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Characterizations of a KHz Pulsed Laser Detection System

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Abstract

A KHz Pulsed Laser Detection System was developed employing the concept of charge integration with an electrometer, in the NASA Goddard Space Flight Center, Code 618 Calibration Lab for the purpose of using the pulsed lasers for radiometric calibration. Comparing with traditional trans-impedance (current-voltage conversion) detection systems, the prototype of this system consists of a UV-Enhanced Si detector head, a computer controlled shutter system and a synchronized electrometer. The preliminary characterization work employs light sources running in either CW or pulsed mode. We believe this system is able to overcome the saturation issue when a traditional trans-impedance detection system is used with the pulsed laser light source, especially with high peak-power pulsed lasers operating at kilohertz repetition rates (e.g. Ekspla laser or KHz OPO). The charge integration mechanism is also expected to improve the stability of measurements for a pulsed laser light source overcoming the issue of peak-to-peak stability. We will present the system characterizations including signal-to-noise ratio and uncertainty analysis and compare results against traditional trans-impedance detection systems.

Keywords: charge integration, electrometer, shutter, KHz pulsed laser, Ekspla, radiometric calibration

1. Introduction

The traditional double-monochromator based spectral irradiance and radiance responsivity calibration comes with two major shortcomings: low radiant power with wide bandpass and difficulty reaching a calibration uncertainty less than 1%. With the development of the continuous-wave (CW) and quasi-CW tunable SIRCUS (Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources) lasers, detector based calibrations are available; and the calibration uncertainty can reach levels less than 0.25%. But in practical implementation, those CW or quasi-CW lasers are expensive and difficult to automate.

Kilohertz pulsed optical parametric oscillators (OPO) based tunable lasers are commercially available, e.g. Ekspla NT242 series. They are much more affordable than the tunable CW or quasi-CW lasers and are fully automated over a wide spectral range from 210 nm to 2600 nm. At present, these systems deploy a kilohertz repetition rate with 3 ~ 6 nanosecond (ns) pulse duration which yields an approximate 10^{-5} duty cycle; in other words, its peak/average power ratio is about 10^{+5}. That makes it difficult to stretch and extend by using fiber optics and/or integrating spheres; and theoretically, could cause saturation problems when conventional measurement systems consisting of a detector, a trans-impedance amplifier and a digital multi-meter are used [1]. In practice, the more than 10% pulse-to-pulse power fluctuation in the KHz OPO laser is another drawback toward its use as a calibration light source.

Our work here is to develop a KHz pulsed laser detection system, which can overcome the pulse-to-pulse fluctuation and the saturation problem caused by the small duty cycle from the KHz OPO laser and to further explore the possibility of using the Ekspla laser in our remote sensing calibration work. This includes BRDF

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measurements, in-band and out-band filter characterizations, and system level instrument responsivity measurements.

2. System Description

The system employs the concept of charge integration. It consists of an electrometer, a UV-enhanced Si detector and a computer controlled laser shutter system. Figure 1 shows the main components and the set up.

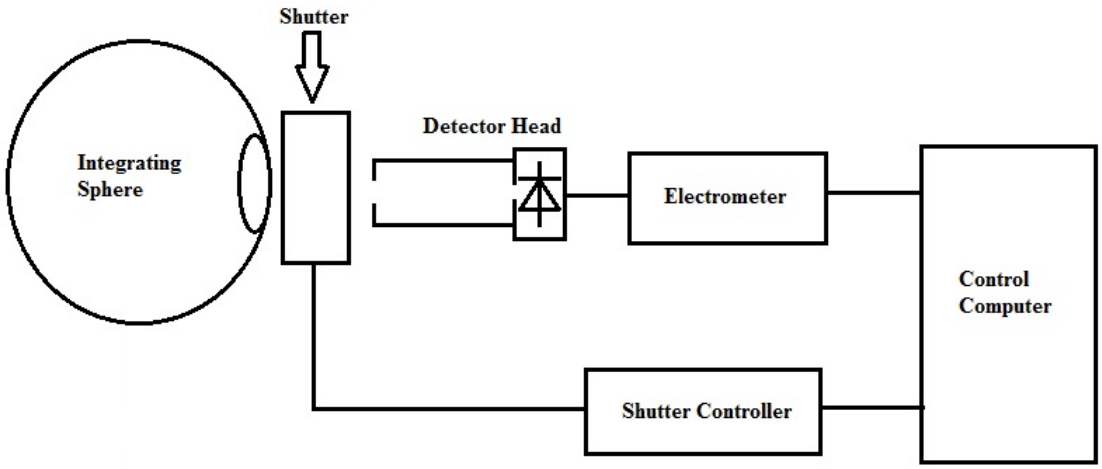


Figure 1 Main Components and System Layout

The operational principle of this concept is illustrated in Figure 2. In situation 1, when the shutter opens, a pulse train impinges onto the detector and the detector converts it into photon current *i* (t) and sends it directly to the electrometer. The electrometer starts accumulating charge before the shutter opens and ends slightly later than when the shutter closes to make sure all the laser pulses are captured and counted. The electrometer works equivalently as a constant capacitor to hold all the incoming charge, and the charge integration is like a stair. The charge readout (units in Coulombs) is proportional to the capacitor voltage:

$$Q = \int i(t)dt = C \star V$$

This system can be treated as an energy accumulator, it measures all the pulses' energy in a specific time range. We assume that the laser pulse-to-pulse fluctuation is statistically random. By employing the "integration" or "accumulation" idea, we expect this system will eliminate the possible saturation problem caused by the small duty cycle and will smooth out the pulse-to-pulse fluctuation.

In situation 2, when a CW light source is used, the incoming light can be considered as a nearly constant signal; and the charge integration is like a slope. In either situation, all the incoming optical energy is captured and accumulated. Theoretically, this pulsed laser detection system can be used to work with both pulsed laser light sources and CW light sources.

