ArtStar

A video camera characterization system

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Abstract:

This is primarily a report on a measurement system designed for testing the type of video cameras commonly used in occultation observations. The emphasis is on describing the system capabilities in detail. However, a Watec 910HX was used as the camera-under-test and a side-effect of system testing produced the following findings:

1) There is no 'deadtime' in the response of the 910 to light. A 10 microsecond wide light pulse was used to probe every temporal position in an exposure frame and its presence was registered correctly in every position.

2) Previous studies have shown that, provided the camera settings are selected so that pixels do not saturate, the Watec 910HX response curve is highly linear. This is used to demonstrate that a pulse width modulated LED, with the pulse edges synchronized to field and frame times, can act as a linear illumination source for test purposes.

3) A currently unrecognized/ignored camera delay of 0.410 milliseconds was measured. It arises from an offset between the field timing pulses (used as VTI reference points) and the internal 'shutter' operations of the camera. While this offset was detected by VEXA, it apparently was not emphasized. It is likely that this effect is present in all NTSC and PAL format cameras and some consideration should be given to altering camera delay tables to include this value, small though it is.

1 Introduction

Re-purposed surveillance cameras, like the Watec 910HX, have been and continue to be extremely effective and relatively low cost tools for recording star and asteroid occultations. But this “re-purposing” has a consequence: the manufacturers have no obligation to characterize the performance of their cameras for occultation timing applications --- they don't view these cameras as scientific instruments in the same way that astronomers are compelled to --- so it's up to motivated users to measure and report on the “missing specifications”.

To fill this “specification gap”, several systems have been built and used to determine camera specifications needed for precision occultation timing. In chronological order, the ones known to me are:

1.1 VEXA 2.0 (Video Exposure Analyzer)

Built by Gerhard Dangl in 2007 as an upgrade from the 1.0 model developed in 2006, this system, like EXTA, uses a set of precisely timed LEDs (10 of them) that can be imaged by the camera and the observed pattern of lit LEDs used to measure exposure timing. The system is described at (http://www.dangl.at/vexa/vexa.htm).

The purpose of VEXA, abstracted from Gerhard's description is:

> “VEXA is a simple microprocessor-controlled-circuit for showing and testing the exposure duration of a video camera or a video module. VEXA is a tool to show the beginning and the end of optical exposure within every single video field. This tool was designed to test cameras with an exposure duration of a field or shorter...”

This system uses a LM1881 composite video synch pulse extractor to make field timing information available to the microprocessor. ArtStar does the same but adds the GPS 1pps signal as an additional input.

One of the diagrams Gerhard published shows an 'offset' between Vsynch and the exposure window of the CCD. ArtStar makes a similar measurement and gives this offset a value of 410 microseconds for the NTSC model of the Watec 910HX. This is described in section 7.

1.2 EXTA (Exposure Time Analyzer)

Built by Gerhard Dangl in 2011 (www.dangl.at/exta/exta_e.htm), this system focussed on determining the integration performance of cameras. For this, and other contributions to occultation timing, he was awarded the 2015 Homer F. DaBoll award by IOTA.

The purpose of EXTA, paraphrased from Gerhard's preamble:

> “The EXTA device was primarily made for help in exposure time analysis of astronomy video records. To get results as accurate as possible we have to know about the relationship between the real exposure time in the camera and the time inserted in the analog camera output signal by the VTI device.”

A comprehensive report of measurements taken on 11 cameras (8 with integration capabilities) using EXTA can be found at (www.dangl.at/ausruest/vid_tim/vid_tim1.htm).

1.3 SEXTA (Southern EXTA)

Built by Dave Gault and Tony Barry in 2014, this is an open-source version of the EXTA design.

The purpose of SEXTA:

> SEXTA was built to conduct tests in support of the of ADVS (Astronomical Digital Video System) project.

A report on its design is available at (www.tonybarry.net/TB_-_Homepage/SEXTA.html).

1.4 DASCO (Digital Artificial Star CONtrol)

Built by Gerhard Dangl in 2012/2013 (www.dangl.at/dasco/dasco_e.htm), this system simulated a pair of stars by illuminating a pair of 0.2mm holes drilled in a brass plate. The illumination was carried to the holes by optic fibers. The lit holes were then imaged from across a room by a telephoto lens attached to the video camera.

The purpose of DASCO (in Gerhard's words):

> The primary goal for this development was a device which can simulate light signals from stars. With artificial star signals several measurements and tests can be accomplished inside a house without any influence from sky background, atmosphere, seeing and other weather conditions.
>
> DASCO can change star brightness in a fast dynamical range of 8-bit for video or in a dynamical range of 16-bit for astro CCD imaging. It can produce a relative fast brightness change in a saw tooth shaped light curve for video light curve measurements. But it can also produce relative star signal brightness changes with amplitude steps in the range from small 0.01mag up to 1.0mag.

One particularly important feature of this system was a stepper motor drive that allowed the star pair to be “drifted” across the CCD array. The resulting measurement showed clearly the light modulation caused by the micro-lens array that is used by the most sensitive CCD chips.

1.5 Star Chamber

Built by Tony Barry and Dave Gault in support of their ADVS project (approximately 2013/2014), this system uses a mailing tube with three fiber optic cables projecting into the tube at one end and an optics stack at the other end to focus the three “stars” onto the CCD array of a video camera. LEDs in close contact with the other end of the fiber optic cables illuminated the “stars”. The LEDs were individually driven from variable constant current drivers that could be switched on and off to simulate occultations.

The purpose of Star Chamber:

> Star Chamber allows simple simulated occultations via a manually operated switch. In a private communication, Tony Barry said that he had thought/planned to add microprocessor control to the LED on/off circuit, but ultimately there was insufficient need for such control --- the simple switch was enough for ADVS test purposes --- so the idea was shelved.

My thanks to Tony Barry and Dave Gault for graciously sharing with me details of their setup in a series of emails late in 2014. The physical design of Star Chamber has been 'borrowed' as the basis of ArtStar.

1.6 ArtStar (Artificial Star)

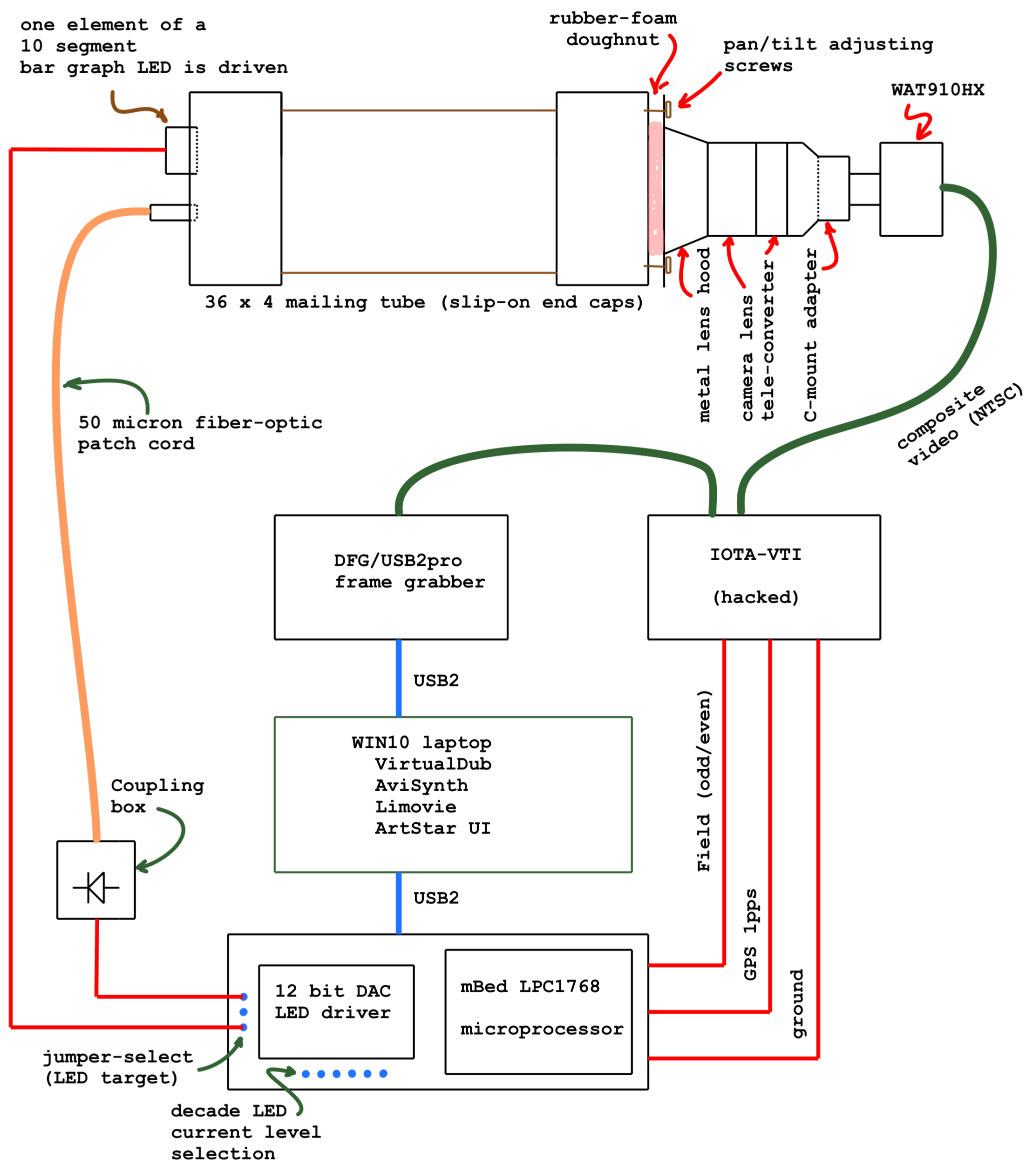
This system utilizes the optical architecture of Star Chamber in conjunction with microprocessor control of the target LED illumination. The microprocessor can synchronize LED current changes to internal operations of the camera by using field pulses extracted from the composite video. It can also use the GPS 1pps signal to produce precisely timed artificial occultations.

The purpose of ArtStar:

> This system makes it possible to determine camera response curves, probe for dead times (periods where the camera cannot respond to light changes), directly measure camera/VTI delays, measure camera frame time (to 9 digits), test the effects of various camera settings (like 3DNR) on occultation timing, test the effect of various lossy codec compression schemes on occultation timing, and perform a hi-fidelity 'replay' of actual observations so that different camera setups can be tried to see if an alternate setup might have yielded better/equivalent results.

We begin the detailed description of ArtStar with the following diagram...

2 ArtStar Block Diagram



ArtStar block diagram

2.1 ArtStar hardware diagram description

Starting from the upper left corner of the diagram and proceeding clockwise...

Two 'targets' are poking through the left-hand end cap.

> One target is the open end of a 50 micron multi-mode glass fiber optic patch cord that attaches with a standard bayonet style connector. (One comment that I had received from Gerhard referred to the difficulty of keeping small holes (DASCO used 0.2mm drilled holes) clean and clear, but the fiber optic patch cord has been trouble-free in that regard.) When lit, the resulting 'star' images realistically on the CCD array with very star-like 3D profiles in Limovie and shows that a radius 3 central aperture captures most of the lit pixels.
>
> The other target is one element of a 10 segment bar graph LED display. This provides a large image of more uniformly lit pixels. This target type was found to be easier to use and interpret for some of the measurements.

The 36 inch long 4 inch diameter mailing tube is of the telescoping variety --- there is a center tube (brown paper) with a two-part white outer sleeve and cap.

The optics stack screws onto the metal lens hood using the filter threads of the camera lens. Currently, it can accommodate either a 52mm or a 49mm filter diameter through use of an adapter. The metal lens hood is epoxied to an aircraft grade birch plywood header which is in turn attached by three 6 x 32 hex cap head screws which project through a 1/4” black foam rubber doughnut and into mating nuts that are epoxied to the rear of the plywood header on the right-hand end cap. This is the classic three-point mirror mount and allows either of the “targets” to be imaged anywhere on the CCD array.

The optics stack itself has a primary requirement that the assembly can focus on the targets which are about 36 inches away. The optics stack components were provided by Tony George and I found it necessary to use the tele-converter that he included in the kit to achieve the needed focus requirement.

The video camera is a new WAT910HX/RC (serial number EIA 01882) that I purchased for these tests.

An IOTA-VTI v3.01 is used for the GPS based timing. A cable was added to bring out the Field signal and the GPS 1pps signal. (My thanks to Walt Morgan for his help in identifying the proper access points on the board.) The Field signal identifies which field (odd or even) that the composite video is outputting. The GPS 1pps signal is taken directly from the GPS device, not the one that drives the yellow front-panel LED. There is a 7 microsecond offset between the two --- not consequential, but also avoidable.

The frame grabber is a product of Imaging Sources (model DFG/USB2pro) and features uncompressed Y800 (8 bits per pixel grayscale) output. VirtualDub is used to capture the output of the frame grabber and write a Lagarith lossless compressed file.

