Shutter Performance Analysis of the LUND/DMI Earthshine Telescope

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Ahmad Darudi & Rodrigo Badínez

1. Analysis of Shutter Performance

As the calculation of the Earth´s albedo is based on the ratio between the measured earthshine and sunlit irradiances, the use of a fast shutter is essential to properly control the exposure time and to avoid the smearing effect. This is very important for all the operational modes of the LO/DMI Earthshine telescope except for the Lund Mode that only needs to take long exposures.

The present section reports the characterization of the shutter response of the Earthshine telescope. The shutter is the VS25 model from Uniblitz(Vincent Associates UNIBLITZ), and it has an opto-electronic synchronization system that provides an electronic signal that allows obtaining the opening time of the shutter. In order to calculate the pulse width of the synchronization pulse, a NI-6229 data acquisition card and codes running in LabVIEW were used. The input with a timebase of 80 MHz of the A/D card was used to produce precise measurements of the pulse width.

As the goal of the Earthshine project is to achieve albedo measurements with 0.1% of accuracy, estimations of the amount of precision for the exposure time measurement were also made.

1.1 Experimental Setup

Two different experiments were performed in the optical laboratory using a photodiode (Thorlabs FDS100) and a digital oscilloscope (Tektronix TDS2014B) to measure the shutter response. In both cases the light from a thermal light source was collected using the Earthshine Telescope where the CCD detector was replaced by the Thorlabs photodiode, as shown in Figure 1. The used light source was a light bulb powered by a switching-mode DC voltage source.

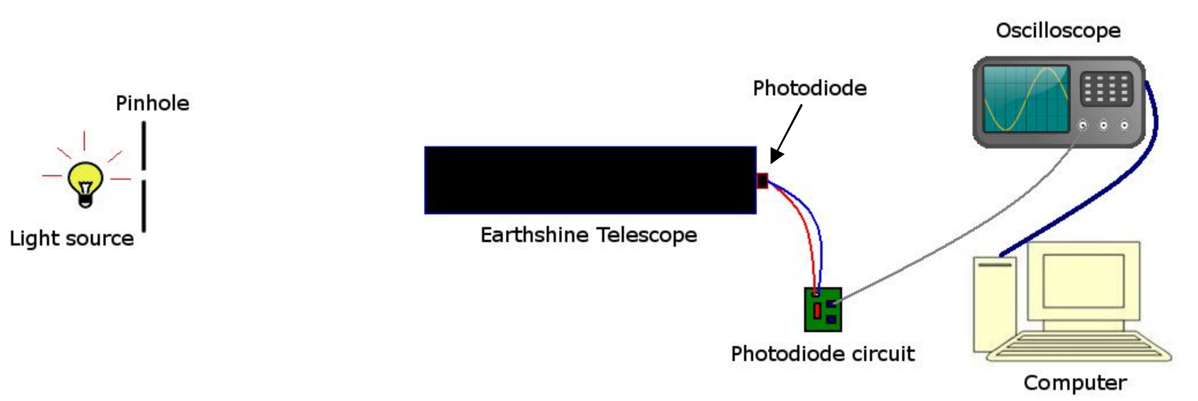

Figure 1 - Experimental setup. The shutter was tested at its operating location inside the Earthshine Telescope.

In the first experiment curves of the exposures were obtained using the photodiode while the values of the exposure times obtained with the opto-electronic synchronization system were recorded simultaneously; this was done for several exposure times in order to measure the accuracy of the synchronization system. In the second experiment 100 measurements of the same exposure time were taken with the photodiode and with the synchronization system to analyze the precision of its repeatability.

1.2 Electronic Setup

The photodiode FD100 was connected according to the recommended circuit diagram (showed in Figure 2) using a bias voltage of 20 Volts, and a load resistor R_L of 10kΩ in order to reduce the response speed and linearity of the element. The value of the resistor was chosen in virtue of existing tradeoff between signal amplitude and speed of response (for a load resistor of 10kΩ a rise/fall time of 10µs was found experimentally for the circuit, using a periodic signal in a LED as light source with a rise/fall time about 1µs).