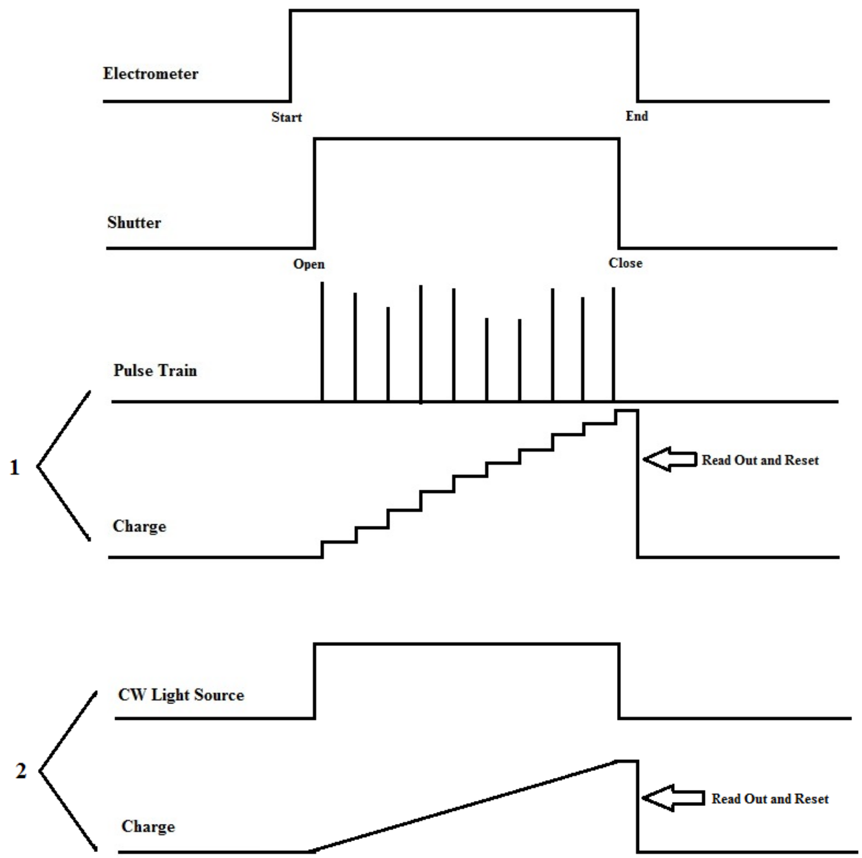


Figure 2 Operation Principle of Charge Integration

The UV-enhanced Si detector chosen for this work was the Hamamatsu S2281 with a ϕ11.3 mm in diameter. Fore-optics were used to make the detection system work in radiance mode.

3. Light Sources and Other Measurement Instruments

In order to ultimately characterize the KHz pulsed laser detection system, we decided to start the characterizations with a CW light source which is a well-characterized, LED-based stable uniform light source. The other reason we wanted to do so is that we had no knowledge about how our other measurement instruments would work with the KHz pulsed OPO.

The measurement set up is shown in Figure 1. The light sources used in these measurements include a LED-based stable uniform light source and an Ekspla NT 242 series KHz pulsed tunable laser. Other instruments used in these measurements include a NIST calibrated Si trap detector with a Keithley 6485A picoammeter; an Oriel Merlin single-channel system with a Si detector head; and the Filter Radiometer Monitor System (FRMS). A brief description for each instrument is provided below.

The LED-based stable uniform light source is comprised of an integrating sphere and a set of four LEDs of different wavelengths. The integrating sphere is lined with Spectralon and is 30.5 cm in diameter with a 10 cm opening and 4 ports for mounting LEDs emitting light at in 405 nm, 565 nm, 735 nm and 850 nm respectively. This sphere is shown in Figure 3. Its short-term output stability is within 0.1%, and is considered an extremely stable instrument for characterizing detectors and remote sensing instruments. Detailed documentation can be found in an SPIE proceeding. [2] Figure 4 shows the stability monitor data for the LED light source at 565 nm wavelength.