The laptop used for video capture is an Apple MacBook Pro running Windows 10. I found it necessary to setup this laptop using the Dual Boot option so that Windows is running 'natively' rather than in a virtual environment (I've used both Parallels or VMware Fusion successfully with other, less demanding, programs). Initially, I tried running WIN 10 in a virtual environment on the MacBook. Very erratic behavior resulted with unexplained and all-too-frequent crashes of the program used to capture a video --- I tried Limovie, VirtualDub, and IC Capture 2.4 as the capture software --- all failed. An Imaging Sources engineer confirmed that the USB drivers are too slow when running in a virtual environment --- they can't keep up with the frame grabber (which is unforgiving of that particular situation). I'm providing this extra bit of information for any out there that may be struggling with running certain high-performance “Windows” programs on a Mac.

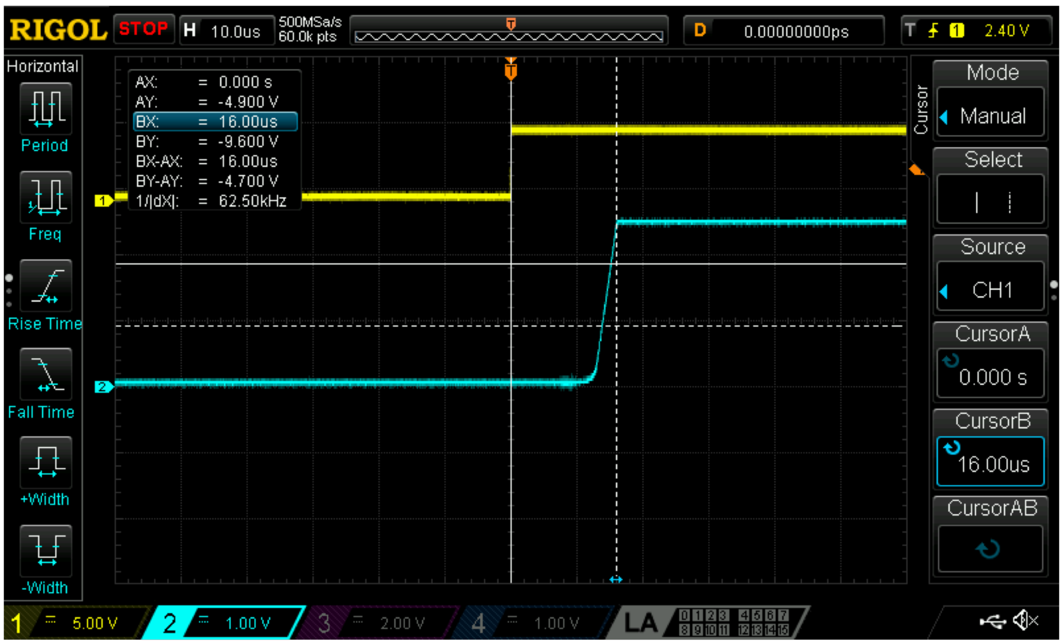
The electronics for driving the selected target LED is uncomplicated: there is an mBed LPC1768 microprocessor, two 8 pin ICs, and about a dozen discrete components (mostly resistors and a few capacitors). One of the 8 pin ICs is a 12 bit DAC (digital to analog converter). The other IC is a dual op-amp used to construct a voltage controlled current source for driving the LED and a 'stiff' reference voltage for the DAC.

Finally, there is a plywood box that allows a standardly packaged 5mm LED to be press-fit on one side so that it comes in very close proximity to the end of the fiber optic patch cord mounted from the opposite side. This is the same arrangement used in Star Chamber except that here the patch cord attaches with a bayonet style connector (for easy assembly) and the LED is easily replaced.

3 LED driver

The LED drive is at the heart of ArtStar --- its characteristics govern what tests can be conducted --- so it's a good place to start the detailed discussion of the system.

The selected target LED is driven by a voltage controlled current source. The control voltage comes from a 12 bit DAC (digital to analog control) that the microprocessor commands via an SPI interface (a three wire serial interface). Below is an oscilloscope picture showing the timing characteristics of this drive system:



The yellow trace is the Field signal from the IOTA-VTI. The edge shown is where the transition from the 'even' field (low) to the 'odd' field (high) occurs. That transition causes an interrupt in the microprocessor. The LPC1768 is particularly well-behaved in its response to interrupts --- it has a low-jitter consistent time of response to an interrupt of about 5 microseconds.

The blue trace shows the current being delivered to the LED (more precisely, it shows the voltage across a resistor that carries all of the LED current).

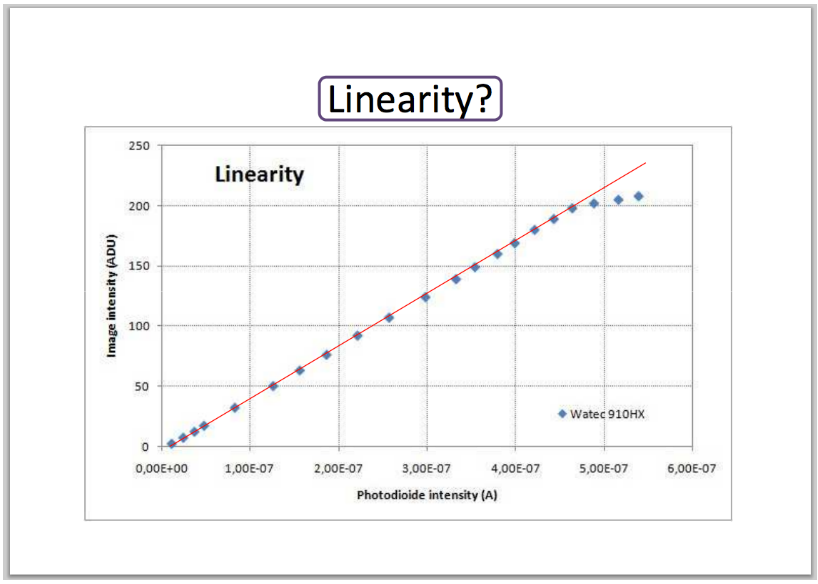
Prior to the even to odd transition, the LED was 'off'. At the edge, the microprocessor responded to the interrupt by commanding the DAC to send full voltage (2.5 volts) to the voltage-controlled current source. The resulting scope trace shows that the transition from no current to full current through the LED takes about 4 microseconds (limited mostly by the slew rate of the op-amp that supplies the current) and is gratifyingly well-behaved.

By 16 microseconds after the edge, the LED is at full current. This small delay is inconsequential compared the field duration which is greater than 16,000 microseconds, but is calibrated out in the software anyway. This is explained more fully in the section on deadtime detection.

A similar trace is observed when the LED is turned off.

4 Primary illumination modulation mode

Because ArtStar LED on/off times can be synchronized with each field, and the LED drive is well-behaved, it becomes possible to consider the use of PWM (pulse width modulation) to vary the illumination to the camera. The logic is this: the CCD photon capture mechanism is inherently a linear process --- it would be perfectly linear except for photon arrival statistics; PWM is also an inherently linear process --- the number of photons emitted by the LED (when driven by a regulated current drive) will be directly proportional to the 'on time' of the LED (provided power levels are such that die heating can be ignored --- that is the case here --- current levels are always several orders of magnitude lower than the nominal operating current). Amplifiers added by Watec as part of post CCD processing have the potential of introducing non-linearity, but a study by the International Meteor Organization has measured the linearity of the Watec 910HX and found the following behavior:

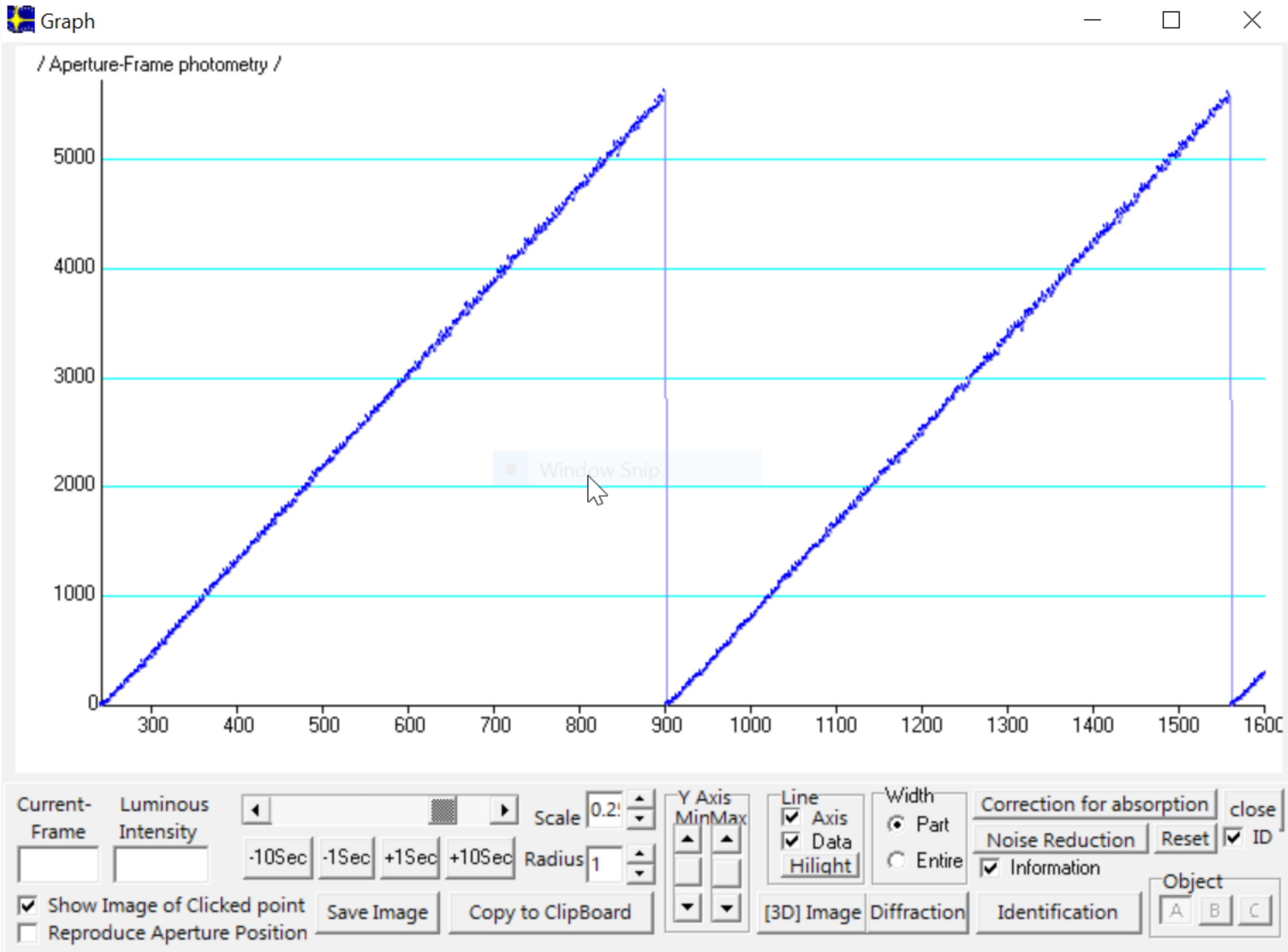


The above slide was presented as part of a report on the Watec 910HX performance presented at the 2013 International Meteor Conference. Here is a link to that paper (Performance of Watec 910 HX). (I don't know why the question mark in the title --- I conjecture it was due to the kink at level 200 --- but that's easily explained as the anti-bloom gate being triggered.)

So the linearity of the overall Watec 910HX camera, from the CCD, through post CCD processing electronics, through formatting into composite video output, and finally captured by a frame grabber is confirmed by comparison with a scientific grade photodiode detector and amplifier.

The above test was performed on an optics bench using an integrating light sphere to provide a source of uniform illumination to the camera. The question now is whether a pulse width modulated LED, with the start of the light pulse synchronized with each field and with a pulse width that can be varied from 0 to 100% of a field time can be used as an equivalently linear illumination light source.