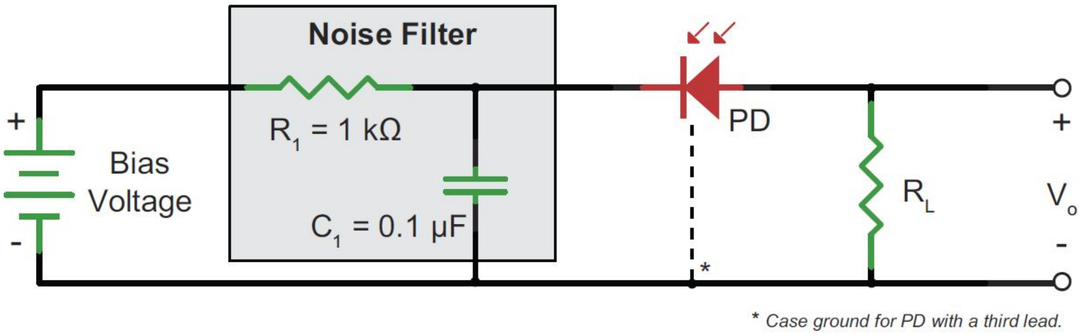

Figure 2 - Photodiode circuit diagram used (from THORLABS FDS100 Specification Sheet (Thorlabs, Inc.))

1.3 Calibration Curve

The photodiode output voltage was acquired with the digital oscilloscope: The NI LabVIEW *Signal Express* software was used to control it and transfer the data. The Earthshine telescope LabVIEW VI program was used to control the shutter and to record the optoelectronic synchronization output signal. To obtain the calibration curve 12 different exposure times were selected, and for each one 10 measurements were done. Examples of curves obtained with the photodiode for different exposure times are shown in Figure 3.

The telescope VI software directly gave the measured exposure time by the mechanical shutter measuring the synchronization pulse width through the NI-6229 data acquisition interface of the PXI telescope control computer. For the analysis of the photodiode signals, a MATLAB™ code was created to calculate the exposure time using the FWHM criterion for the pulse width.

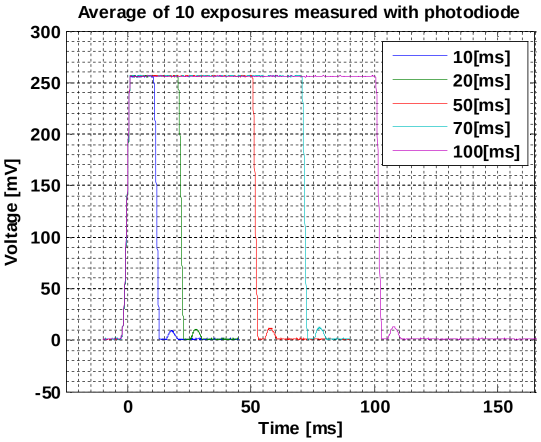

Figure 3 - Example of shutter curves obtained with ther photodiode for different exposure times

The obtained data from both, photodiode and shutter’s opto-electronic synchronization system, are shown together in Table 1 and graphically in Figure 4.

Requested [ms]	Mean of exp.times from PD curves [ms]	STD of exp.times from PD curves [ms]		Sync. signal mean[ms]	Sync. signal STD[ms]	
8	**8.992**	0.017	[0.19%]	**4.7497**	0.0143	[0.30%]
10	**11.986**	0.019	[0.16%]	**7.9565**	0.0135	[0.17%]
20	**21.834**	0.019	[0.09%]	**17.7958**	0.0123	[0.07%]
30	**31.858**	0.024	[0.08%]	**27.8240**	0.0189	[0.07%]
40	**41.868**	0.019	[0.05%]	**37.8570**	0.0175	[0.05%]
50	**51.872**	0.041	[0.08%]	**47.8550**	0.0171	[0.04%]
70	**71.876**	0.035	[0.05%]	**67.8685**	0.0186	[0.03%]
90	**91.83**	0.067	[0.07%]	**87.8628**	0.0169	[0.02%]
100	**101.84**	0.052	[0.05%]	**97.8668**	0.0059	[0.01%]
150	**151.84**	0.052	[0.03%]	**147.8769**	0.0103	[0.01%]
200	**201.85**	0.053	[0.03%]	**197.8833**	0.0117	[0.01%]
220	**221.88**	0.042	[0.02%]	**217.8888**	0.0103	[0.01%]
	Average STD [ms]:	**0.037**	**[0.07%]**		**0.0139**	**[0.06%]**