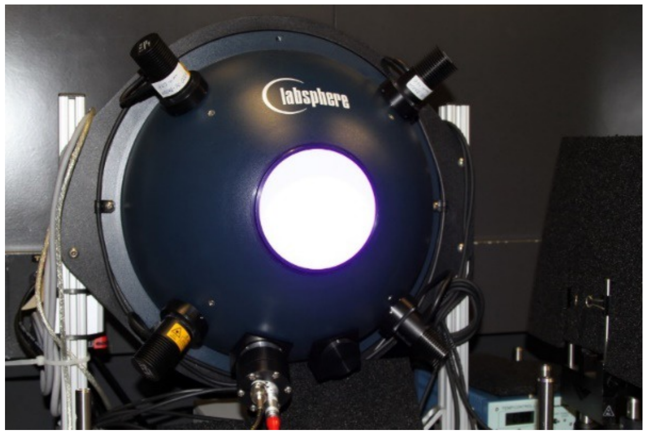


Figure 3 LED-based Stable Uniform Light Source with 4 LEDs

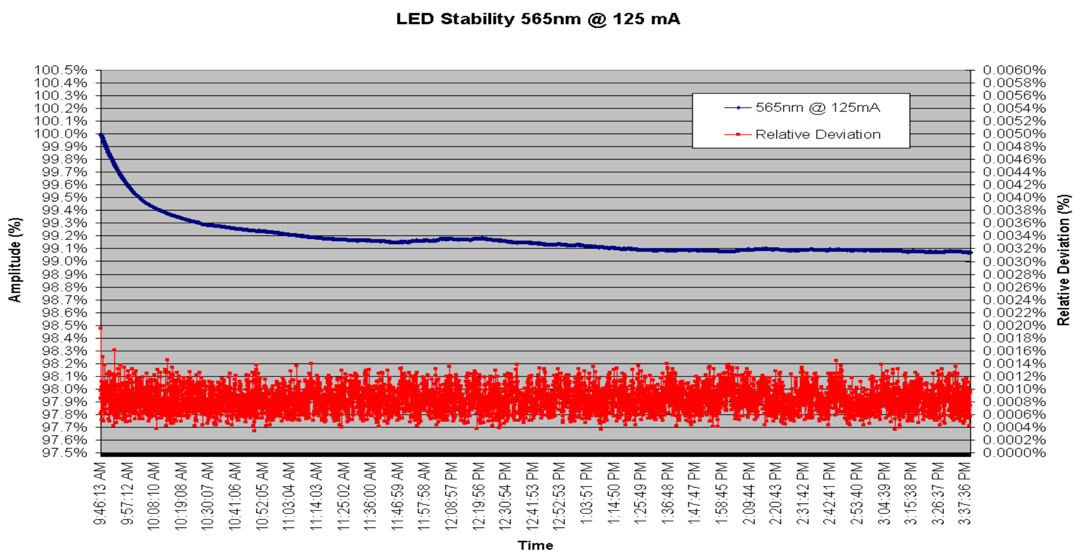


Figure 4 Short-Term Stability of LED-Based Light Source

The Ekspla NT 242 series KHz pulsed tunable laser is a one box instrument which includes the pump laser and the OPO system. The tunable spectral range is from 210 nm to 2600 nm with a spectral pulse energy distribution shown in Figure 5. The typical linewidth is less than 5 cm^{-1}, which yields the following band-passes in nm: 0.13 nm @ 400 nm, 0.12 nm @ 500 nm, and 0.32 nm @ 800 nm. The laser pulses exhibit a wide pulse-to-pulse power fluctuation, and this situation is illustrated in the Figure 6 oscilloscope trace.

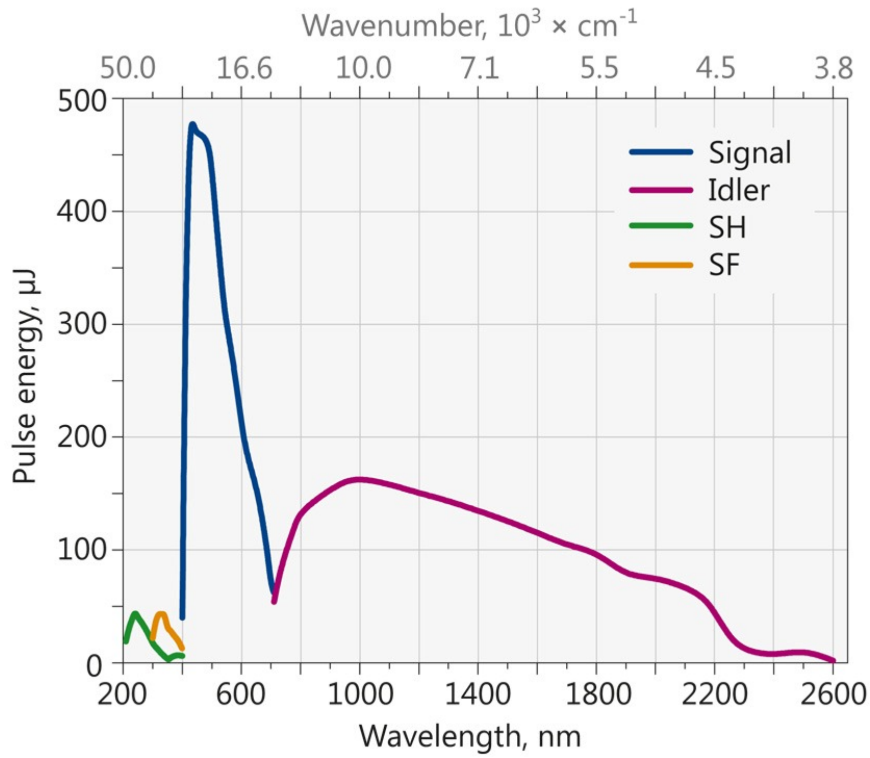


Figure 5 Typical Output Pulse Energy of NT 242

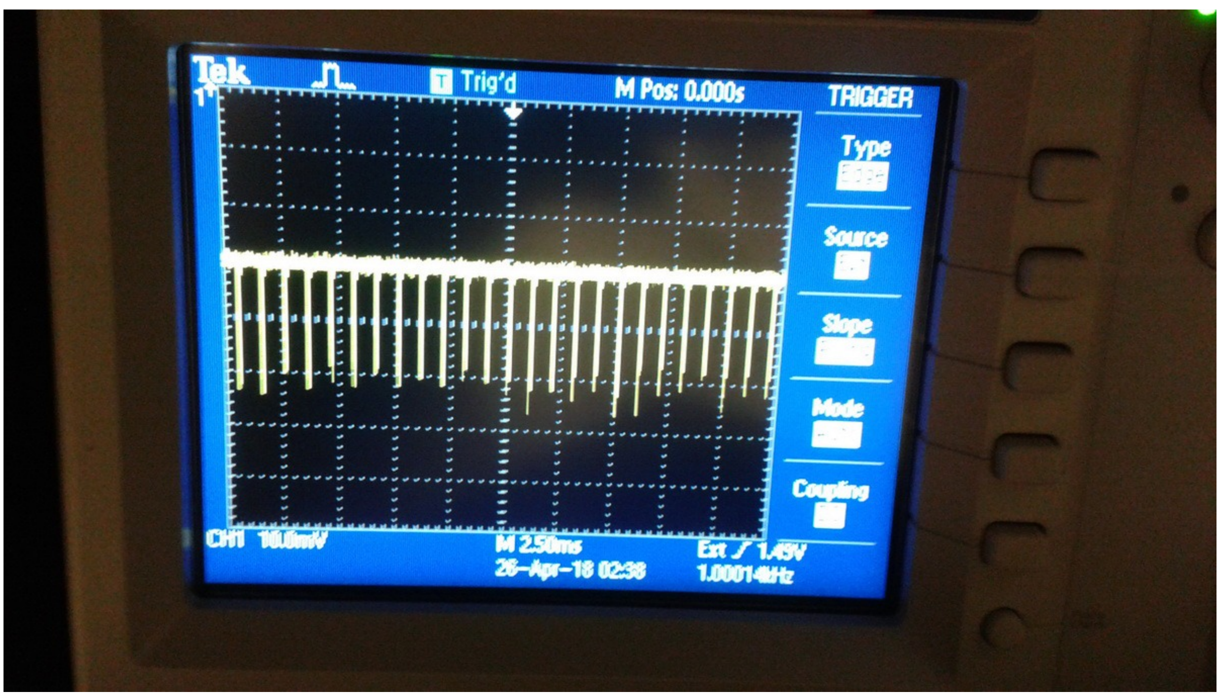


Figure 6 Pulse-to-pulse Variation from NT 242 Series Laser

The trap detector system was calibrated by NIST in the spectral range from 300 nm to 1100 nm. The Gershun tube located in front of the detector elements enables the trap detector system to work in radiance mode.