To examine this conjecture, the following test was run: the Wat910 exposure mode was set at 2x (two fields) integration mode with non-saturated pixels (max pixel was about 130). The bar graph LED was the target and the Limovie aperture was set at 3,23,25 (Lunar). The LED pulse width was varied from 0 to about 95% of the field time and used to illuminate both fields, resulting in linearly increasing illumination. The pulse width increment was 25 microseconds from field to field, accumulating linearly until the max pulse width was reached where the sequence simply repeats with the following results:



The results are visually very linear. Subsequent least-squares fitting of first order, second order, and third order polynomials confirmed that the visual impression is correct. One ramp of a test curve (not the one shown above which was freshly prepared for this paper) was extracted, trimmed at the ends slightly, and polynomials fit with the following results:

```
9.0488e+02 + 8.0766e+00 * x                                   (stdev residuals: 10.56)
9.0585e+02 + 8.0668e+00 * x + 1.6322e-05 * x^2                (stdev residuals: 10.55)
9.0690e+02 + 8.0459e+00 * x + 1.0387e-04 * x^2 - 9.7765e-08 * x^3 (stdev residuals: 10.54)
```

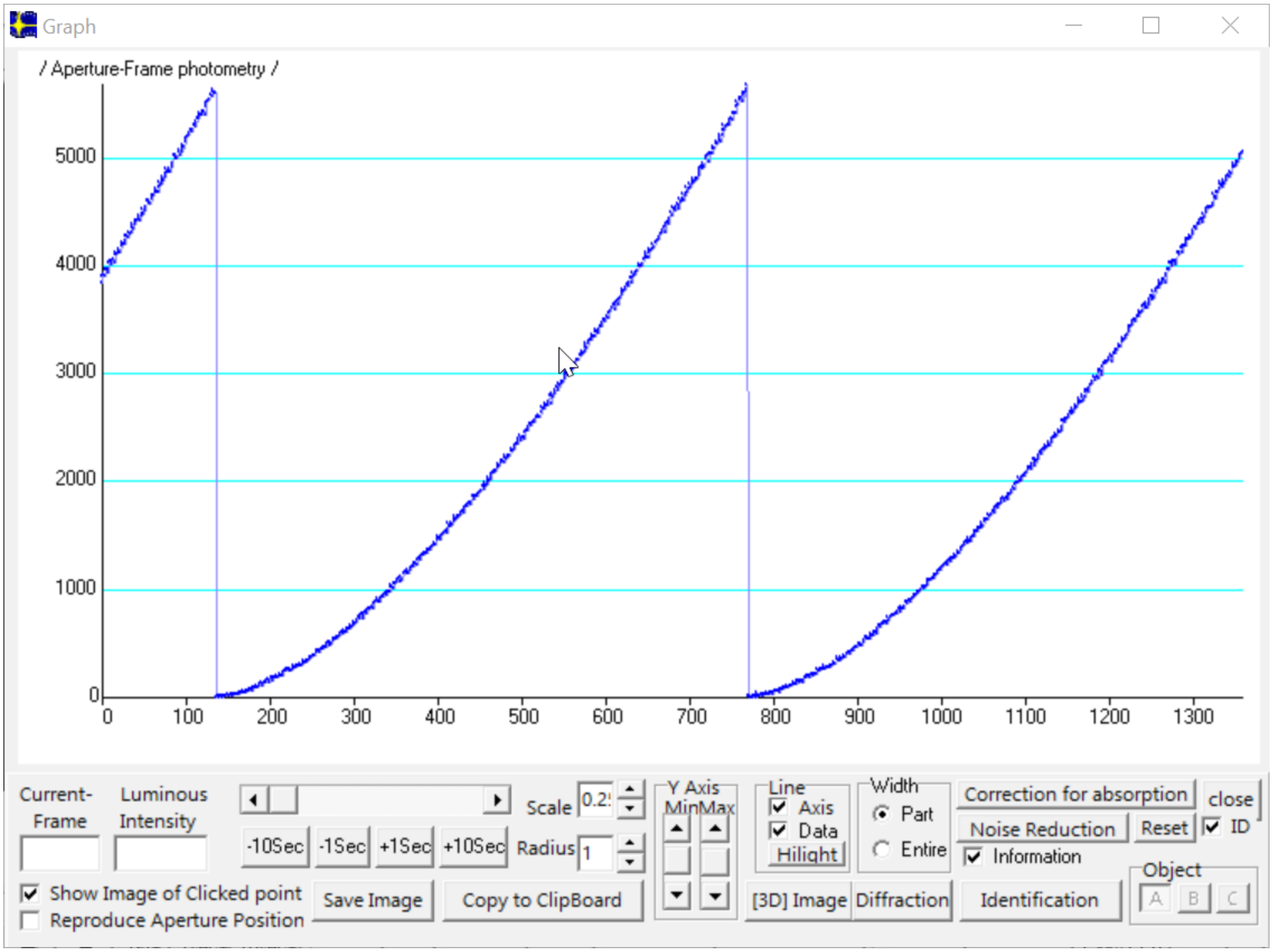
Based on the above results, the PWM mode of illumination modulation was selected as the default mode of operation for ArtStar.

It's worth noting that the bump-free nature of the response indirectly suggests that there is no detectable 'deadtime' at this camera setting. This will be directly confirmed later when we examine the results of a measurement procedure dedicated to probing for the the existence of 'deadtime' by illuminating every field position with a 10 microsecond light pulse that is 'walked' from the beginning to the end of the frame.

4.1 Alternate illumination mode

It is also possible to run the LED in CM (current mode). In this mode, the current to the LED is directly modulated and the CCD is continuously illuminated by whatever light the LED produces at that current. Of course, in this mode, the illumination will depend on the relationship between LED light output versus drive current.

A test similar to that shown above was run with the same camera setting (2x) and same max pixel reading (approx 130). The LED current was increased linearly from 0 to 25 microamps with the following Limovie result graph:



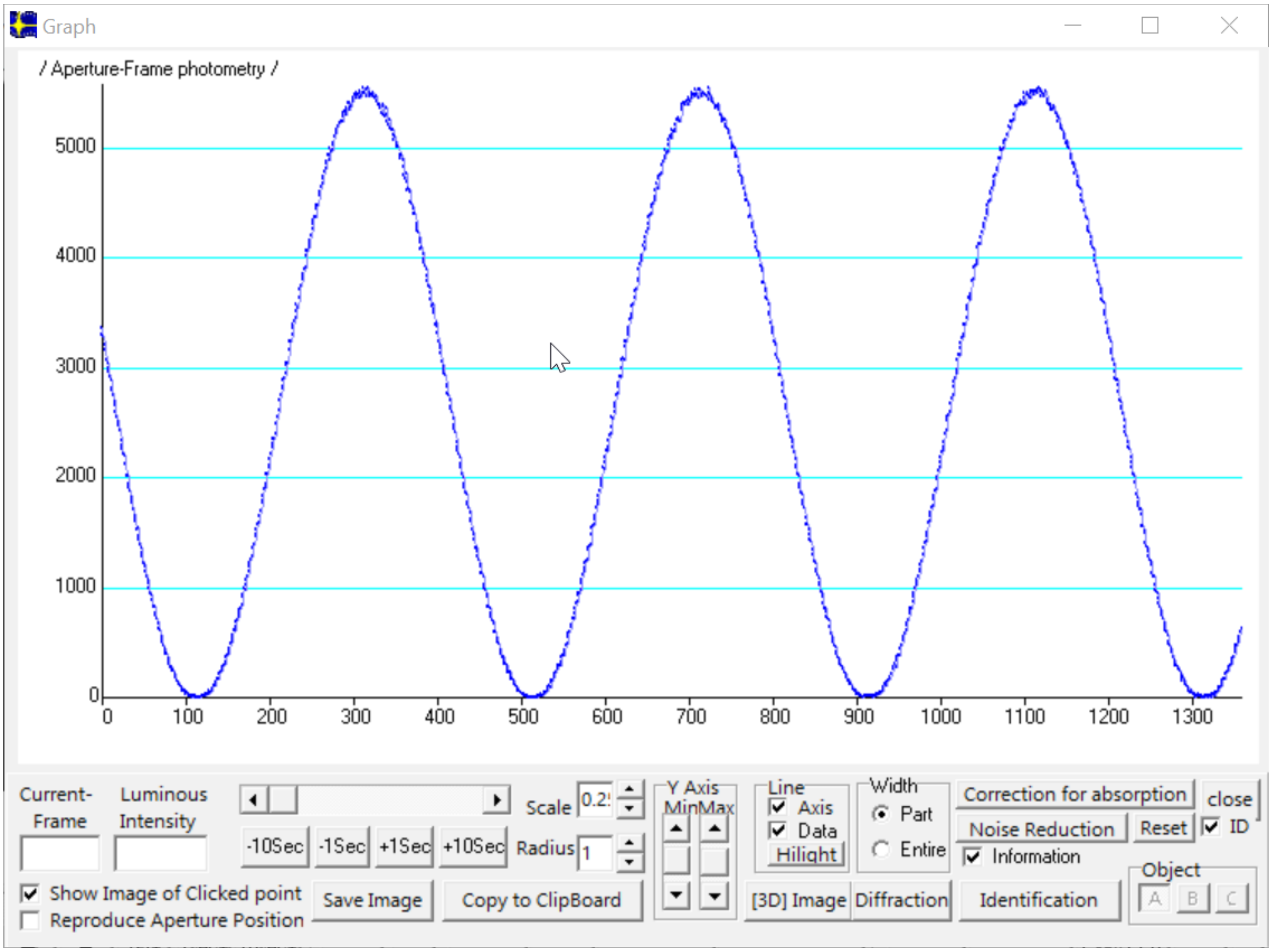
The same Limovie aperture settings were used (3,23,25 Lunar) with the result that the same max intensity of about 5500 was achieved. Using 'current mode' modulation of the LED in this instance results in the measurement of the LED response curve (light out versus current) rather than the camera response curve as the camera response curve has already been shown to be linear. While it might be possible to linearize the LED current response through a compensating look-up table, the effectiveness of the PWM illumination made that effort seem not worthwhile.

5 Arbitrary light curves

The ArtStar microprocessor has enough ram to allow for a 10,000 point light curve to be either internally computed or loaded from an external file.

5.1 Builtin functions to fill internal light curve

There are two builtin functions that can be commanded from the UI (user interface) to fill the internal light curve array: one computes a sine wave modulated light curve; another computes a sawtooth. Here is the sine curve:



As in the earlier tests, the Wat910 is in 2x mode, the LED current is unchanged, and the Limovie aperture was set to 3, 23, 25 (Lunar) for processing.

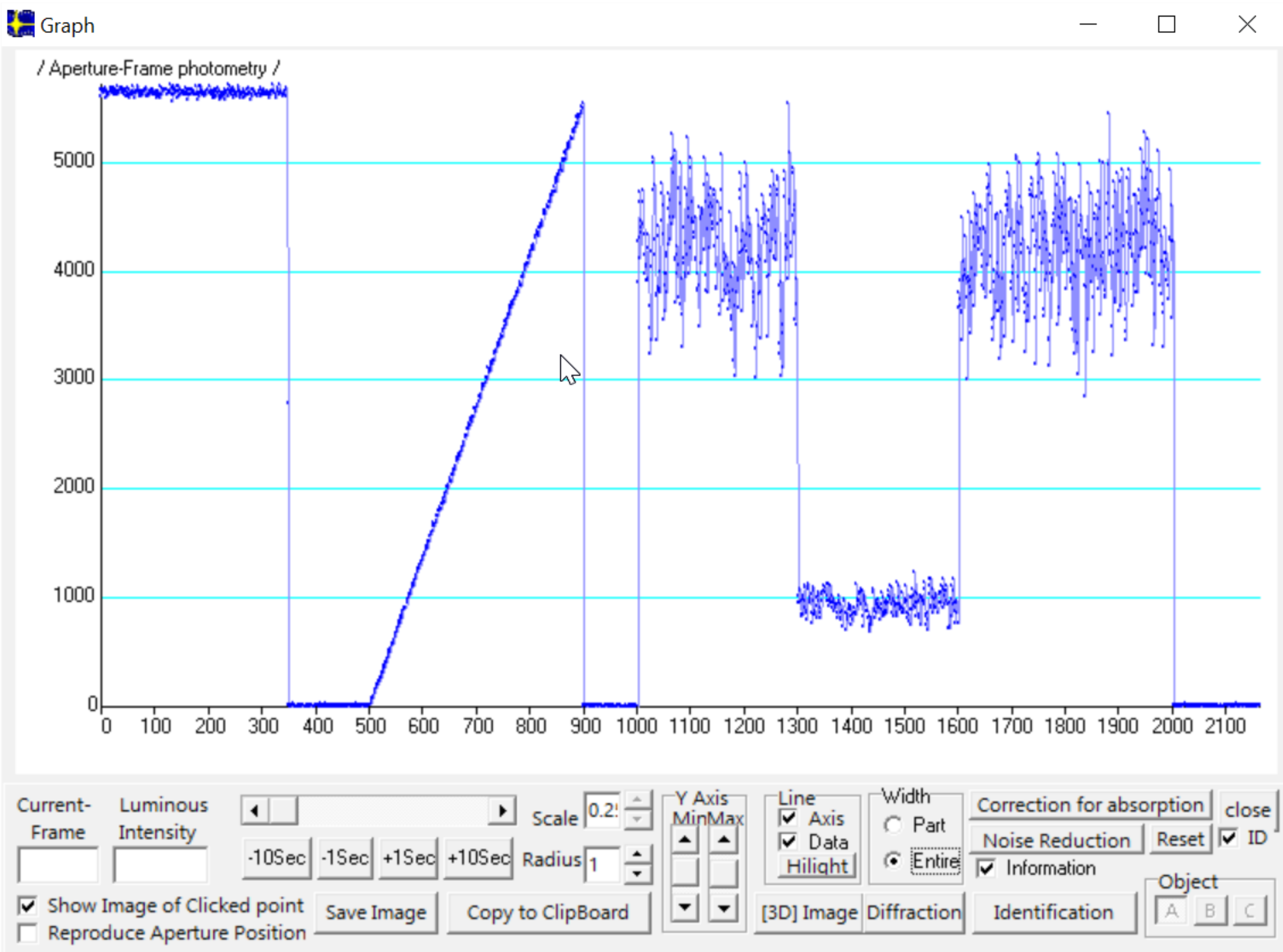
The only use for the builtin light curve generation is to show the 'playback' fidelity to be expected from a light curve. The sawtooth pattern is not shown because the sine curve is enough to demonstrate the expected fidelity. This hi-fidelity playback capability is to be exploited by 'replaying' real light curves.