Table 1 – Mean values and standard deviations of the measured exposure times obtained from the photodiode (second and third columns) and from the optoelectronic synchronization signal of the Uniblitz shutter (last two columns). Standard deviations are also shown as percentage of the mean value inside brackets.

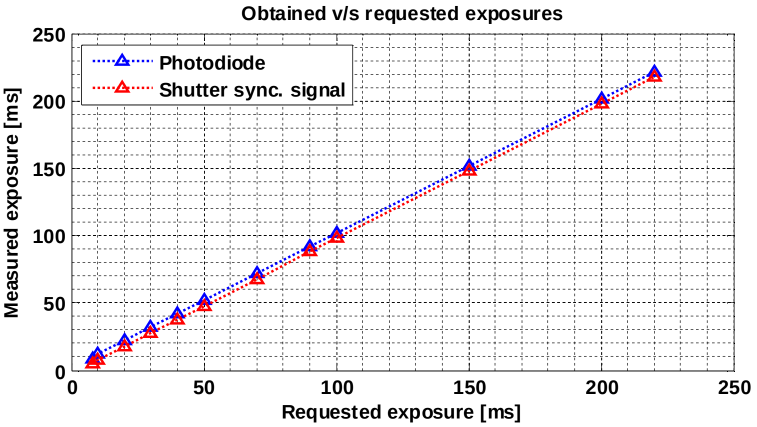

Figure 4 – Measured exposures using photodiode and shutter’s synchronization system versus requested exposures.

The difference between the two measurements of the exposure times is presented in Figure 5 using error bars to indicate the quadratic addition of both standard deviations.

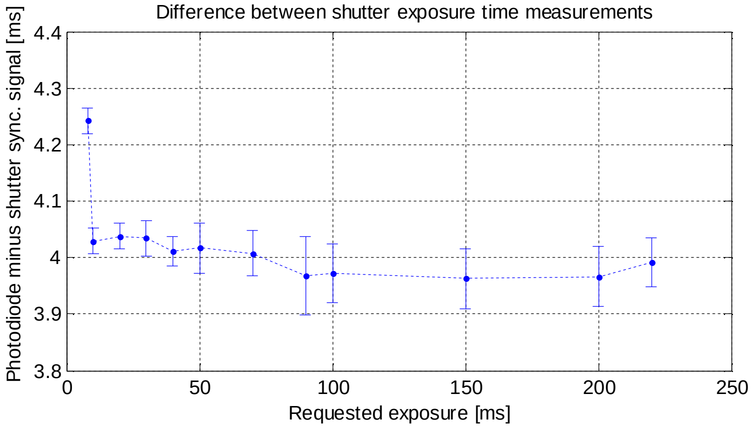

Figure 5 - Difference between measured exposure times obtained using the photodiode and the optoelectronic synchronization signal from the shutter.

It can be seen from Figure 5 that the difference between the exposures measurements increases for shorter times, and also a non-linear behavior is observed for the shortest exposures. Consequently, the linear part of the calibration curve relating the measurements from both sensors was obtained doing a linear regression excluding the 8ms data; its result is shown in Figure 6.