The Oriel Merlin system is a digital lock-in amplifier with a chopper controller. The Si detector head consists of a UV-enhanced Si detector and a trans-impedance current to voltage converter. Its voltage output is read out by a lock-in amplifier. It works in radiance mode as well.

The FRMS is the primary filtered monitoring system in our calibration lab. Its filter wheel contains 1 opaque blocking element and 11 specific bandpass filters focusing on 11 wavelengths of interest to the remote sensing community. The detector used in the FRMS is a UV-enhanced Si detector, and the pre-amp is a traditional trans-impedance current to voltage converter. The voltage output is read out by a digital voltage multi-meter (DVM). Detailed documentation can be found in an SPIE Applied Optical Journal paper. [3]

4. Measurement Descriptions

The working procedure of the pulsed laser detection system is depicted in Figure 7. In each cycle, the electrometer makes two measurements. The first measurement was made with the laser shutter closed, and the second measurement was made with the laser shutter open. The incoming light energy was calculated by subtracting the first measurement from the second measurement. The first measurement is treated as the DARK signal of the system. We also define “Window Time” as the time from shutter open to shutter close in units of milliseconds (ms).

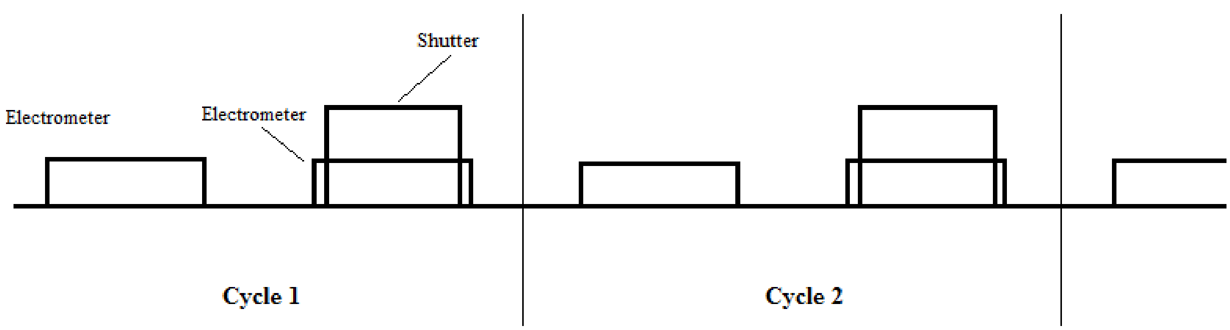


Figure 7 Working Procedure of the Pulsed Laser Detection System

4.1 Characterizations with CW light source (LED-based stable uniform light source)

The CW set up is similar to Figure 1 and is shown in Figure 8. The trap detector was used as the reference instrument. The red-boxed components are all set inside a light-tight enclosure to eliminate stray and ambient light.

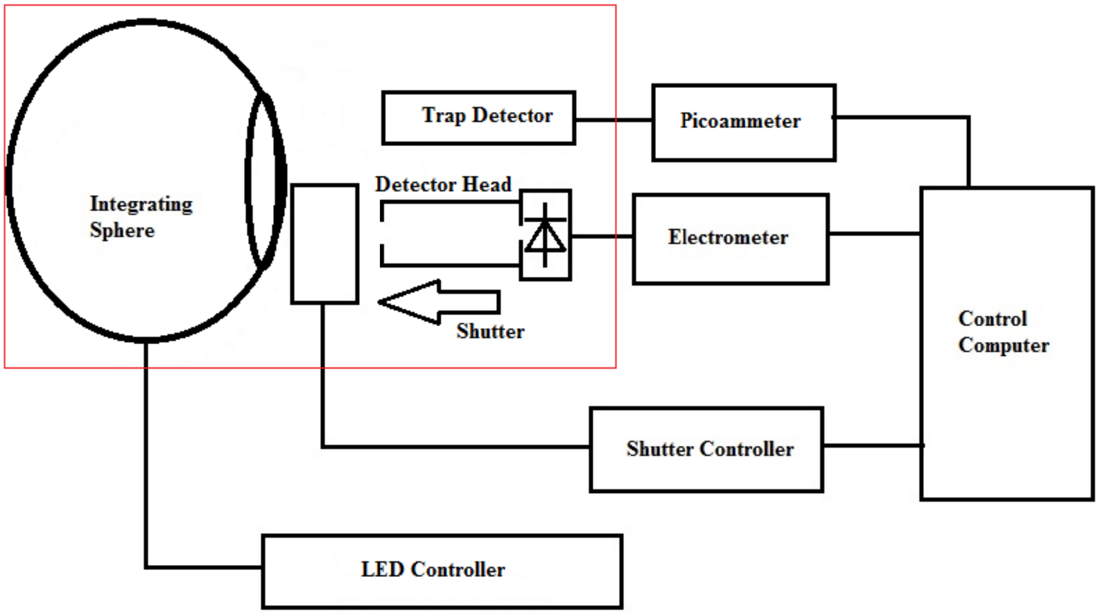


Figure 8 Pulsed Laser Detection System Characterizations with CW Light Source

Figure 9 Set Up Inside the Light-Tight Enclosure

The measurements included Window Time linearity, detector responsivity linearity against the reference trap detector followed by a noise and an uncertainty analysis.

To measure the Window Time linearity, we kept the LED-based light source under a constant output level, gradually increased the Window Time from 100 ms to up to 10000 ms, and measured the charge outputs correspondingly in an effort to check if the charge outputs are indeed proportional to the Window Time.

Then we set the Window Time constant, at say 1000 ms. We changed the LEDs' driving current so that the light output levels would be changed and both charge output and trap detector output would be recorded correspondingly. The trap detector's outputs were used as reference to compare with the electrometer's charge outputs to determine the detection system's responsivity linearity.