5.2 Playback of an external light curve

ArtStar accepts an externally generated light curve csv file. It reads R-OTE format files, chosen for their simplicity, for the import of actual observations. In addition, R-OTE is able to generate artificial light curves with statistically realistic scintillation noise.

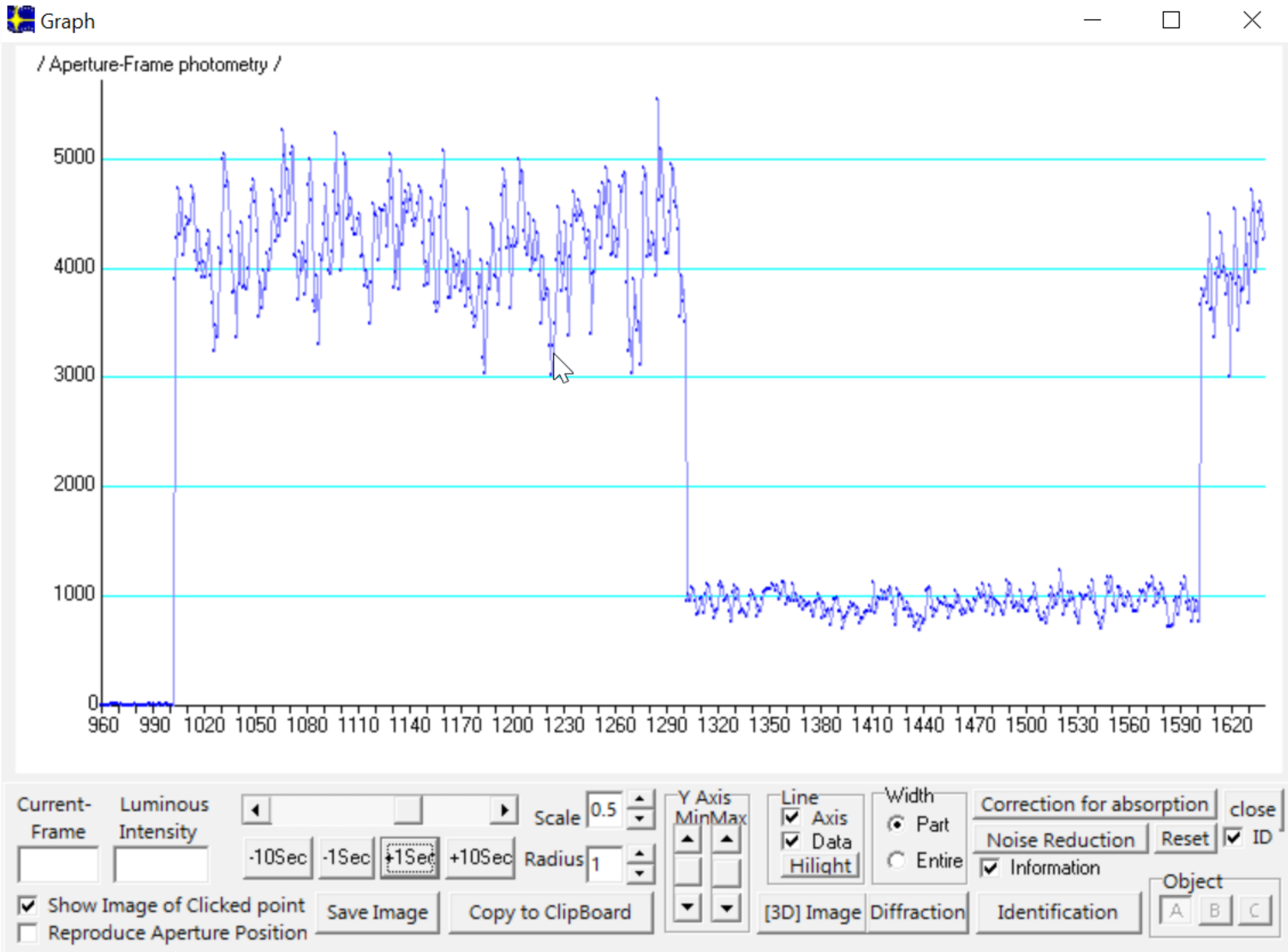
The motivation for this feature was a desire to test the effect of different camera settings (integration levels, gamma, IRE, etc) on occultation timing. The use of different frame grabbers would also allow the effects of lossless versus MP4 (or other) compression to be examined. It enables one to start with a real recording taken at, for example, settings of 2x, gamma 1.0, IRE 7.5 and 3DNR off and replaying the light curve back into the camera, but with different camera settings and possibly a different codec. This will result in a new Limovie light curve traceable to a real observation so that apples-to-apples comparisons can be made.

The example below is a square wave occultation generated artificially by R-OTE. The scintillation noise has realistic statistics, particularly its temporal characteristics (as measured by its auto-correlation spectrum). The LED current and camera settings are the same as all previous tests shown and the Wat910 is operating in its linear range --- the replay protocol includes a linear intensity ramp prior to the 'replay' so that there is a record of the camera response curve given the settings selected.



The first (flat) section shows the output with the LED lit at max PWM intensity for that current selection. This is followed by a short separator section where the LED is off. Then a linear light ramp is presented to document the camera response curve. After another short separator section with the LED off, the actual replay is done. At the end of the externally supplied data points, the LED is once again turned off.

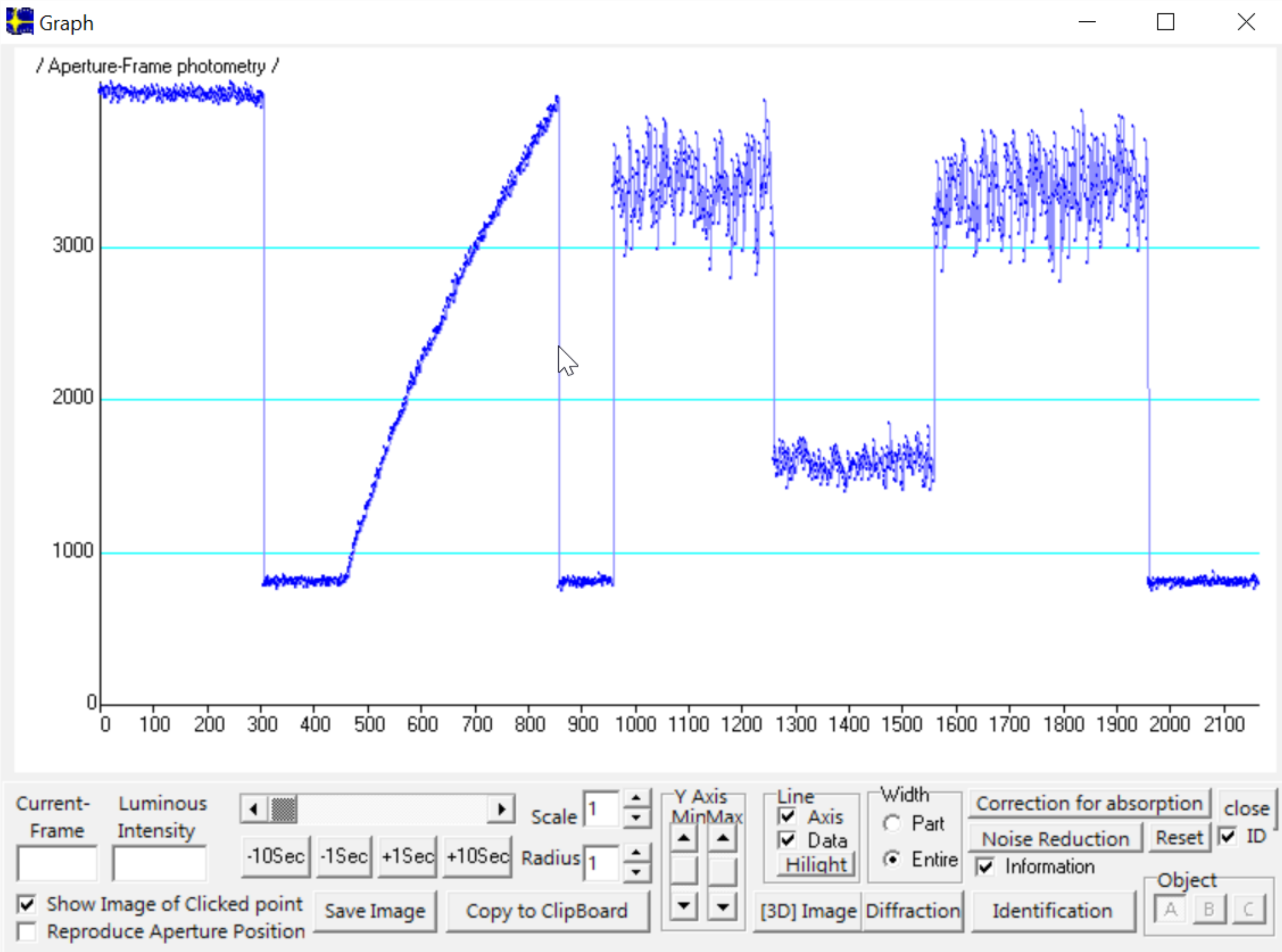
A zoomed section of the same curve is shown below:


Graph
/ Aperture-Frame photometry /
5000
4000
3000
2000
1000
0
960 990 1020 1050 1080 1110 1140 1170 1200 1230 1260 1290 1320 1350 1380 1410 1440 1470 1500 1530 1560 1590 1620
Current-Frame
Luminous Intensity
Scale 0.5
-10Sec -1Sec +1Sec +10Sec
Radius 1
Y Axis MinMax
Line Axis Data Hilight
Width Part Entire
Correction for absorption
close
Noise Reduction
Reset
ID
Information
Show Image of Clicked point
Reproduce Aperture Position
Save Image
Copy to ClipBoard
[3D] Image
Diffraction
Identification
Object A B C

5.3 Replay with saturated star

All of the examples so far have been produced using the bar graph LED, and the LED current (or camera gain) chosen so that no pixels are clipped. That's the ideal case. But what if an observer is unable to record under this 'ideal' circumstance. Then what happens? Here's an example designed to explore such a 'non-ideal' recording.

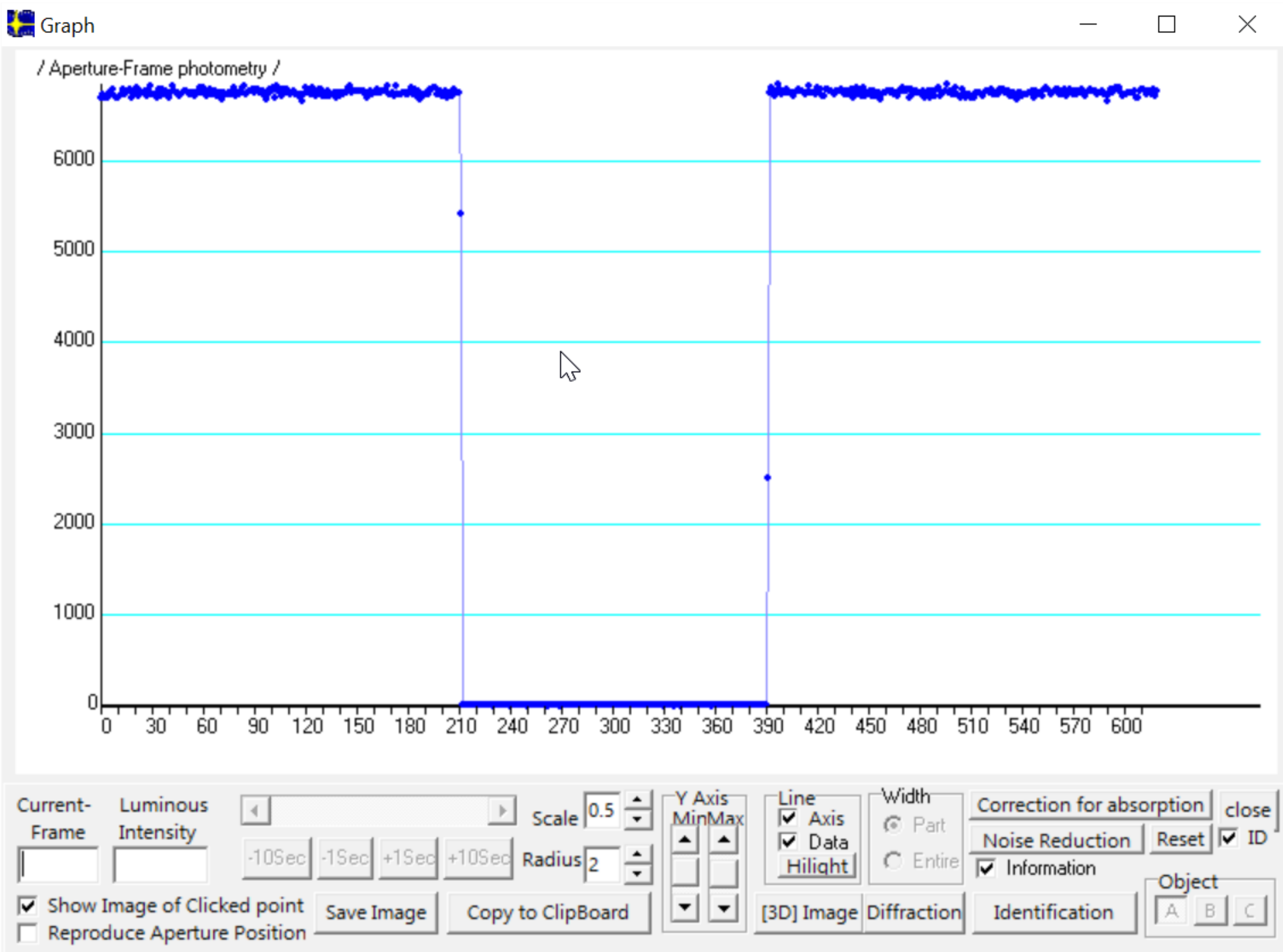
The example below is a replay of the same light curve used in 5.2 but this time using the fiber optic star (instead of the bar graph LED) with saturated pixels for the camera settings selected. This was accomplished by first setting the LED current that would result in no clipped pixels (unsaturated) and then multiplying that value by 10, causing the star image to saturate. The Limovie central aperture had to be opened to 8 to completely enclose all of the lit pixels and the 3D diagram of the 'star' showed prominent clipping. The non-linearity of the camera response curve is obvious, yet the replay (visually) closely follows the original light curve. Limovie and Tangra have the capability of performing PSF photometry, designed to 'linearize' such light curves. The effect of such treatment will be explored in a separate paper.