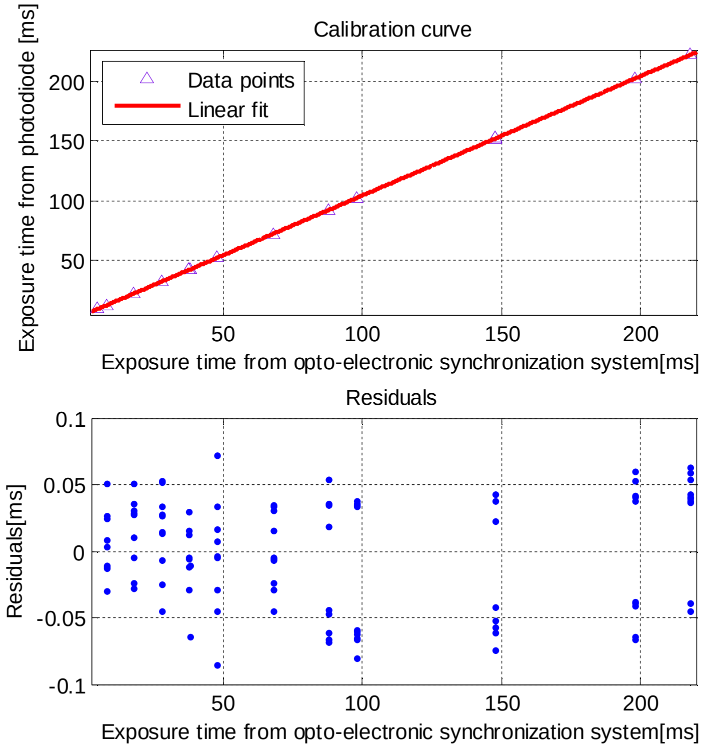

Figure 6 - Calibration curve between the measurements of the photodiode and the synchronization signal from the shutter.

The parameters obtained of the linear regression calculated in MATLAB™ are:

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Linear model:
     f(x) = p1*x + p2

Coefficients (with 99.9% confidence bounds):

       p1 =      0.9997 ± 0.0002
       p2 =       4.028 ± 0.022 [ms]

Goodness of fit:
  R-square: 0.9999996
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The uncertainty on the coefficient *p1* is the error in the slope of the linear calibration. It corresponds to 0.02% of the exposure, regardless its value. The uncertainty on the coefficient *p2* is an additive error showing the ambiguity in the constant level, and its importance is higher for shorter exposures. It corresponds to 0.1% of the 22ms, and is the 0.11% and 0.22% of exposures of 20ms and 10ms respectively.

1.3.1 Discussion

It was observed that there is a systematic difference between the measured values of the two sensors, and also between the requested and obtained values for both sensors. The values obtained with the shutter optoelectronic synchronization system have high precision (standard deviation ~15µs) although they present a bias of roughly 4ms. This high precision is due to the fast response of the optoelectronic synchronization system (based on the interaction between an infrared emitting diode with an infrared sensitive detecting transistor(Vincent Associates UNIBLITZ)) and the high sampling frequency of the DAQ card. The large bias between the two measurements is in part due to the different criteria used to determine the pulse width. While in the photodiode calculations used the FWHM criterion, the optoelectronic synchronization signal is activated only when the shutter is open more than the 80%(Vincent Associates UNIBLITZ). However this effect can explains a bias up to 2ms only. A possible explanation for this large bias is that unnoticed saturation was reached in the photodiode before reaching the maximum height of the pulse; this would trim the higher part of the pulse and consecutively expand its FWHM pulse width. A future experiment will be done to clarify this matter.

The obtained linear regression for the calibration curve has R-square value very near to the unity, indicating a very good fit. The vertical dispersion observed in the residuals shown in Figure 6 is due the lower precision of the photodiode measurements compared to the precision of the synchronization system. However, as the residuals are more or less symmetrically distributed with respect the axis their effect is cancelled producing a good linear fit. As it was previously mentioned, the uncertainty in the slope of the calibration curve is 0.02% for all the exposures, and the uncertainty of the constant term is lower than 0.1% for exposures higher than 22ms. The uncertainty of the calibration is also of the order of 0.1% for the short exposures, with a maximum value of 0.22% for 10ms.

