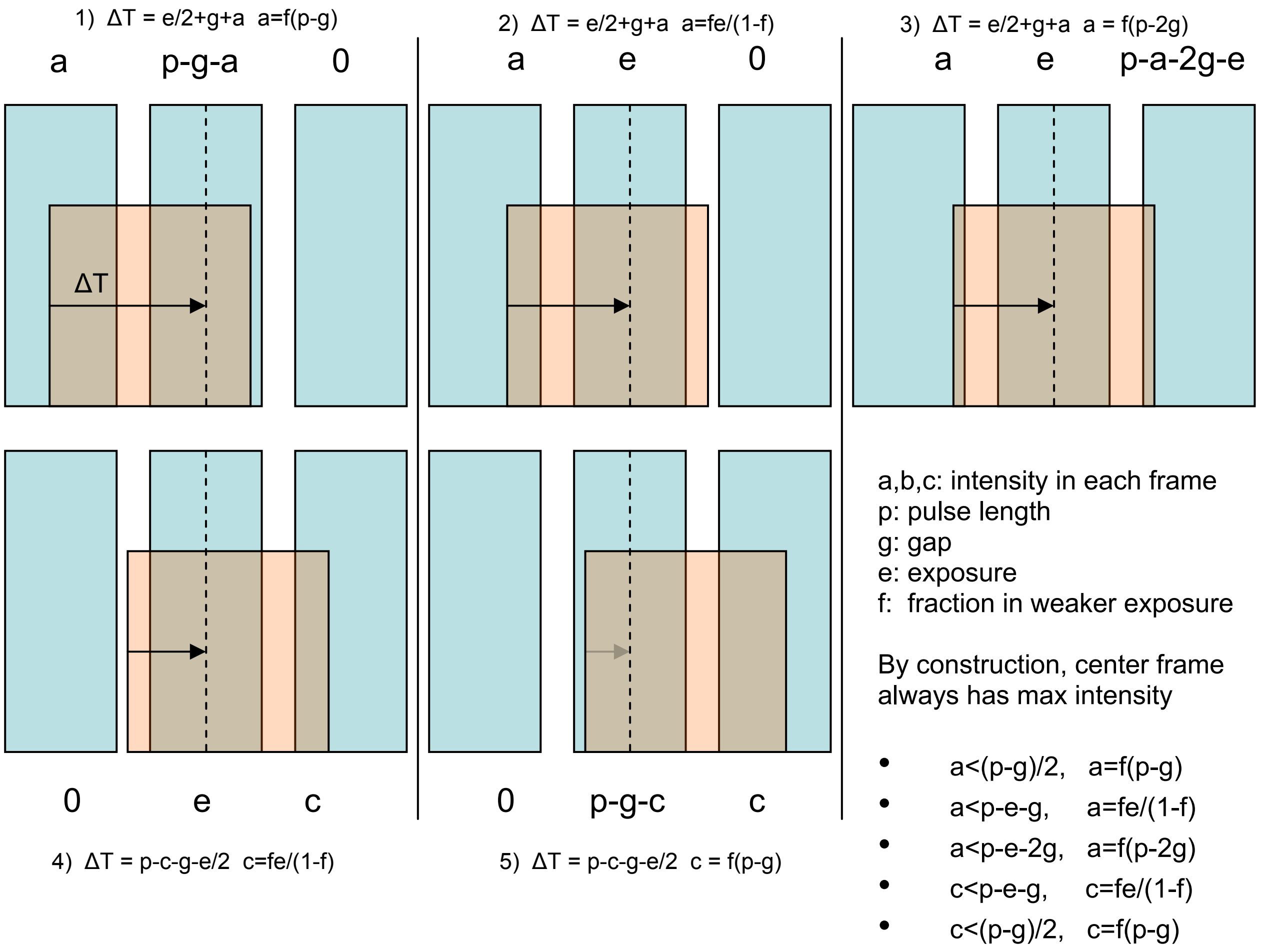


The regularity of the pattern suggests the pulse pairs can be used to interpolate the exact time of the center of each video frame. This is sketched below.



In the sketch above, (A) shows the video stream coming in and being hit with an LED pulse that straddles two frames. The goal is to determine the offset of the center of the central frame from the leading edge of the LED pulse. This is done by calculating the interpolation factor, f, shown in (B), from each trio of overlapping frames with the central frame strongest. A trio is used because of the possibility that all three frames are touched by the pulse, as shown in (C).