Graph
/ Aperture-Frame photometry /
3000
2000
1000
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100
Current-Frame
Luminous Intensity
Scale
-10Sec -1Sec +1Sec +10Sec
Radius
Y Axis MinMax
Line
Axis
Data
Hilight
Width
Part
Entire
Correction for absorption
Noise Reduction
Reset
Information
close
ID
Show Image of Clicked point
Reproduce Aperture Position
Save Image
Copy to ClipBoard
[3D] Image
Diffraction
Identification
Object
A B C

6 GPS timed artificial occultations

By using the GPS 1pps signal from the VTI, ArtStar can generate time-stamped artificial occultations with precisely known D and R times. When the Limovie light curves are analyzed with R-OTE, the D and R times should be values like 4.0000 seconds. If instead, a value of 4.0592 seconds is found, the fractional part (0.0592 seconds) is a direct measure of the camera/VTI delay.

For example, again using the bar graph LED and the camera operating with no pixel clipping, the following light curve was produced (a 6 second GPS accurate duration was chosen as the test occultation):



The obvious intermediate values at D and R are caused by the GPS 1pps turning the LED off at D and then on at R somewhere inside a frame exposure. These intermediate values can be exploited to refine time calculations by the procedure most often referred to as sub-frame timing. Such a procedure is only justified if there is negligible deadtime and the camera response curve is linear (intensity versus time). These conditions are satisfied for the Wat910 (when there is no pixel clipping) --- this was demonstrated in section 4 and further confirmed in the deadtime discussion of section 7.

When R-OTE was used to calculate D, R, and duration from the Limovie time-stamped light curve, the results were:

```
D (seconds) @ 2016-02-27 16:18:35.050170
R (seconds) @ 2016-02-27 16:18:41.050339
dur (seconds) 6.000169
```

Additionally, R-OTE reported:

```
B = 7382.77   Bnoise = 32.02
A =  632.62
```

The noise has a Gaussian distribution, so the 1 sigma time error can be calculated from the camera response curve (intensity versus time). That calculation is:

```
(frame-time / (B - A)) * Bnoise =
(33.3665 ms / (7382.77 - 632.62)) * 32.02 = 0.158 ms = 158 microseconds
```

The duration was expected to be exactly 6 seconds, so the error in the duration determination is 169 microseconds. GPS jitter is less than 15 ns by actual measurement, so it's not a factor. The duration result would be reported as:

```
dur = 6.000169 +/- 0.000158 seconds
```

so the measured value lies just outside the 1 sigma error bars and well within 2 or 3 sigma.

The fractional part of the D and R times gives directly the combined effect of camera delay and VTI offset. The average value in this test is 0.050255 seconds. If the delay were exactly 3 fields, it would be 0.050050 seconds. This is calculated from the precise frame time of the Wat910 as determined by ArtStar using the GPS 1pps signal during startup (discussed in section 8). The value reported there was 33.3665040 ms and used here.

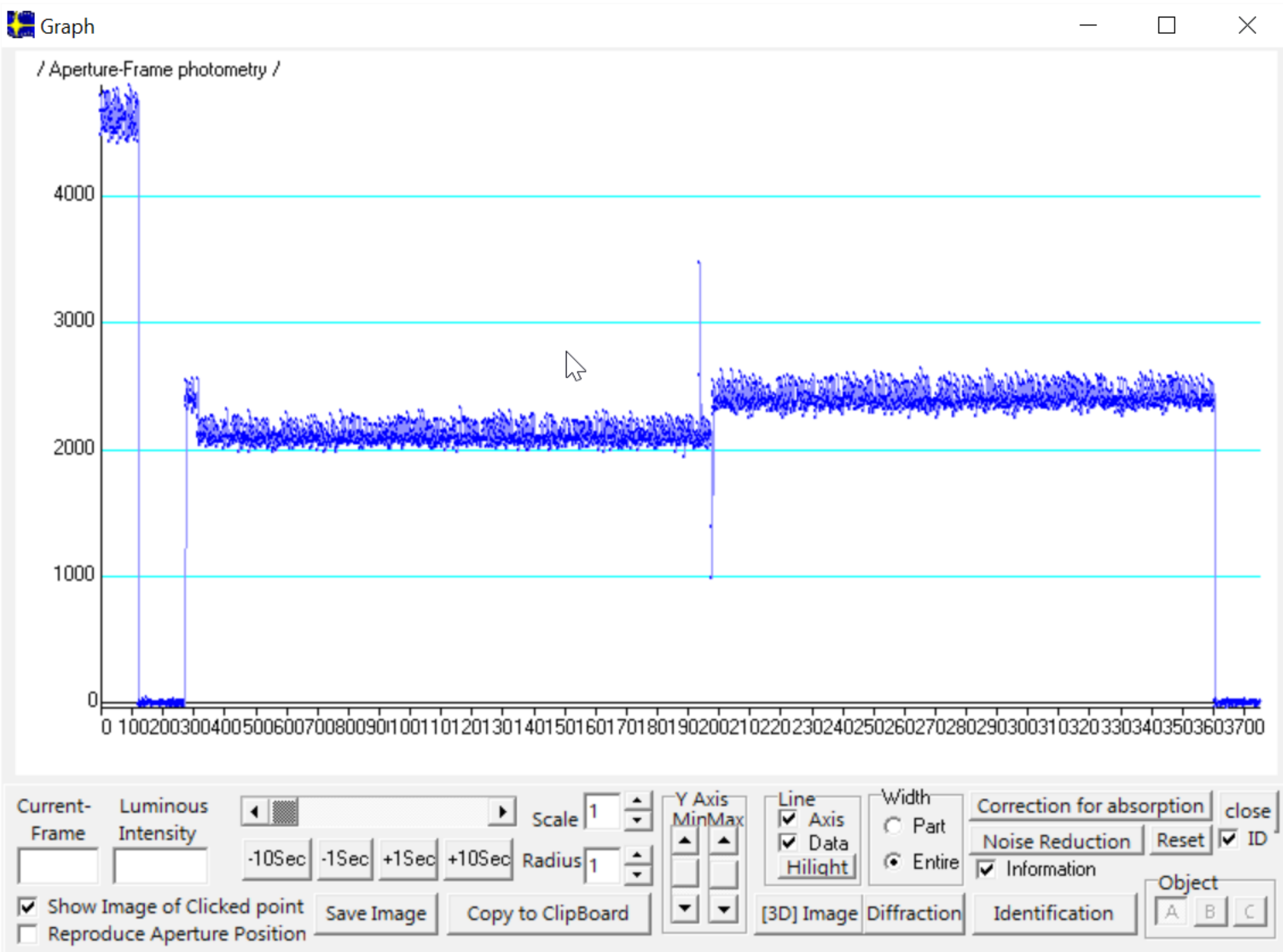
So there is a difference of about 205 microseconds from the expected value. The 1 sigma timing error calculated above is applicable here as well, so the measured D and R times, after a 3 field correction has been applied, lie just outside the 1 sigma error bar and inside 2 or 3 sigma.

7 Deadtime detection

While the camera response curve shown in section 4 suggests strongly, but indirectly, that there is effectively no deadtime (a period of time where the CCD is unresponsive to light changes) in the Wat910, a more direct test is available to explore this aspect of camera behavior.

Deadtime probing operates by using a small, fixed duration light pulse, and moving the temporal position of that pulse from the start of a frame to the end. In the test below, a 10 microsecond light pulse is used as the 'probe'.

It is important to note that the camera mode for this test was set to E.I., not 2x. This allows the effect on each field of the frame to be seen without the commingling that occurs when the 2x mode is used. Once again, the target is the bar graph LED and there is no pixel clipping. The test resulted in the following Limovie graph:



In the leftmost part of this curve, ArtStar is illuminating both fields with the 10 microsecond light pulse. Then, after a short separator section where the LED is off, the light pulse is turned on at the beginning of the even field and then advances 10 microseconds per frame until the pulse is at the end of the odd field.

Because the Limovie circular aperture includes a slightly different number of pixels from the even field than it does from the odd field, it becomes possible to identify which field is being exposed and reported by the camera by its intensity.

Immediately after the start of the even field, we are actually seeing light gathered from the previous odd field exposure. About 40 frames later, the amplitude changes and the even field exposure is now in effect. The spikes just before the probe hits the odd field are reproducible and possibly associated with internal electronic activities associated with a field change.

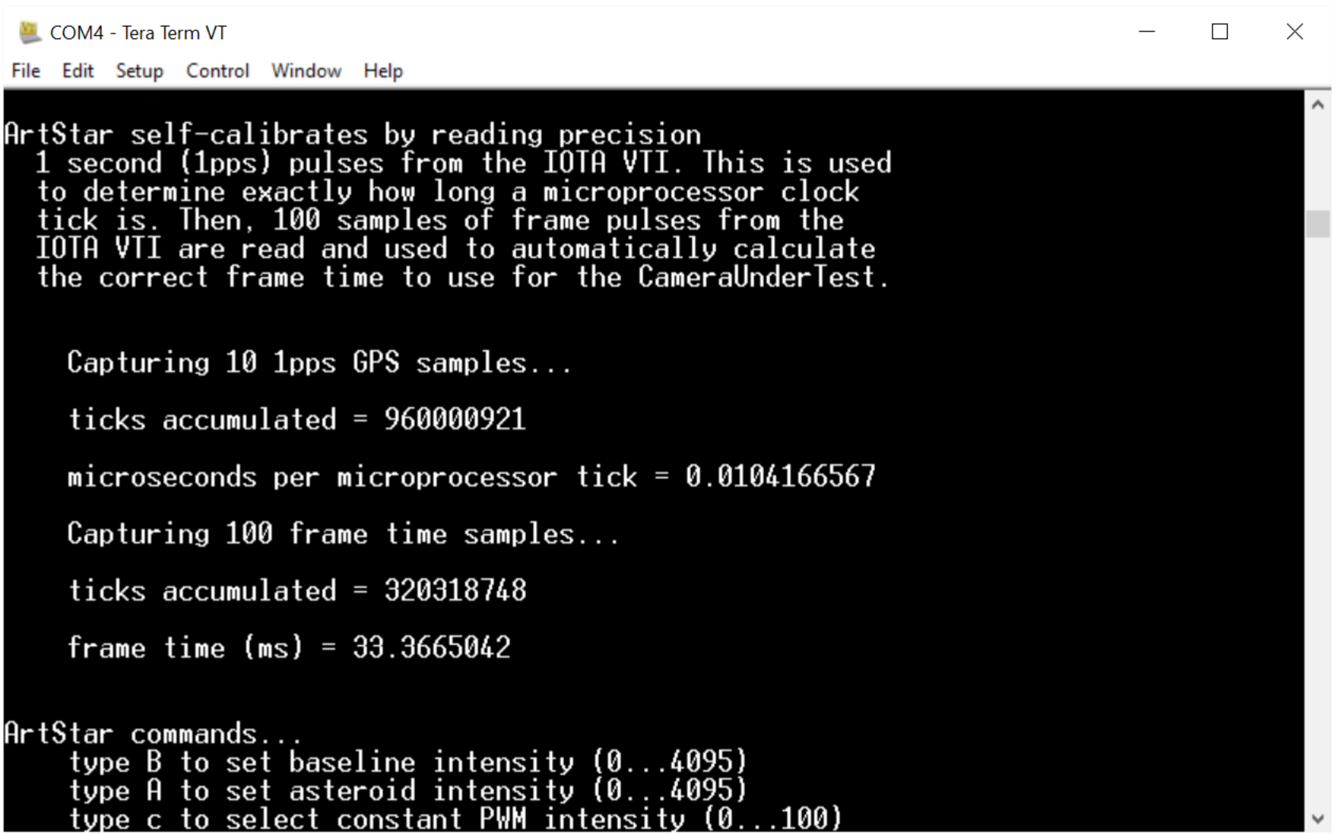
8 Calibration of NTSC/PAL frame timing

Accurate frame rates are needed: occultation reduction programs use this value to validate time stamps. For long observations, the actual frame rate of the camera needs to be known to 8 or 9 digits in order for this 'validation' to be performed.