4.2 Characterizations with Ekspla NT 242 series pulsed tunable laser

The pulsed laser detection system was characterized by CW light source and provided some knowledge on how it performs, also we have gained some knowledge on how it performs. We also gained some confidence on what we could expect when we used it with the pulsed laser light source.

The pulsed laser light source measurement set up is shown in Figure 10. Three traditional measurement instruments were used in a cross-characterization with the pulsed laser detection system: the trap detector with a picoammeter Keithley 6485A, the Oriel Merlin lock-in amplifier system and the FRMS.

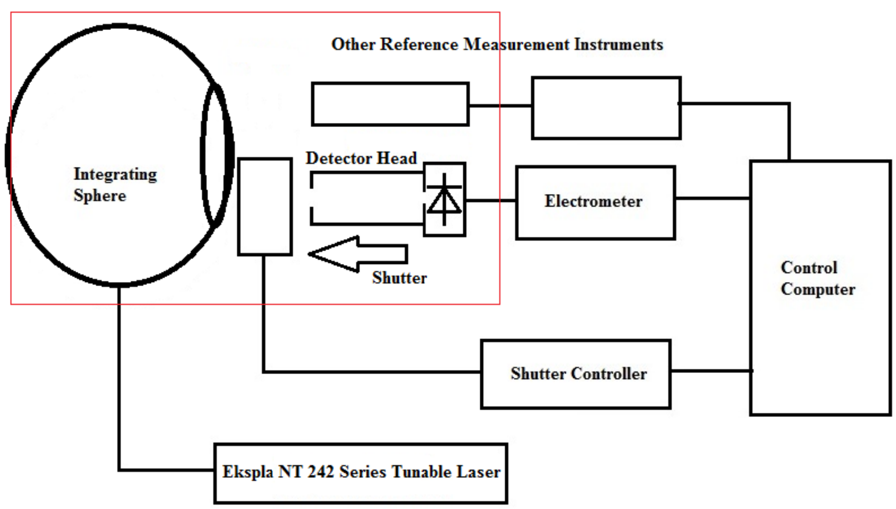


Figure 10 Pulsed Laser Detection System Characterizations with Ekspla NT242

As they were in the characterizations using the CW light source, the components inside the red box were set inside a light-tight enclosure to ensure the elimination of stray and ambient light.

The characterizations using the Ekspla laser included Window Time linearity, detector responsivity linearity against reference measurement instruments, noise and uncertainty.

The measurement procedure for Window Time linearity is identical to the CW light source. In the detector responsivity linearity characterizations, the laser power level was changed by using 25% and 50% Neutral Density (ND) filters. This characterization was also used to determine if the traditional measuring instruments were experiencing any saturation-induced issues.

5 Measurement Results

5.1 Characterizations with LED-based stable uniform light source

Table 1 shows the results of Window Time Non-linearity measurement at a wavelength of 850 nm. The Reference Number corresponds to the Window Time, and the Non-linearity was calculated by comparing the Measurement Coefficient to the Reference Number.

850 nm@50 mA	Window Time	Reference Number	Measurement Coefficient	Non-Linearity
	100ms	1	1	0.00%
	200ms	2	2.002343425	0.1172%
	300ms	3	2.997005187	0.0998%
	500ms	5	4.990355715	0.1929%
	1000ms	10	9.973954649	0.2605%
	2000ms	20	19.93891292	0.3054%
	3000ms	30	29.90320303	0.3227%
	5000ms	50	49.82745716	0.3451%
	10000ms	100	99.62442357	0.3756%

Table 1 Window Time Non-linearity characterization with LED @ 850 nm

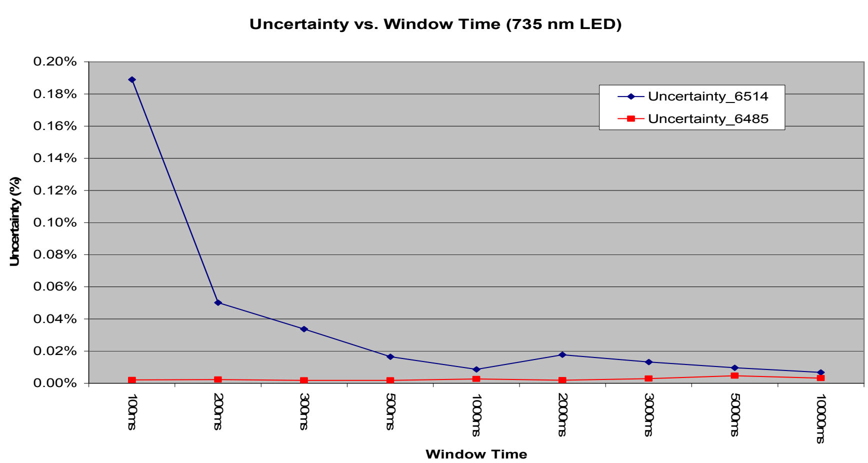


Figure 11 Window Time vs. Uncertainty with LED 735 nm

Figure 11 shows the relationship between Window Time and measurement uncertainty at a wavelength of 735 nm. The blue line represents the pulsed laser detection system and the red line represents the trap detector.

With the increment of the Window Time, the measurement uncertainty of the pulsed laser detection system quickly drops and gradually gets close to that of the trap detector. These results can also be seen in the noise performance comparison between the trap detector (6485) and the pulsed laser detection system (6514) in Figure 12.