There are five possible cases of pulse overlaps, with corresponding interpolation modes, as shown below.



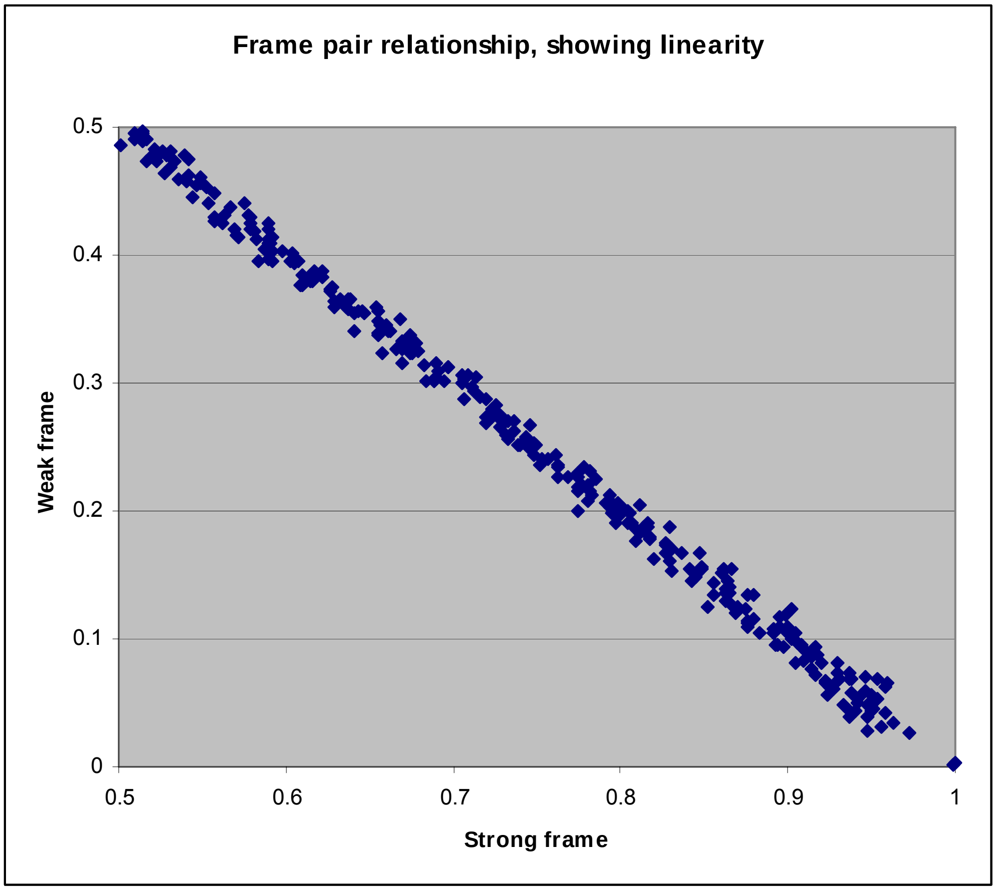
a,b,c: intensity in each frame
p: pulse length
g: gap
e: exposure
f: fraction in weaker exposure