In order to accommodate both NTSC and PAL format cameras without resorting to a jumper block, ArtStar uses the GPS 1pps signal to calibrate the microprocessor clock. It then proceeds to time 100 frame pulses. In addition to automatically adjusting to PAL or NTSC, the resulting frame times are accurate and repeatable to 9 digits. Only the ninth digit changes when repeated measurements are performed close together in time (to minimize temperature effects).

This capability provides a way for the temperature dependence of frame times to be explored should someone be motivated enough to enclose the camera in a temperature controlled enclosure while using ArtStar.

Below is a segment of the startup screen displayed by the ArtStar UI:

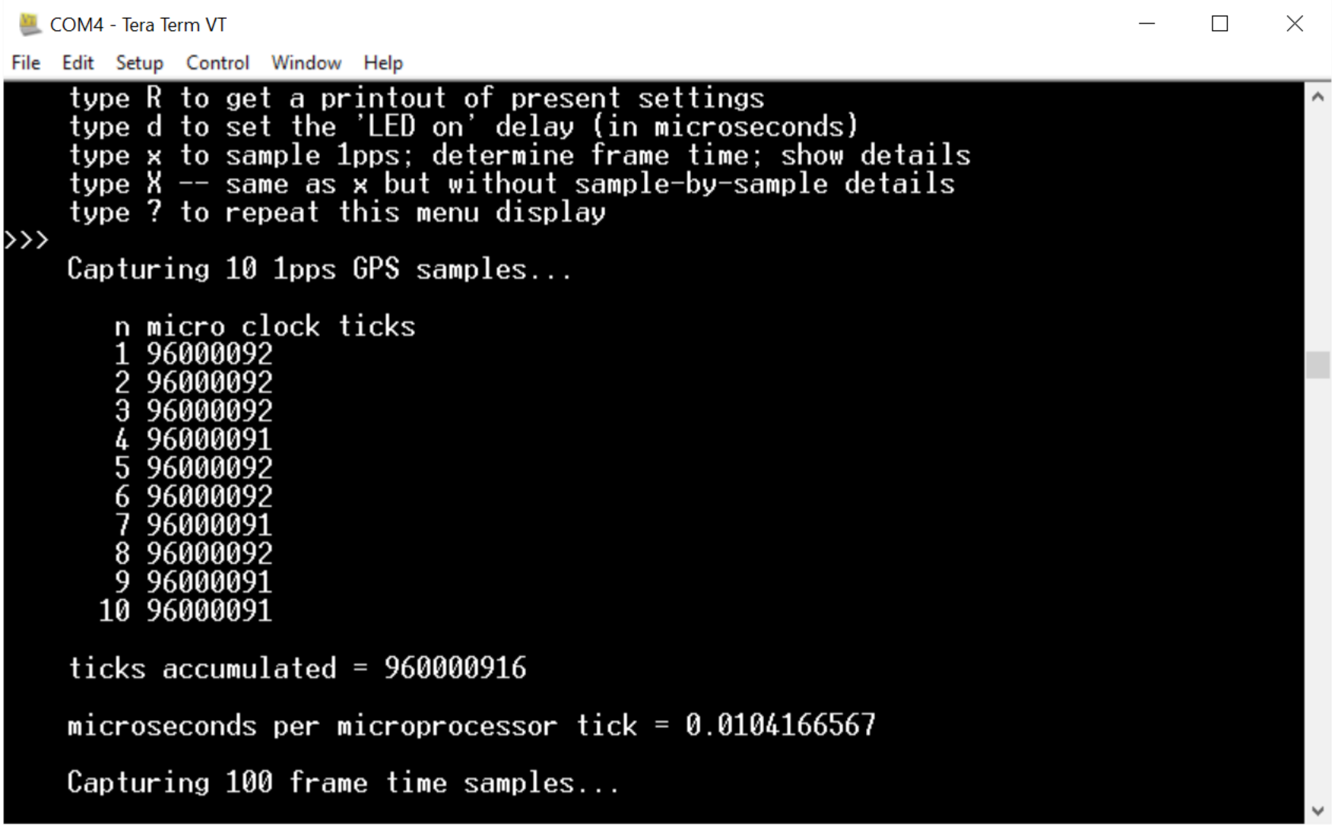


The mBed microprocessor clock runs at a nominal speed of 96,000,000 hz, so the value of 960,000,921 'ticks' for 10 seconds of counting is reasonable.

The calibration procedure can be triggered by a UI command that will show details of the capture. Of interest is any 'jitter' in the GPS 1pps signal. On the next page is a section of the UI screen showing the details of the 10 GPS 1pps 'captures'. The capture resolution is one microprocessor tick (close to 10 nanoseconds).

At the time the measurement was performed, 7 satellites where in use by the GPS chip and it is clear that 'jitter' is in the 5 to 10 nanosecond range, which is quite good as it includes not only GPS jitter but microprocessor clock jitter as well.

The same level of detail is available for the 100 frame time samples, but the 9 digit stability of repeated frame time estimations tells the story well enough.




```
    type R to get a printout of present settings
    type d to set the 'LED on' delay (in microseconds)
    type x to sample 1pps; determine frame time; show details
    type X -- same as x but without sample-by-sample details
    type ? to repeat this menu display
>>>
    Capturing 10 1pps GPS samples...

       n micro clock ticks
       1 96000092
       2 96000092
       3 96000092
       4 96000091
       5 96000092
       6 96000092
       7 96000091
       8 96000092
       9 96000091
      10 96000091

    ticks accumulated = 960000916

    microseconds per microprocessor tick = 0.0104166567

    Capturing 100 frame time samples...
```

This display shows 'capture details' and was triggered after startup by typing a lower case x at the command line.

9 Field by field illumination

ArtStar can light the target LED field by field from a pattern supplied by the user. This can be helpful in exploring the difference between camera 'shutter' settings (using Wat 910 notation).

The pattern is input as a string of 'x' and '-' characters. An 'x' character in a field position causes that field to receive full illumination. A '-' character turns the LED 'off' during this field. The first character of the string corresponds to the even field (as defined by the composite video Field signal). When the end of the string is reached, it is repeated.

On the next page are three Limovie graphs of the result of applying the following illumination pattern:

```
“x--x----xx-----xx-----”  (user supplied pattern: x = 'on'  - = 'off')

“eoeoeoeoeoeoeoeoeoeoeo”  (field 'parity': o = odd  e = even)
```

The pattern was chosen to provide differently 'phased' frame illumination. The first frame gets only the even field lit while the second frame gets only the odd field lit. Where the 'xx' pattern appears, they have a different phasing as well --- one of them bridges a frame boundary.

The bar graph LED was the target. Limovie was run in field mode with a Lunar aperture of 4, 23, 25. The LED current is unchanged between runs --- the only change was the camera shutter mode which was varied from 1/60, to E.I., and finally to 2x (again using Wat 910 notation).

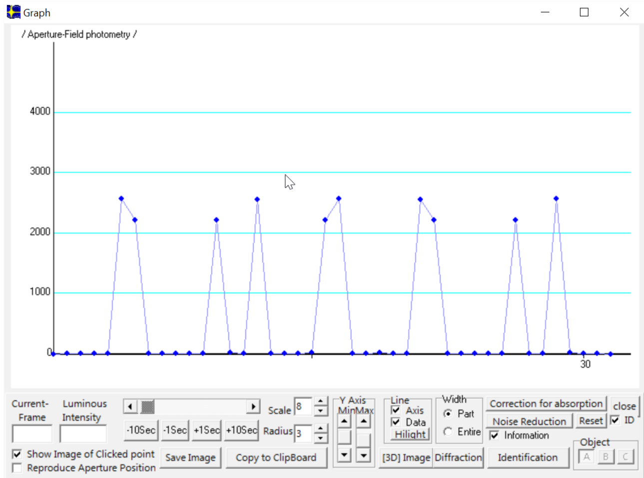
I scaled the Y axis on the Limovie graphs so that the graphs could be directly compared with respect to amplitude.

Limovie included 37 pixels from the odd field and 32 pixels from the even field, so it is possible to distinguish which field contributed the recorded intensity (this is because the 69 pixels enclosed by the central aperture are all similar in intensity, a result of using the bar graph LED as the target).

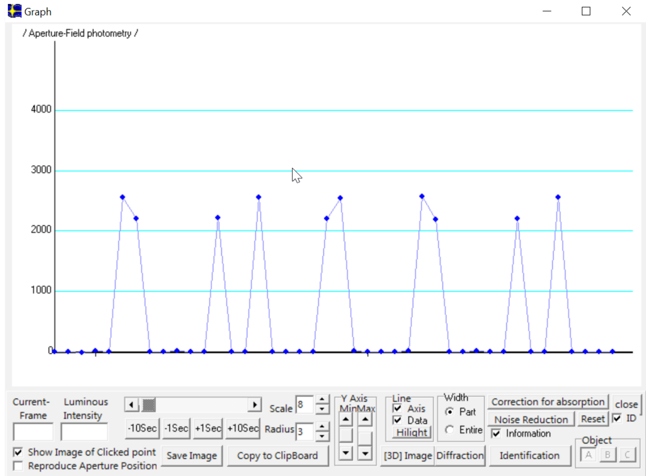
It is clear that the camera response is identical when operated in either E.I. or 1/60 mode (at least when nothing is attached at the AUTO IRIS connector). It's probably wiser to use the 1/60 mode when a non-integrating mode is desired as that avoids the possibility of the 'electronic iris' feature producing an unwanted/unexpected effect.

It's easy to see how the 1/60 and E.I. light curves are related to illumination pattern as there is a simple one-to-one correspondence with the intensity ratio between intensities otherwise expected to be equal explained by the differing pixel counts in the odd and even field. The resulting pixel count ratios correlates very well with the observed intensity ratios.

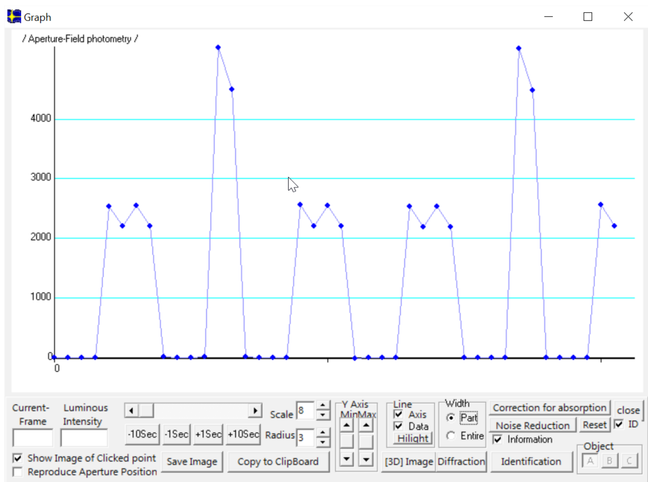
The 2x mode, which integrates two consecutive fields, is much more difficult to understand. It requires a very detailed drawing that accurately reflects the operation of the camera when in integrating mode. Following the light curves shown on the following page, I include a diagram that I hope will help in understanding the details of the 2x light curve.


Graph
/ Aperture-Field photometry /
4000
3000
2000
1000
0
30
Current-Frame
Luminous Intensity
Scale
Radius
-10Sec
-1Sec
+1Sec
+10Sec
Y Axis Min Max
Line
Axis
Data
Hilight
Width
Part
Entire
Correction for absorption
Noise Reduction
Reset
close
ID
Information
Object
Show Image of Clicked point
Reproduce Aperture Position
Save Image
Copy to ClipBoard
[3D] Image
Diffraction
Identification

Shutter: 1/60



Shutter: E.I. (Electronic Iris)

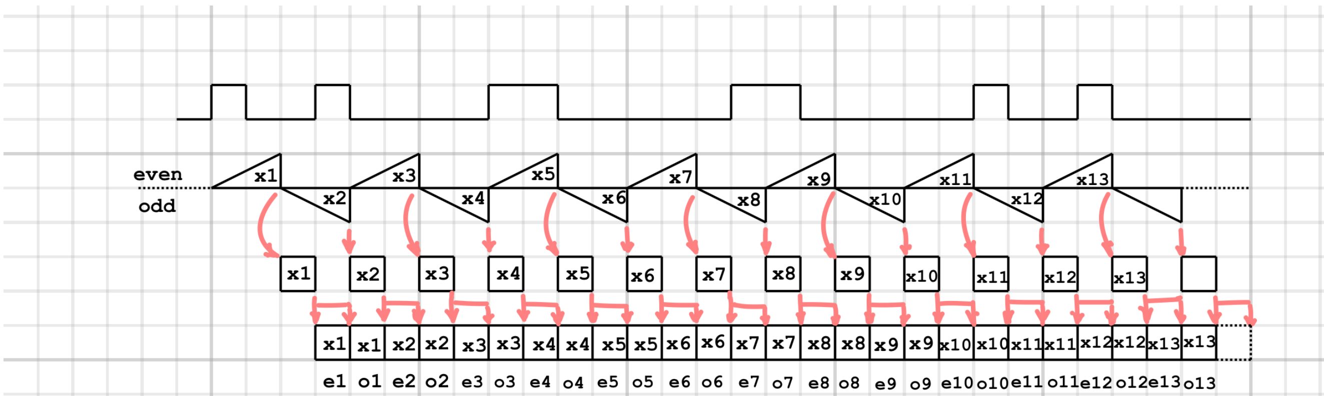


Shutter: 2x (2 field integration)

9.1 Integration diagram

The top line of the diagram below shows the field by field illumination pattern.