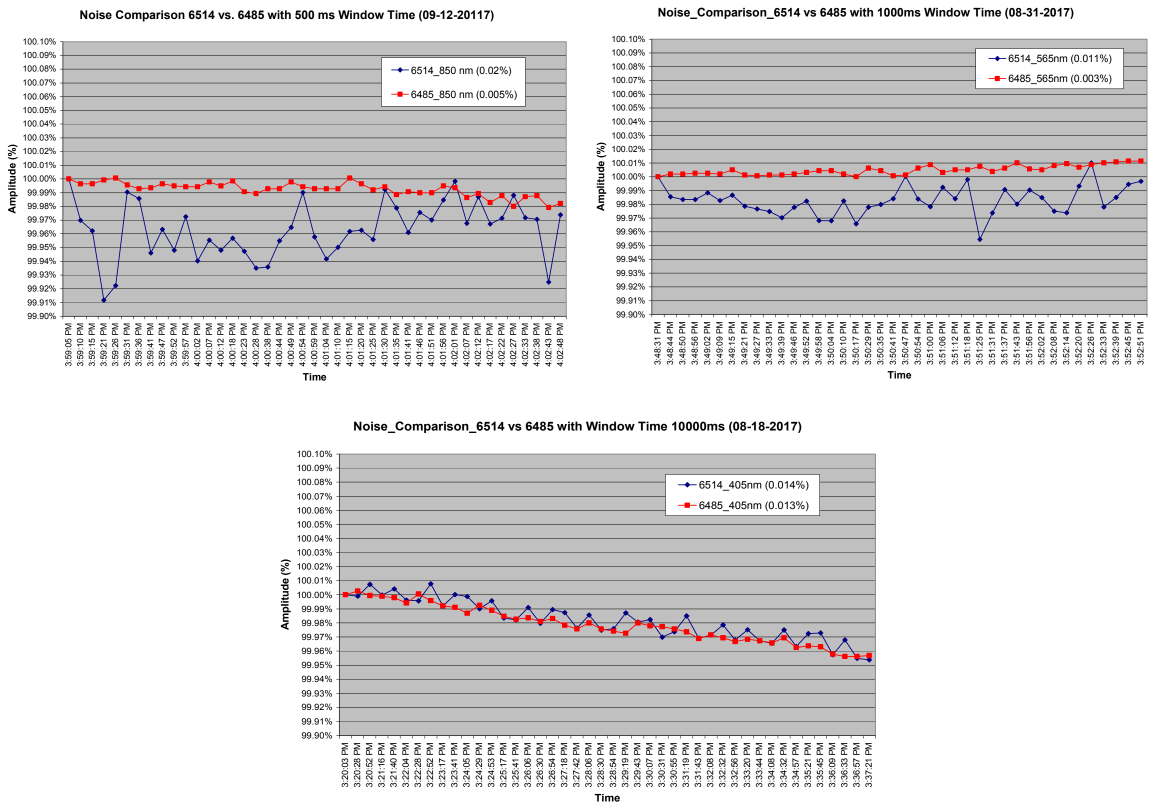
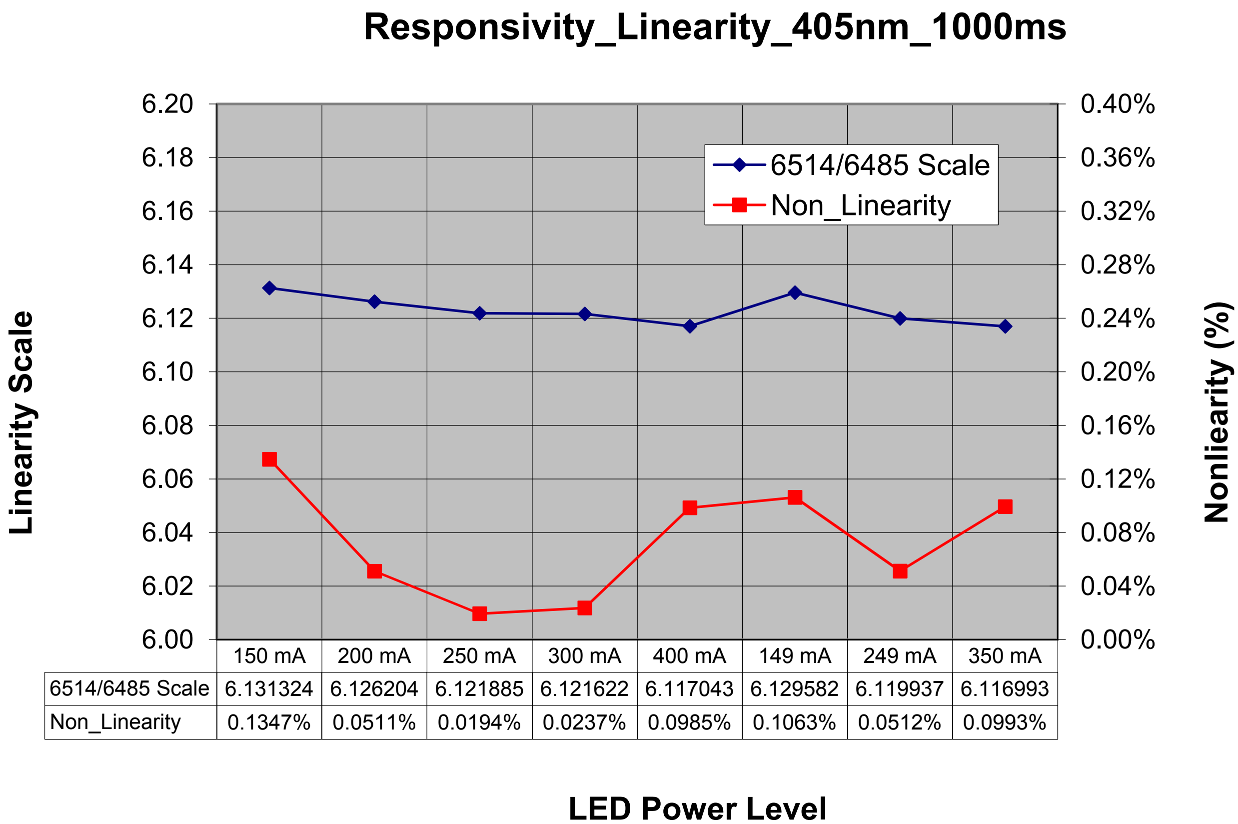