By construction, center frame always has max intensity

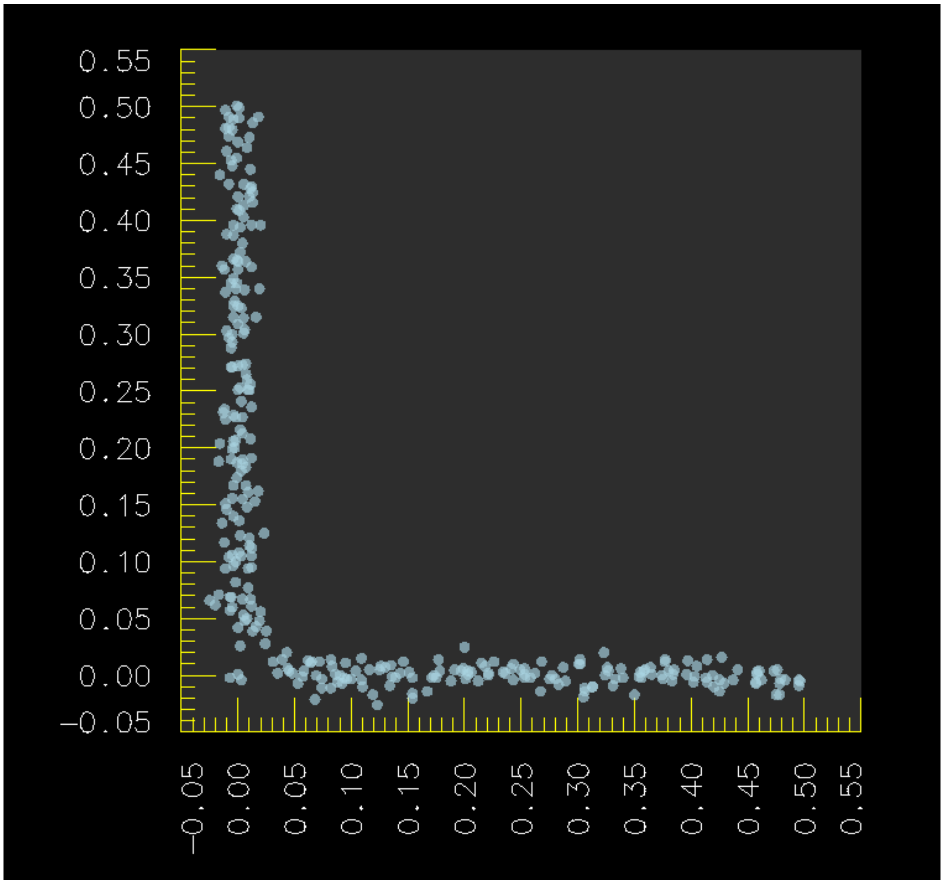
- $a<(p-g)/2$, $a=f(p-g)$
- $a<p-e-g$, $a=fe/(1-f)$
- $a<p-e-2g$, $a=f(p-2g)$
- $c<p-e-g$, $c=fe/(1-f)$
- $c<(p-g)/2$, $c=f(p-g)$

Although five possibilities are shown, for the purposes of this study, with the gap region small and the pulse only slightly longer than the exposure, only a single ratio of the mid-intensity frame to the sum of the three was used to interpolate the frame time.

In order for this method of interpolation to work, the response of the pulses must be linear. For each pulse pair, the plot below shows the stronger pulse on the x-axis and the weaker pulse on the y-axis. The straight line of the plot is consistent with properly linearized video data.



The next plot shows the a and c frames in each trio of pulse frames, i.e. the two frames straddling the central peak. Each is mostly zero while the other is non-zero, except in a very small region where both are nearly zero, which corresponds to the case where the pulse touches three successive frames. This shows as the short diagonal line near 0,0.