The next line shows when the chip is accumulating (integrating) photons in one of its interlaced fields. Take particular note that this diagram shows that there are periods where a field is either held in 'reset' or, equivalently, all of the accumulating charges are being bled off and dumped. This mechanism must exist in order for the high speed exposure settings to work --- exposure times as short as 1/100,000 second are possible with the Watec 910.



The next line depicts the operation of the buffer needed to hold the results of a field accumulation so that it can be repeatedly output at standard field timing --- in this case, each field is repeated twice; in 4x mode, it would be repeated 4 times, etc.

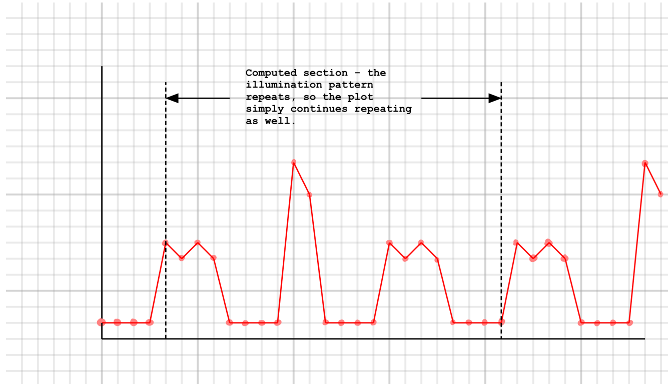
The diagram can be used to 'predict' the 2x light curve that was measured and shown in section 9. We proceed by assigning intensity values to the x values by assigning proportional values based on the illumination pattern. Using this procedure, we would record:

```
x1...x15 = 5,5,0,0,10,0,0,5,5,0,0,5,5,0,0
```

The field by field output results are shown in the first line of the table below. Underneath that line is a code showing which field will display that intensity. Underneath that is the pixel weighted intensity that will be output by Limovie (arbitrarily scaled so that the columns line up nicely):

```
field outputs:5,5,5,5,0,0,0,0,10,10,0,0,0,0,5,5,5,5,0,0,0,0,5,5,5,5,0,0,0,0
parity:       e o e o e o e o  e  o e o e o e o e o e o e o e o e o e o e 0
intensity:    5,4,5,4,0,0,0,0,10, 8,0,0,0,0,5,4,5,4,0,0,0,0,5,4,5,4,0,0,0,0
```

The pixel weightings are now: even = 37; odd = 32. The inversion of the odd/even weights from the E.I. and 1/60 examples is due to the extra camera delay in this mode --- there is a 3 field delay for 2x mode, but only 2 fields of delay for E.I. and 1/60 exposure setting. The resulting plot is:

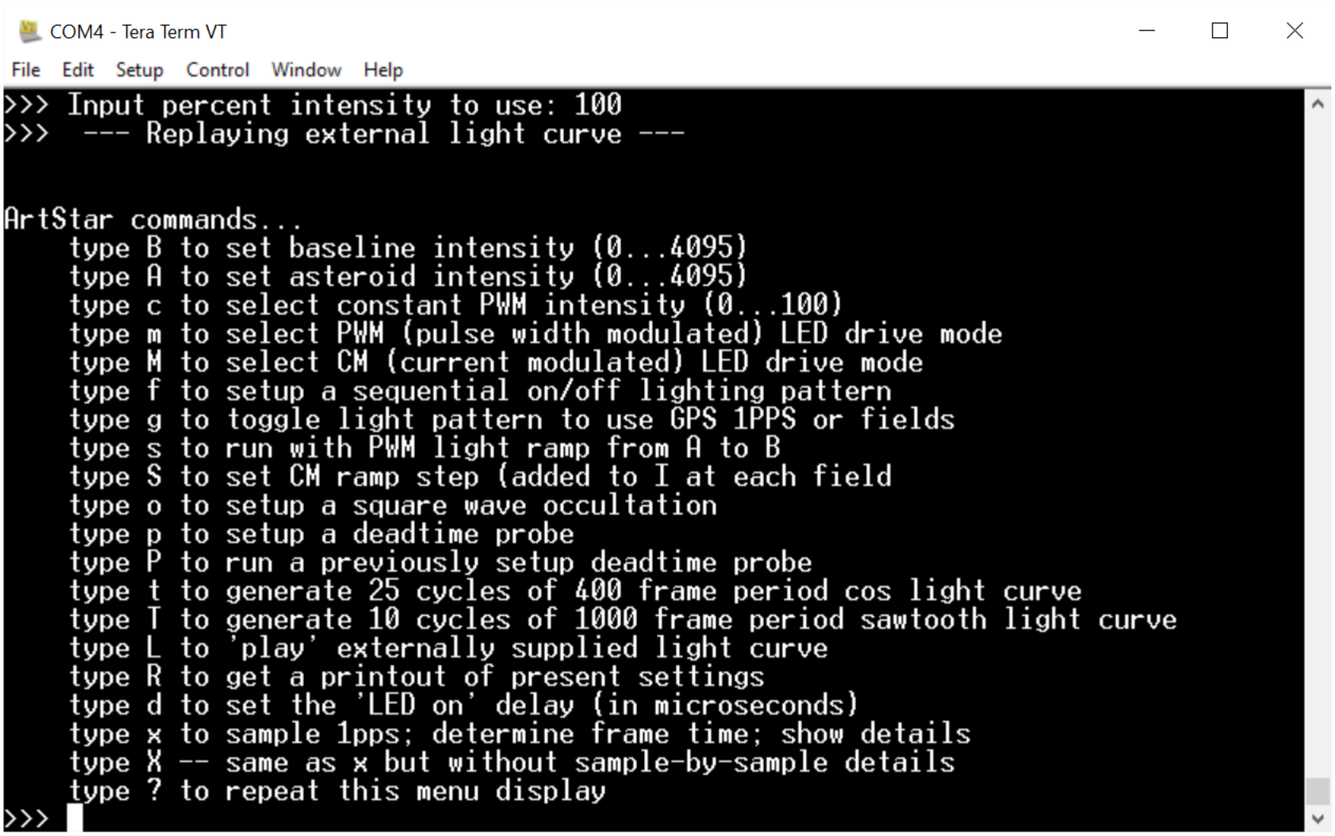

Computed section - the illumination pattern repeats, so the plot simply continues repeating as well.

10 UI (user interface)

The mBed LPC1768 microprocessor board has a USB2 connector. When a USB cable from a laptop is plugged into this connection, it causes the mBed to appear in the laptop file system as an external thumb-drive named MBED. It also supplies 5 volt power to the electronics.

The mBed microprocessor is programmed in C++ using the mBed.org free on-line compiler. All editing is done on-line and a straightforward versioning/archiving system is part of the service. When a program is compiled, if no errors were found, a binary object file is produced to be downloaded to the laptop. A simple drag-and-drop of this file to the MBED folder, followed by a press of the reset button on the mBed board gets the program running.

Once the program is running on the mBed, the USB connection can be utilized as a standard serial port. This mechanism allows primitive, command-line style user interfaces to be created. All that is needed on the laptop side is a 'terminal' program that can perform bi-directional communication. This is the mechanism that ArtStar utilizes to give the user control over the various functions that it can perform. Below is a screen-shot of the 'menu' that the ArtStar UI presents to the user:



Some of the 'commands' initiate a dialog with prompts to the user to enter additional values. For, example, the line at the top of the display is the dialog that results when a lower case c is typed at the prompt.

The next line shows the response when an upper case L is typed at the prompt.

11 ArtStar availability

From the beginning, one of the goals of the ArtStar project was to make it feasible for multiple copies to be built --- there are simply too many cameras and too many possible tests for a single installation to satisfy all the needs.

Therefore, I'm making the ArtStar system (or portions thereof) available to any serious researcher at cost.

I define the ArtStar system as those parts of the diagram shown in section 2 except for the laptop, the frame grabber, the VTI, and the optics stack to the right of the metal lens hood.

The parts cost of a complete system is about $200. Shipping costs would be specific to method and destination.

I would ask that a recent model IOTA VTI be sent to me so that a cable can be added to bring out Field, GPS 1pps, and Ground.

Support for the system is via Skype --- the value of being able to share screens and converse verbally cannot be overstated, so I consider it a requirement (sadly, I only speak english).

The circuit board is equipped with convenient oscilloscope probe attachment points for monitoring Field, GPS 1pps, and LED drive current. It is helpful, but not necessary to have an oscilloscope so that the exact operation of the LED illumination can be confirmed. Alternatively, should there be a question, a Skype session would allow me to make any desired scope measurements for you.

I can be contacted via email at: **`bob.anderson.ok@gmail.com`**

12 Acknowledgments

Thanks are due to Tony George for multiple reasons: at the start of the project he loaned me a Wat120N+ and a 'kit' of parts for building the initial 'optics stack'. Then, he looked over my shoulder as the project progressed and supplied several strategic prods and kicks that drove the development in more useful directions. Finally, he served as the initial reviewer of this report, repeatedly chanting the mantra “tell us more, but keep it simple”.

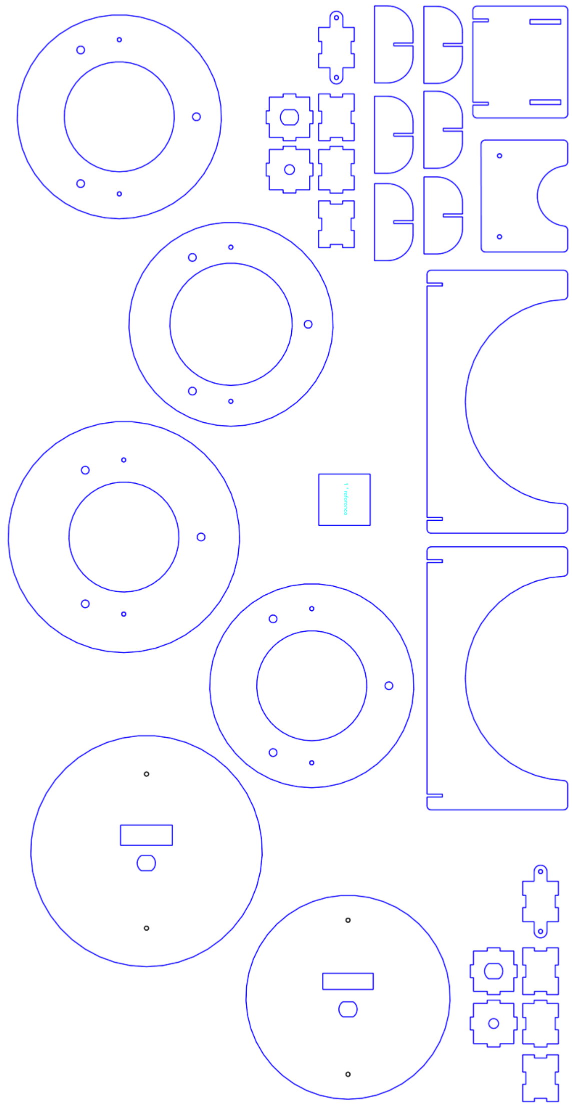
Dave Gault and Tony Barry freely shared details of their Star Chamber device including specific measurements from their setup. That gave me confidence that I was on the right track.

Ted Swift offered several comments in private communications that were helpful during the early part of the concept when the design was still fluid.