Figure 12 Noise vs. Window Time comparison

405 nm Power Level	6514	6485	6514/6485 Ratio	Nonlinearity
150 mA	5.15076E-07	8.40E-08	6.1313	0.135%
200 mA	7.37144E-07	1.20E-07	6.1262	0.051%
250 mA	9.62287E-07	1.57E-07	6.1219	0.019%
300 mA	1.19079E-06	1.95E-07	6.1216	0.024%
400 mA	1.63532E-06	2.67E-07	6.1170	0.098%
149 mA	5.14407E-07	8.39E-08	6.1296	0.106%
249 mA	9.59452E-07	1.57E-07	6.1199	0.051%
350 mA	1.41261E-06	2.31E-07	6.1170	0.099%
Average			6.1231	

Table 2 Detector responsivity linearity against trap detector (6485)



	150 mA	200 mA	250 mA	300 mA	400 mA	149 mA	249 mA	350 mA
6514/6485 Scale	6.131324	6.126204	6.121885	6.121622	6.117043	6.129582	6.119937	6.116993
Non_Linearity	0.1347%	0.0511%	0.0194%	0.0237%	0.0985%	0.1063%	0.0512%	0.0993%

Figure 13 Detector responsivity linearity with Window Time 1000 ms @ 405 nm

Table 2 and Figure 13 show the measurement results of detector responsivity linearity with the LED at a wavelength of 405 nm with the Window Time set to 1000 ms.

From the results above, the LED-based stable uniform light source continues to show its capability to perform instrument characterizations. With shorter integration time, e.g. 1000 ms or less, the shutter is the main source of the measurement uncertainty, and this influence will decrease as the Window Time increases which indicates that the error from the shutter is in a ± 1ms format instead of a ± 1% format.

5.2 Characterizations with Ekspla NT242 series tunable laser

The first characterization was the relationship between Window Time and measurement uncertainty shown in Figure 14 and 15. Figure 14 shows the results using the Ekspla laser operating at 565 nm. The red line is the trap detector data uncertainty, and blue line is the uncertainty from the pulsed laser detection system. The red line maintains a relatively flat profile. The blue line is higher than red line at the beginning, but it gradually drops as Window Time increases and at about 3000 ms Window Time, it goes below the trap detector's measurement uncertainty. The blue line reaches 0.1% when the integration time is at 60,000 ms (1 minute).