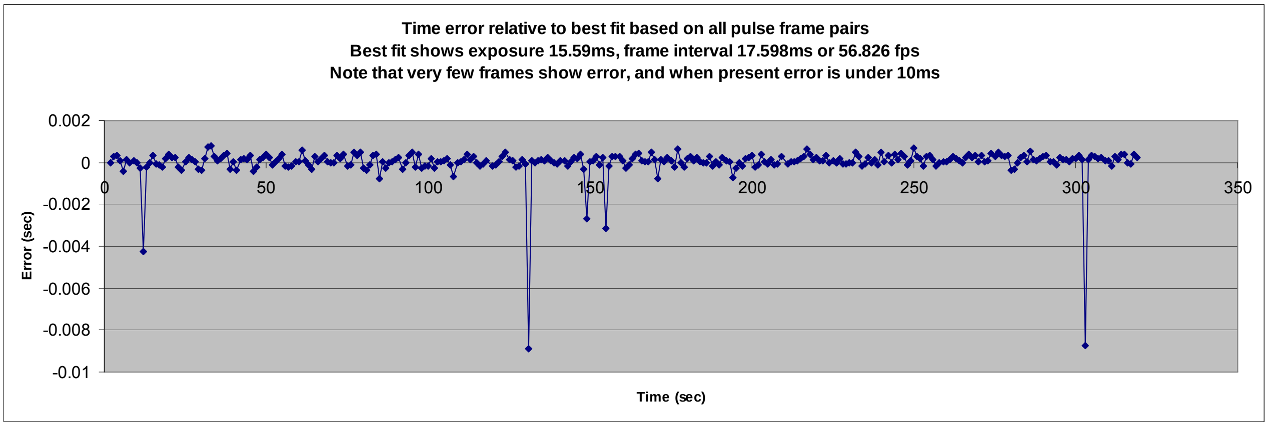


This study was done with version 1.7.0.21 of LucamRecorder, which uses a separate API for writing AVI files. As is common with AVI creation, there are some dropped frames. Since LucamRecorder is mainly intended for stacking images, lost frames are simply discarded, resulting in occasional dropped frames. Other applications, such as LiMovie, that load such avi's, will insert duplicate frames to maintain a fixed time line. Although LucamRecorder provides no direct indication of dropped frames, they can be deduced from LiMovie as pairs of frames with identical measurements.

By studying the LiMovie analysis of the video with a fixed aperture (to guarantee repeated values) I deduce there is roughly a 1.2% chance of a dropped frame in this recording, or on average one per 83 frames. The probability that a given pair containing an LED pulse will have either frame corrupted is then only around 2%. In summary this means that although frames are dropped, the dropped ones can be identified, and the remaining ones are sufficiently numerous to allow synchronization of the timeline.

Note that future versions of LucamRecorder will handle AVI's differently and may result in fewer or no dropped frames. There is also a mode to capture video directly to memory, though the long (8 minutes) of a graze measurement can be large relative to a typical laptop memory. For reference, this 240x240x8bit stream at 57 fps corresponds to 3.2MB/s sustained. This is well within the sustained write rate of a typical laptop, which I think is in the 10-50 MB/s range, though this is hard to determine. This generates 1GB in 5 minutes. The image could be cropped further to 120x120 with a factor of 4 in reduction, as long as periodic error and drift of the star on the mount do not take it out of the field during the recording.

By analyzing the pulse pairs in the avi stream, I could then use Excel and the Solver to determine best fits to the Frame Interval, Exposure, and initial frame offset, based on least squares. The resulting error plot is shown below.



This shows that over five minutes, the center of each frame pair is consistent to within a millisecond. There are 5 pulses that are 5-10 ms in error, but they are due to dropped/duplicated frames that could have been removed directly. The best fit values are FrameInterval = 17.598 ms, or 56.826 fps, and exposure time of 15.592 ms.

To recap, based on pulse pairs that capture the 20ms GPS-synchronized LED flashes on each second, the time of those frames was determined to within a millisecond. This indicates the frame rate and exposure times can be measured very accurately, and the rate of frames is very consistent over many minutes. This gives confidence that frame times between those with LED pulses can be interpolated with similar accuracy.

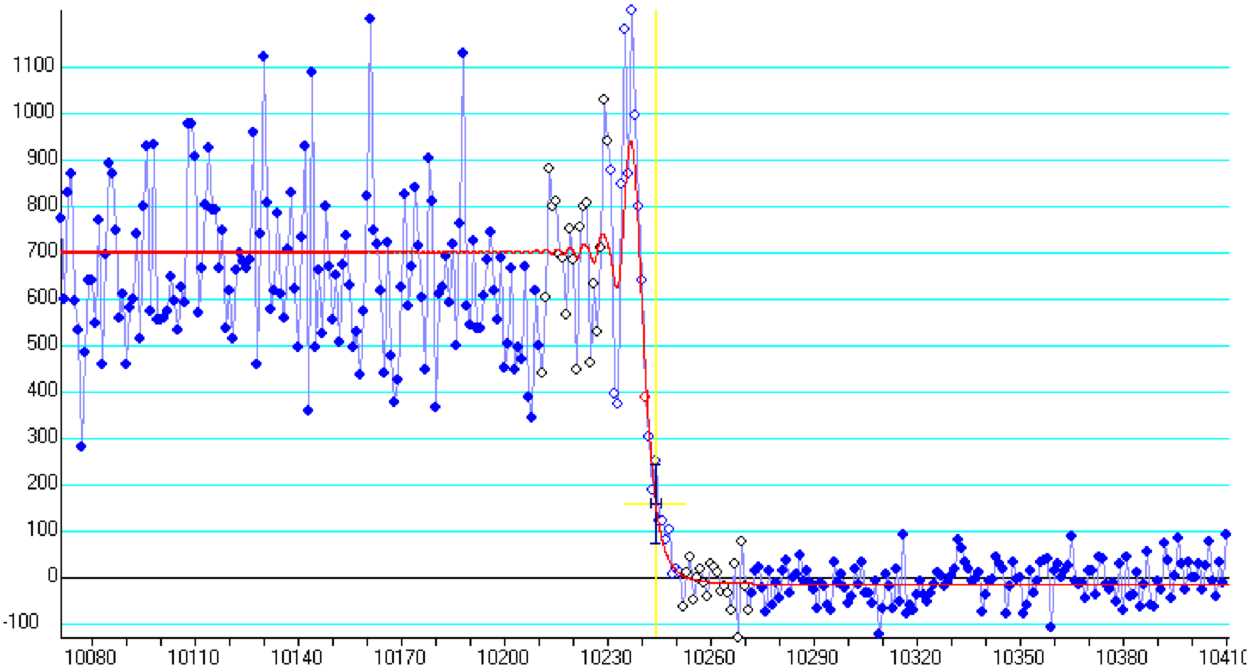
It's important to note that all this timing analysis was done with the occultation recording itself, rather than a separate recording done specific for timing. This means the measurement isn't susceptible to slight changes in frame interval due to temperature or other factors.