The calculated calibration curve allows the correction of the exposure values obtained with the opto-electronic synchronization system of the shutter to achieve the accuracy of the oscilloscope measurements, eliminating any bias. Even if the repeatability of the photodiode measurements is worst, its accuracy (error of the mean value) is better because as we observed the actual shapes of the pulses we know exactly how the definition of width of the pulse is applied.

As a comment, the relative standard deviations of the photodiode measurements shown in Table 1 are not continuously decreasing for longer exposures due the change the time base of the oscilloscope needed to observe the complete width of the photodiode's pulses. The time base used were 25ms for the 8ms exposure, 50ms for 10ms to 30ms exposures, 100ms for 40ms to 70ms exposures, and 250ms for the rest; the corresponding single shot resolutions are 10µs, 20µs, 40µs and 100µs respectively.

The data measured for 8ms exposures was no considered for the calibration because it diverged from the linear tendency.

Also in the photodiode curves a small bouncing back bump after the closing was detected as we can see in Figure 3, with same characteristics for all the exposures. It will be examined in more detail in the next section.

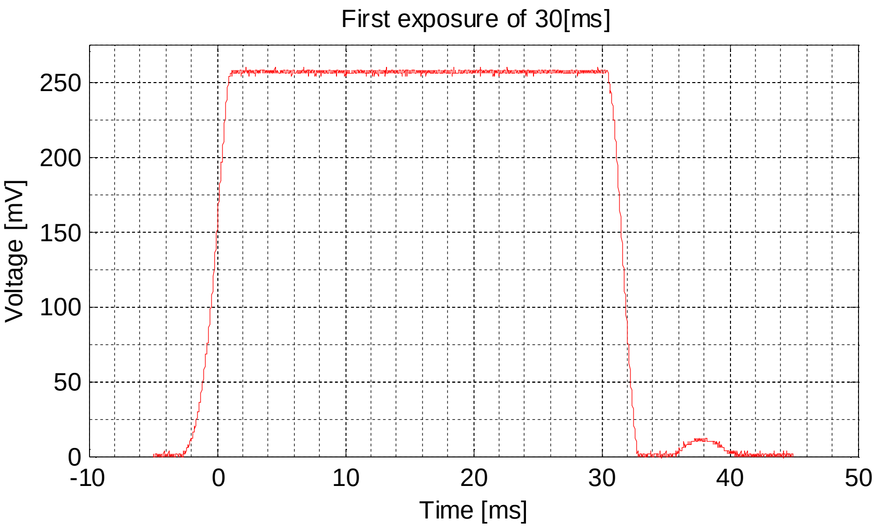
1.4 Repeatability test

In this part 100 measurements were done for only one exposure time using the same setup as in the previous part. The selected exposure time was the minimum of the calibration curve having an error less than 0.1, corresponding to an exposure time of 30ms with a time resolution of 10µs.

As in the previous experiment, the outputs of both sensors were stored simultaneously. However only 62 of the 100 values obtained with the opto-electronic synchronization system of the shutter were valid due a problem with the electric noise filter of the system that led to 38 false detections.