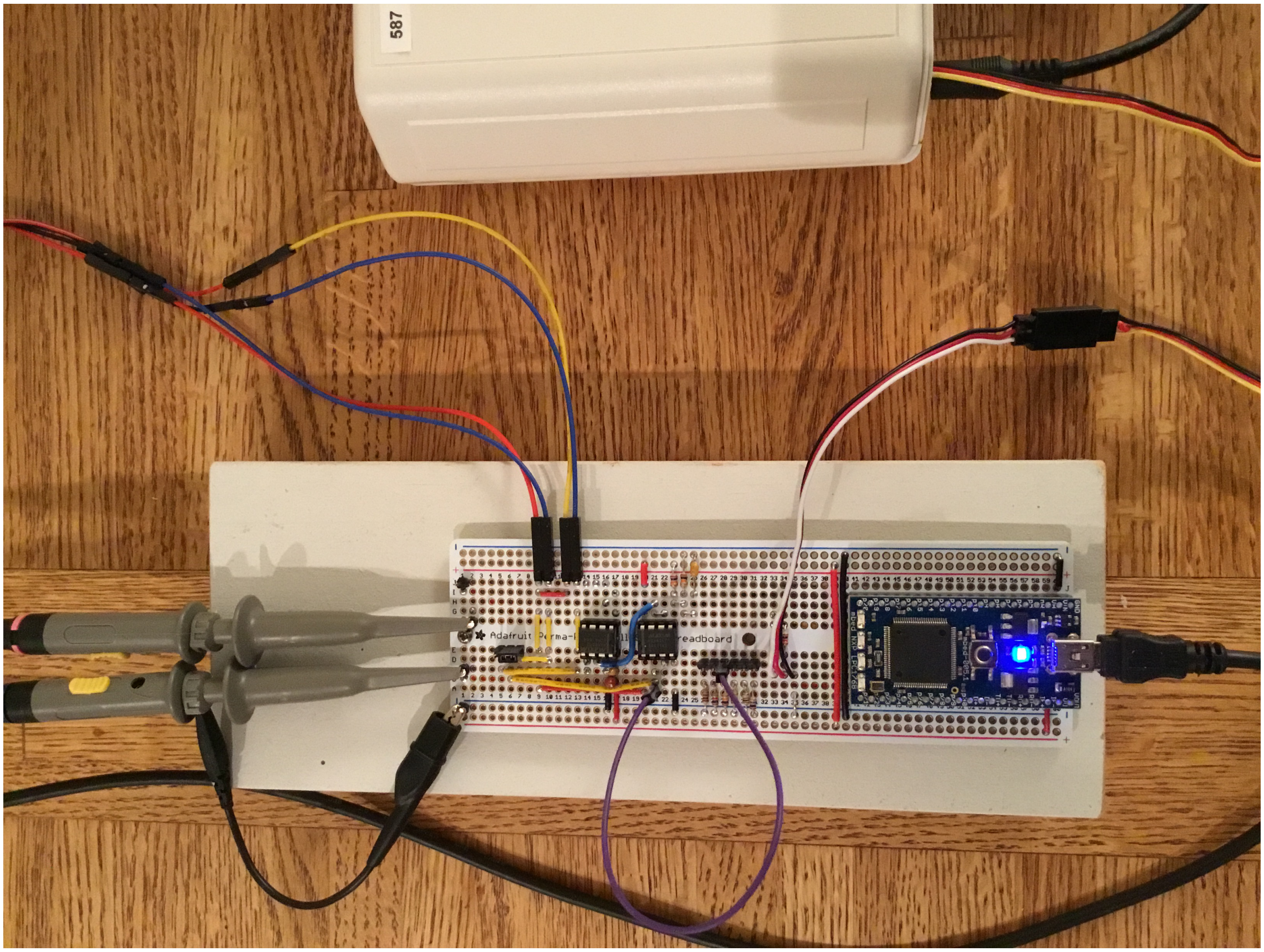
Finally, as one can see from the historical exposition in section 1, starting with Gerhard Dangl's contributions, a number of people have built, described, and utilized camera characterization systems that had as their goal the measurement of video camera performance. ArtStar builds on those efforts.

A special 'shout-out' is owed to Tony Barry who provided a detailed critique of a review copy of this report. He disagreed with one key point that I was making --- his point of view on that matter has prevailed and one section (on linearity) was re-written to reflect our discussions.

13 Appendix A: Photo gallery



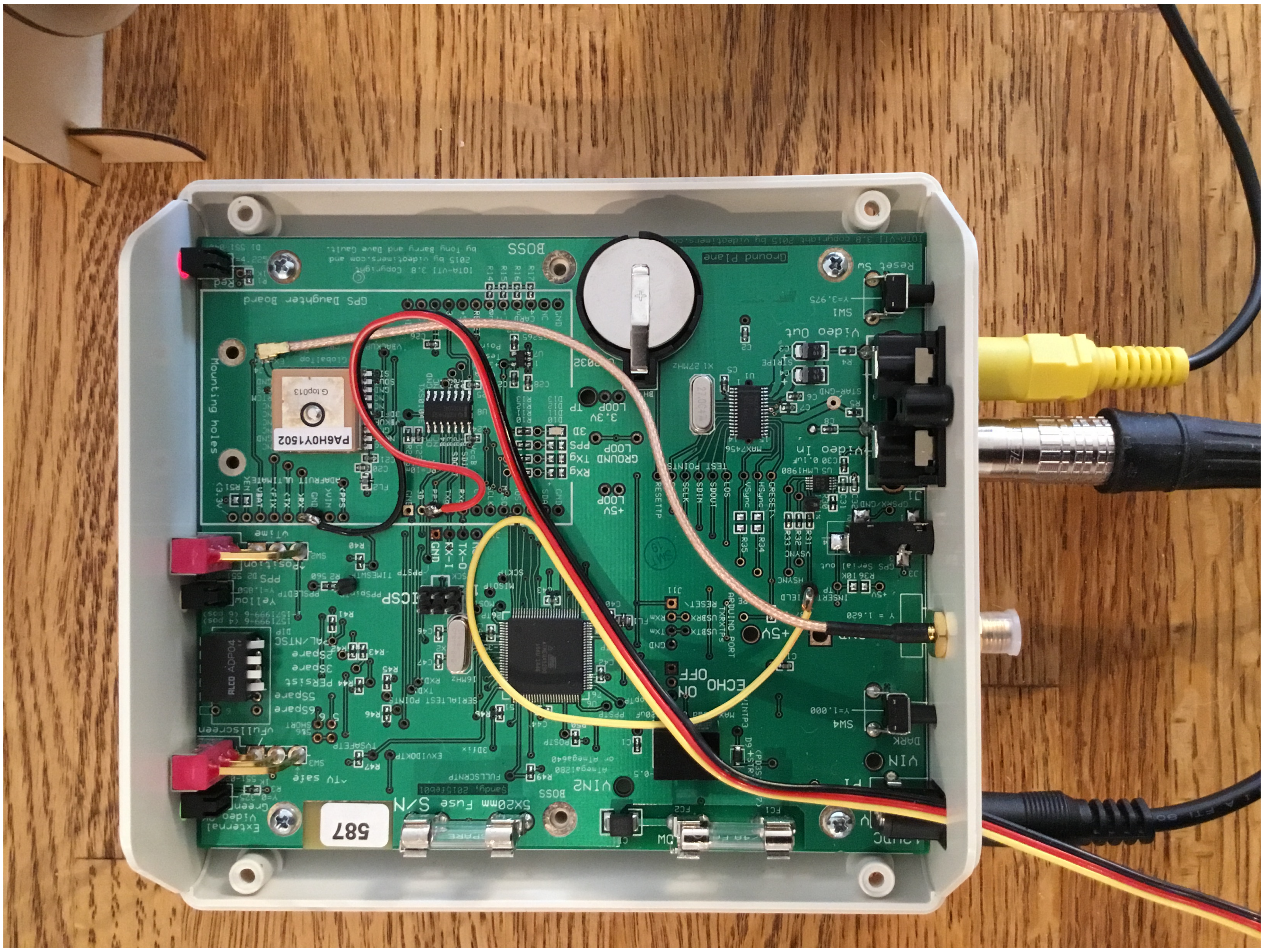
ArtStar mechanical parts. The material used is 1/16" aircraft grade birch plywood. Laser cutting services of these parts were provided by Pololu.com from the drawing shown above (to provide scale, there is 1" x 1" square near the center).



The electronics board “in-use”. It is built on an AdaFruit protoboard --- the mBed and the ICs are socketed --- all other components are soldered in place. The left-hand end of the board has posts so that scope probes can be solidly and conveniently attached. I normally operate ArtStar with oscilloscope monitoring to ensure that the software is doing as requested.

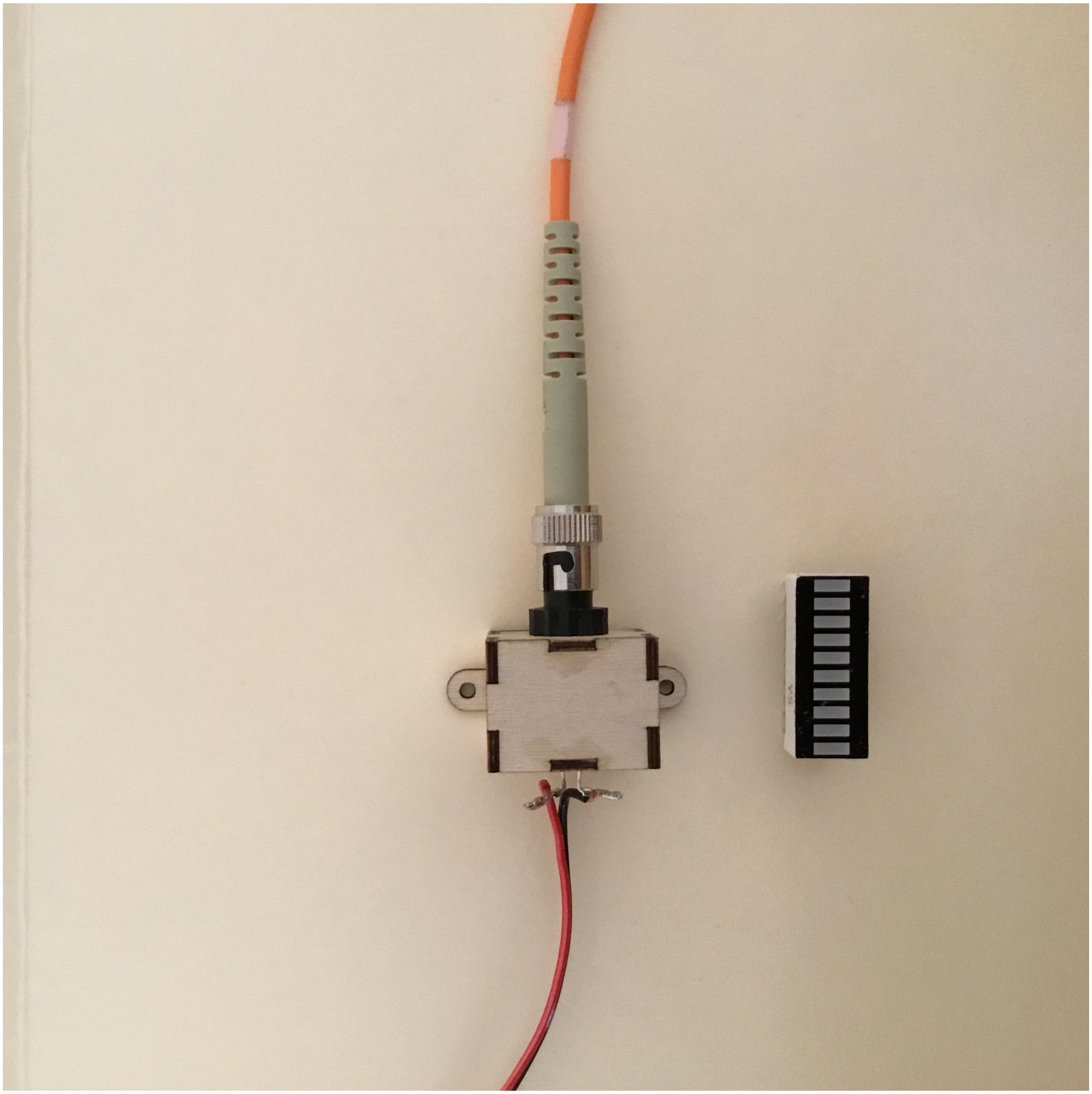
The black cable at the bottom that continues around to the mBed at the right-hand end of the board is the USB cable used for program loading. The same cable provides a serial I/O channel for the user interface. The purple lead is used to select one of the current range setting resistors. In the center of the board is a connectorized ribbon cable for bringing in the VTI signals. The VTI is barely seen at the top of the picture with a brand-new three wire flat ribbon that shares the cutout in the rear panel that houses the power input. This ribbon cable carries the Field, GPS 1pps, and Ground signals tapped from the VTI circuit board.

Finally, the blue/orange and yellow/blue wire pairs are from the two LED targets.



Internal view of IOTA-VTI showing posts added at existing test points and vias with a three conductor ribbon cable soldered to those posts and brought out through existing space above the power connector. Not a difficult 'mod' at all.

A close up of the aim-point adjusting mechanism. There are three (two are visible in this photo) 6 x 32 cap screws that can be tightened and loosened to adjust the aim point of the camera. There is a sandwiched foam doughnut that provides both the pan/tilt flexibility and the restoring force to keep everything snug. The three point geometry adjustment is 'fiddly', but operates smoothly so requires only patience. It is possible to get within a pixel or two of any point on the CCD array (0.5” x 0.5” for the Wat 910).



Closeup of the coupling box that brings the LED in close proximity to the bayonet mount 50 micron fiber optic patch cord that provides the 'star' target.

Next to it is a 10 segment bar graph LED that is mounted next to the 'star' in the end cap. A single segment near the center is lit when this is chosen as the target. It provides a large image that, over a radius of 3 or 4 pixels, is uniformly intense. This uniformity over 45 (Limovie radius 3 central aperture) or 69 pixels (radius 4 aperture) is useful for many measurements.

14 Appendix B: ArtStar electronics schematic