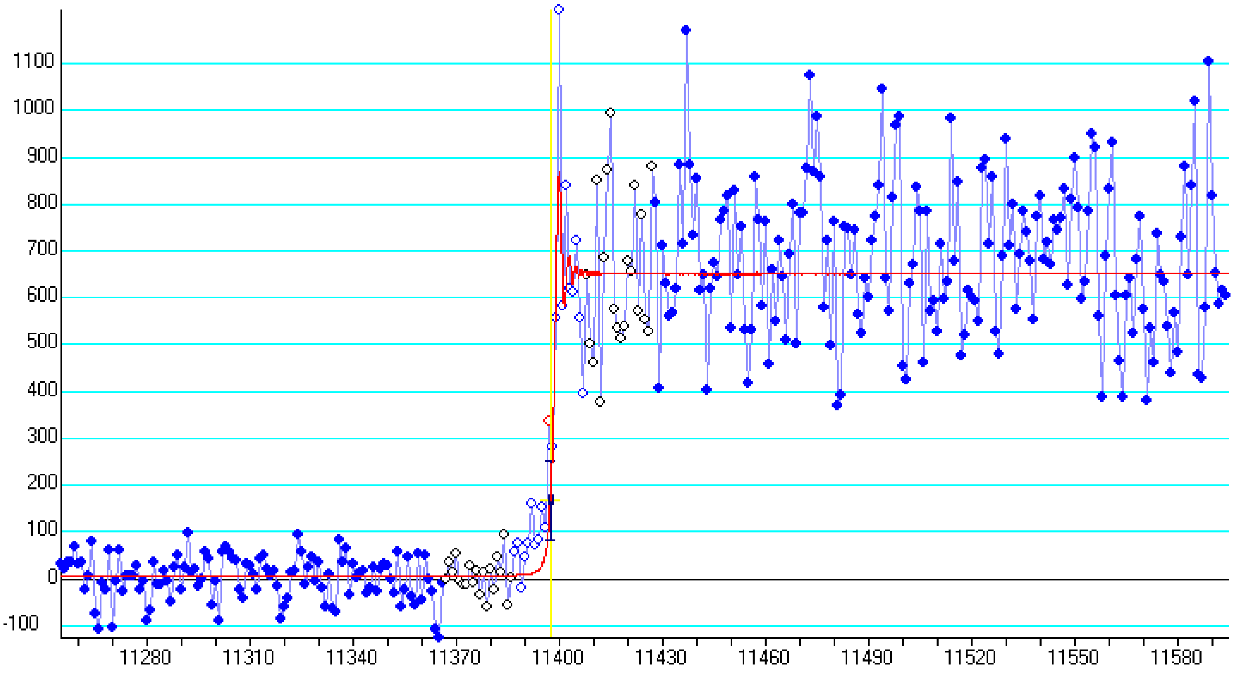
There is a practical detail of determining exactly *which* second each pulse represents. I did this by noting the timestamp of the first frame in the video, as provided by LucamRecorder. This is based on the PC clock. I then used WWV audio to determine, to the nearest second, the true time of the PC clock. I found the PC clock to be about 1.5s in error, which meshed well with the pulse events and pinpointed the actual UT of each pulse, and hence the center of each frame.