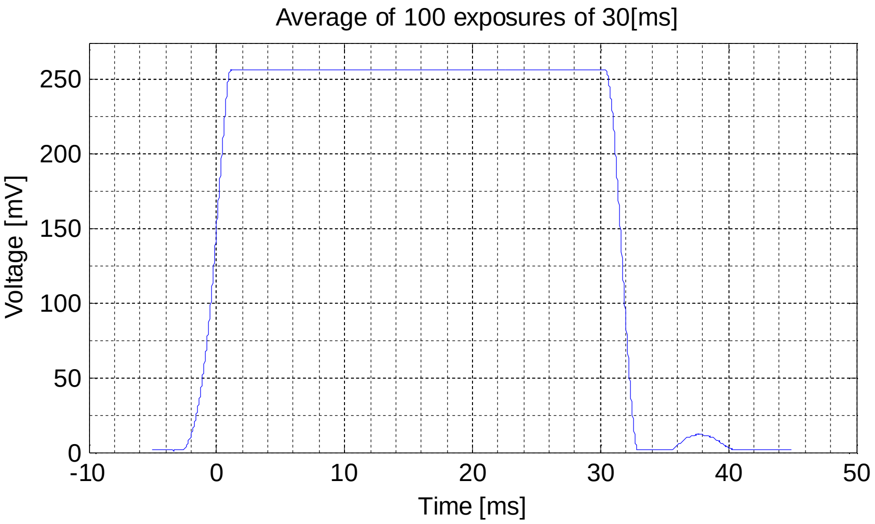
1.4.1 Results

The 100 photodiode curves were averaged to produce a curve almost completely free of noise; a sample of the curve prior the averaging is shown in Figure 7 whereas the average curve is shown in Figure 8.



First exposure of 30[ms]

Figure 7 – Sample of curve obtained with the photodiode and oscilloscope



Average of 100 exposures of 30[ms]

Figure 8 – Average of 100 samples obtained with the photodiode and oscilloscope

The following information was obtained from the averaged curve:

• Time duration (FWHM):	31.86[ms]
• Rise duration*:	2.22[ms]
• Fall duration **:	1.58[ms]

* measured from 10% to 90% of the maximum of the signal

** measured from 90% to 10% of the maximum of the signal

In the curve there is also visible a bounce “bump” signal of the following characteristics:

• Time duration (FWHM):	3.04[ms]
• Delay of bump maximum*:	5.22[ms]
End time (at 10% of maximum) **:	41.76[ms]

- Maximum value:	4.6% of the amplitude of the signal
- Percentage of the main curve (ratio of areas):	0.5%

* measured from the falling edge (at 10% of the maximum of the signal)
** measured from the rising edge (at 10% of the maximum of the signal)

The statistics of the 100 photodiode curves and of the 62 outputs of the opto-electronic synchronization system are presented in the Table 2:

	Mean value [ms]	STD [ms]	STD [%]
Requested exposure time	30	-	-
Photodiode measurement FWHM (100 samples)	31.871	0.0219	0.07
Photodiode measurement FWHM (62 samples)	31.868	0.0222	0.07
Output shutter synchronization system (62 samples)	27.851	**0.0156**	0.06

Table 2 –Statistics of the exposures measured using the photodiode and the synchronization signal of the mechanical shutter. The second row shows the values obtained with the photodiode for the 62 exposures measured correctly with the opto-electronic system.

1.4.2 Discussion

The quality of the obtained curves using the photodiode was satisfactory and exposure, rising and falling times of the signal were calculated from them. The obtained exposure time has better agreement with the requested time than the output of the shutter synchronization system; however, the repeatability of the opto-electronic system of the shutter is better.

The time duration of the pulse, as well as its rising and falling times, are very stable. The only observed problem with the shutter response is the small bump after the closing originated by the bounce back of the shutter; thus it is necessary to add some delay on starting the readout process of the camera of about 10ms to remove the smearing caused by the bump. It was observed that the bump has the same characteristics regardless the value of the exposure time. For the analyzed exposure, i.e. 30ms, the integrated area under the bump corresponds to 0.5% of the main pulse area, and for the shortest exposure it corresponds to the 1.5%. This area is equivalent to 168µs of additional exposure if the photodiode response was perfectly linear and the measurements didn’t suffer of any saturation effects. However this cannot be assured at this time.

Using the obtained calibration curve, it is possible to correct the bias of the opto-electronic synchronization system reducing the error to its repeatability fluctuations. The measured repeatability error of the shutter corresponds to the 0.05% of the mean photodiode exposure for 30ms, and it corresponds to the **0.13%** of the mean photodiode exposure for 10ms.