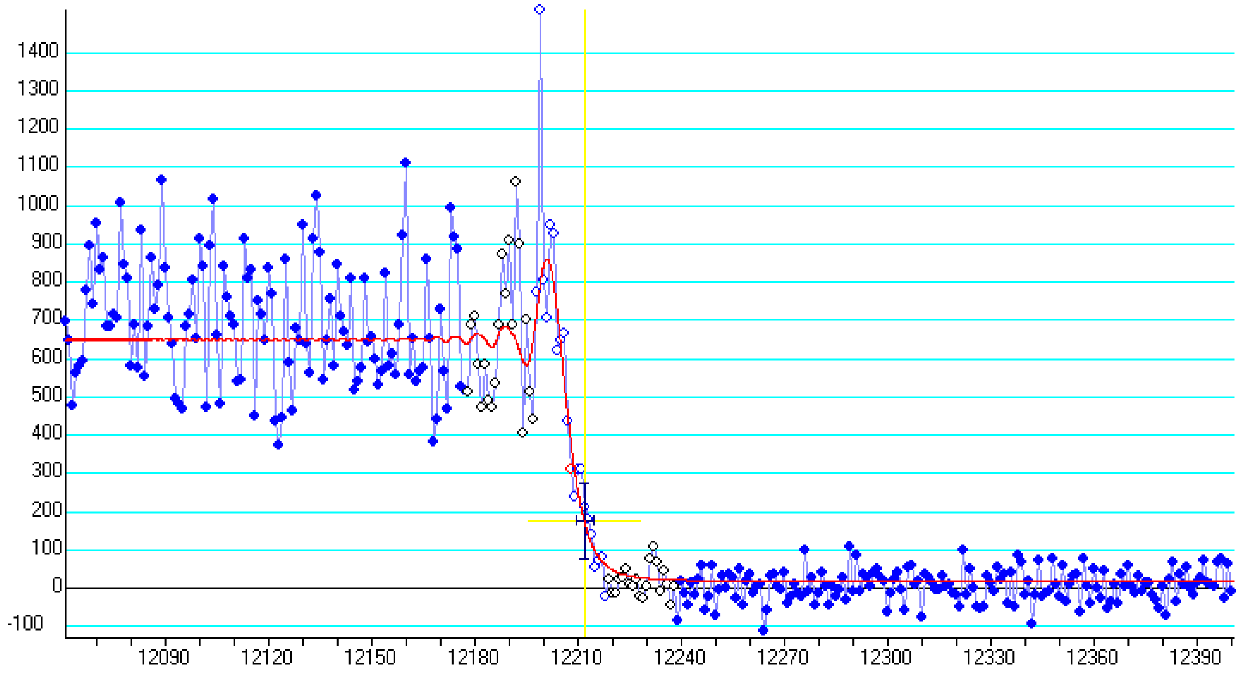
Diffraction Observations

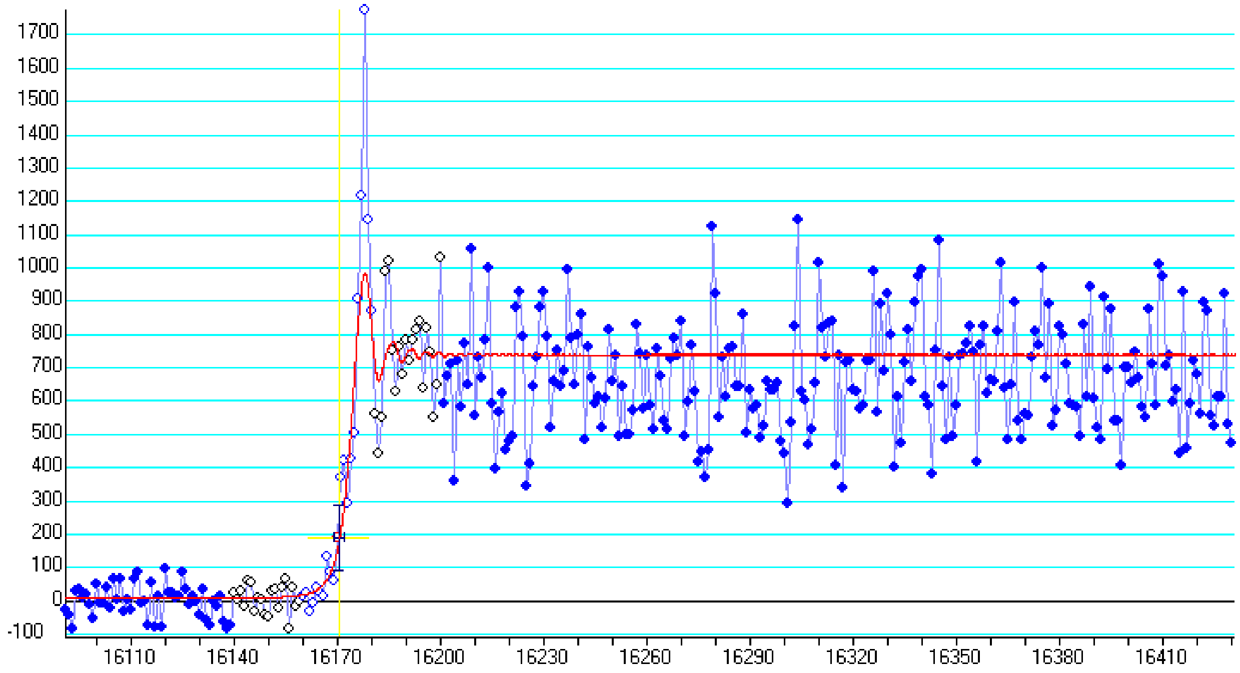
This observation of a graze was meant to be a proof of concept for USB video recording of an occultation, but I see strong diffraction fringes in the result that don't seem to match theory. These fringes are evident in the first plot at the start of this paper, where small blips can be seen at the disappearance and reappearance of the first pair, and strong blips on either side of the second pair.

Below are four plots, including diffraction fits from LiMovie, for the four events. Note that the first fringe is exaggerated – particular for the second pair of events. It doesn't appear to be due to noise or scintillation since you can see coherent changes in intensity along the peaks, and the peak pairs are roughly matched in appearance and intensity. Furthermore, the fringes go very high and then very low – as if the contrast is enhanced.









I am leaving out the actual times of these events because I want to go over the results in detail. But it is evident in the above plots that LiMovie was able to determine the event times with some confidence, and those frame numbers can be matched very accurately to GPS time. The approximate contact angles for the four events are: 82, 67, 85, and 82 degrees.

At present I have no good explanation for the exaggerated diffraction – except for gamma artifacts or unusual lunar limb features. The star is reddish, which may provide greater monochromaticity of the fringes. Another factor is the short exposure time, which is slightly smaller than the frame interval. The shorter exposure time helps sharpen the fringes, but not enough to explain the observed contrast.

I recorded the video with a gamma setting of 2.66, contrast 1, brightness 0, and gain full at 23.8, with exposure setting 16.4. It may have been better to use brightness and contrast to improve the dynamic range of the star signal, but LiMovie allows correction with an inverse gamma setting, which I set to 0.38 for this analysis. The results appear to be linear based on the effectiveness of the background subtraction of the pulse, and on the linear relationship between the pulse pairs shown in the figure above.

Future Work

1. Test future versions of LucamRecorder for dropped frames
2. Compare SKYnyx 2-0m sensitivity to PC164C at different frame rates
3. Compare with Micron CMOS detector, with microlenses
4. Test ability to write directly to memory, possibly with large buffer spooling to disk

In addition, I have plans to make a completely optical time stamp on USB recorded video by projecting a seven segment LED digit through the front of the telescope onto the detector. With a properly matched projection system and a very small digit, the image should be small enough on the detector to allow room for a star measurement. One LED with seven segments can be flashed in synch with the GPS device in a pattern that allows easily automated recognition and interpolation. I will first try a Gray code pattern on the LED segments, yielding 128 distinct patterns, plus additional precision via interpolation.

In order to make the image of the digit small, the projection system must have longer focal length than the telescope itself. This is made easier with a C11 and Hyperstar, which operates at f/1.8. The combination of modern microlensed USB camera with a 279mm aperture, f/1.8 telescope and optical timestamp accurate to a millisecond, all providing lossless digital video at over 100 fps, could be well suited to future occultation measurements.