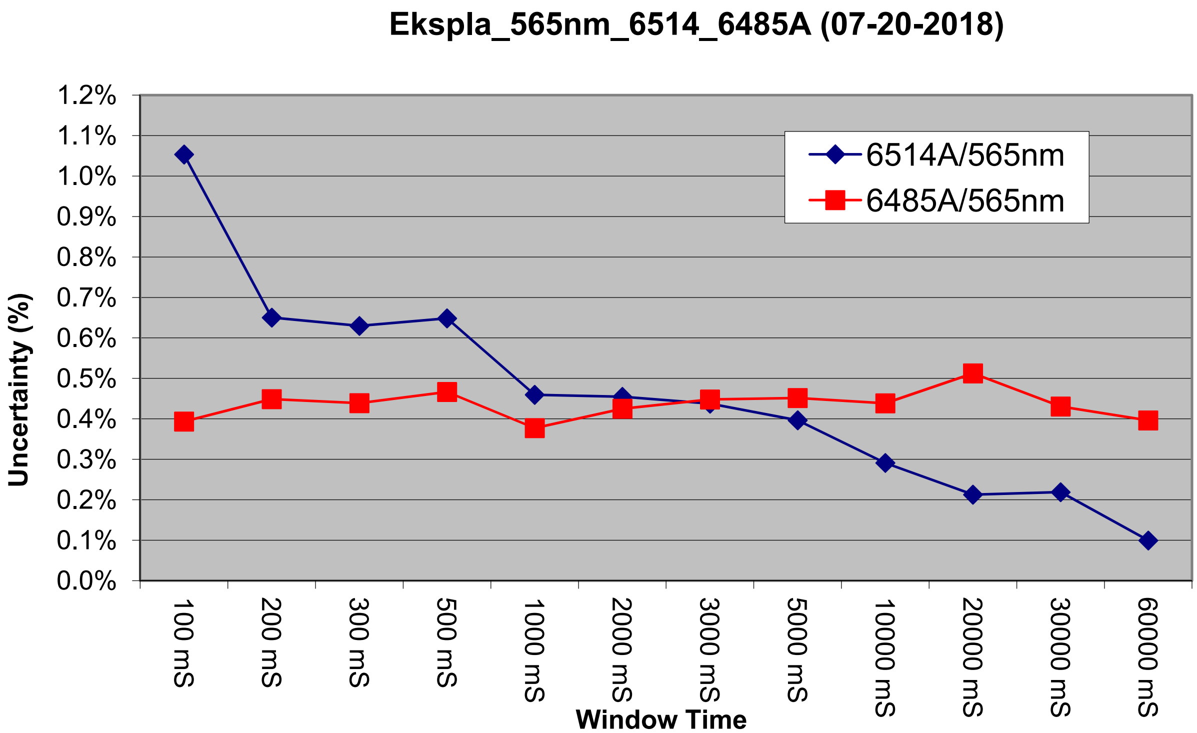


Figure 14 Measurement uncertainty vs. Window Time @ 565 nm

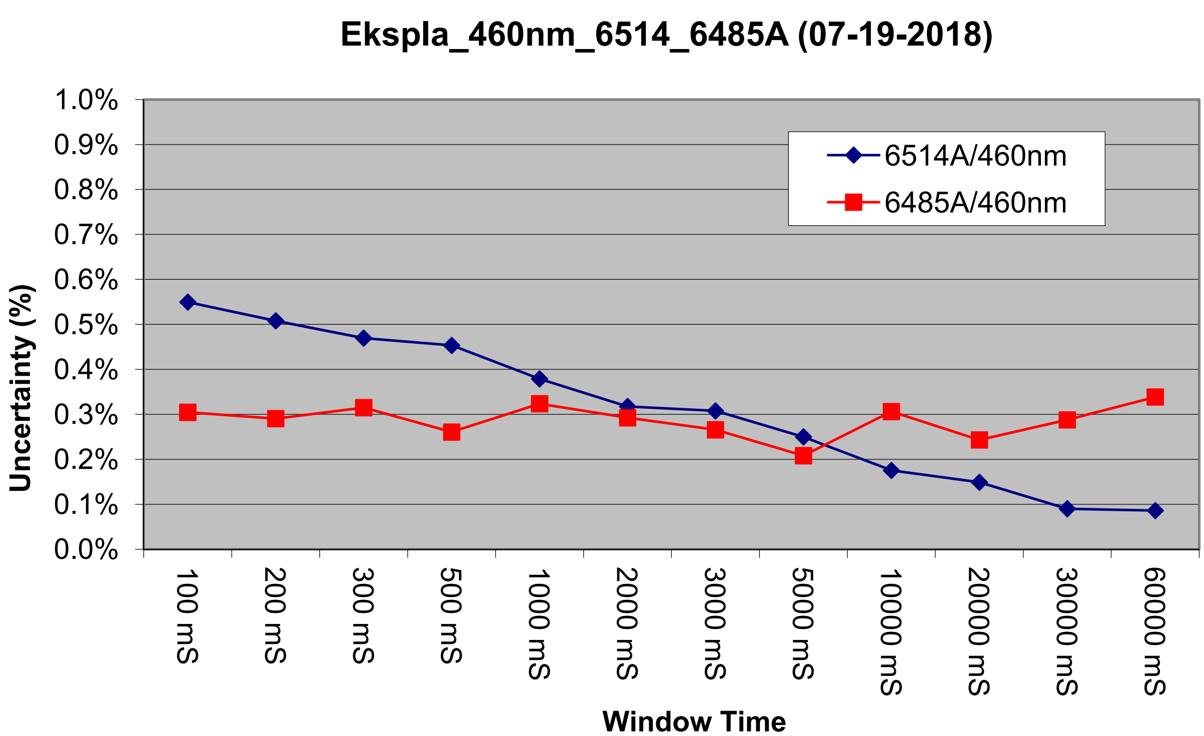


Figure 15 Measurement Uncertainty vs. Window Time @ 460 nm

Figure 15 shows results consistent with those in Figure 14. A comparison between Figure 14 and Figure 15 shows that both the trap detector and the pulsed laser detection system work better at 460 nm than at 565 nm. That can be explained by referring back to Figure 5. The laser has higher pulse energy at 460 nm than at 565 nm which means the measurement uncertainty is wavelength-dependent.

In the detector responsivity linearity measurements, we performed Ekspla laser warm-up monitoring measurements to compare how the pulsed laser detection system and other participating instruments responded to signal change. The Window Time was set to 5000 ms, and maintained unchanged during the whole process. Figure 16 to 18 show the comparisons between pulsed laser detection system (6514) and the three other participating instruments: trap detector (6485A), Oriel Merlin, and FRMS. In these 3 figures, the red line represents the data from the pulsed laser detection system, and the blue line represents the data from one of the participating instruments.

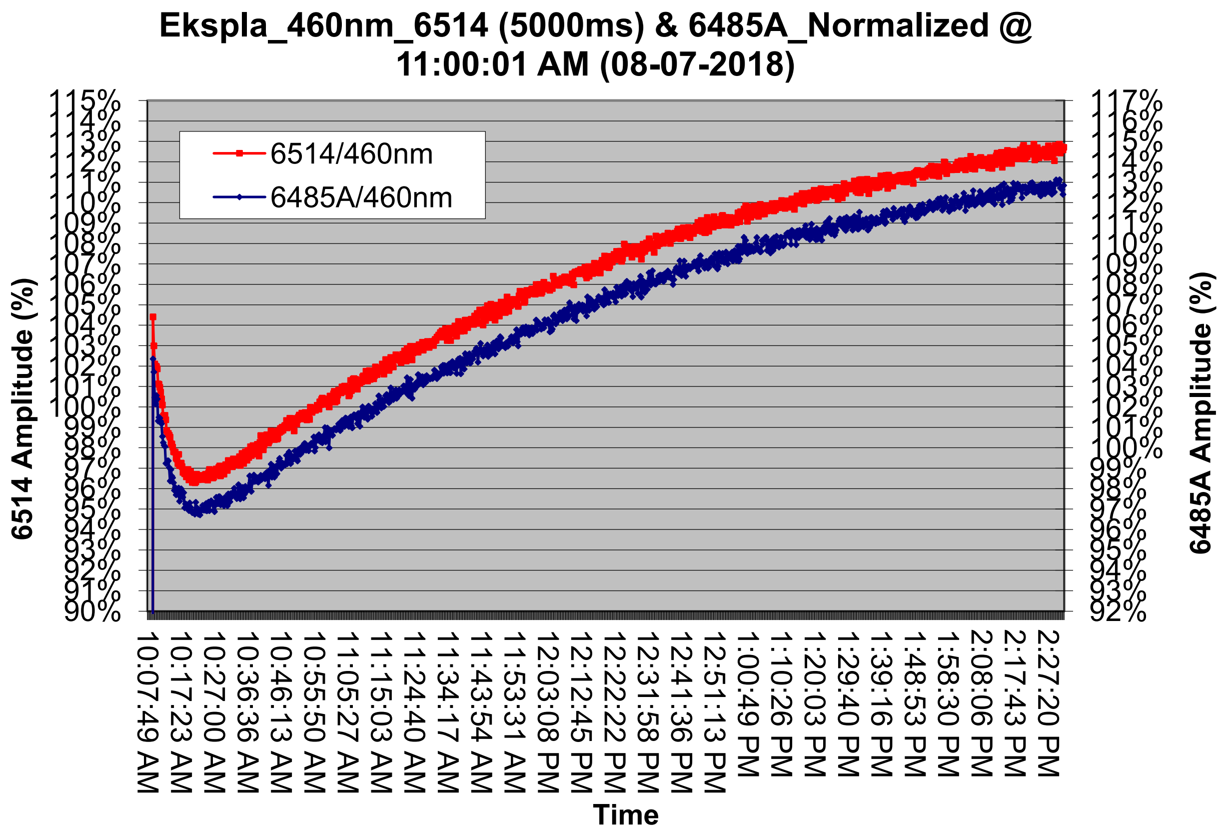


Figure 16 Ekspla laser warm-up: 6514 vs. trap detector

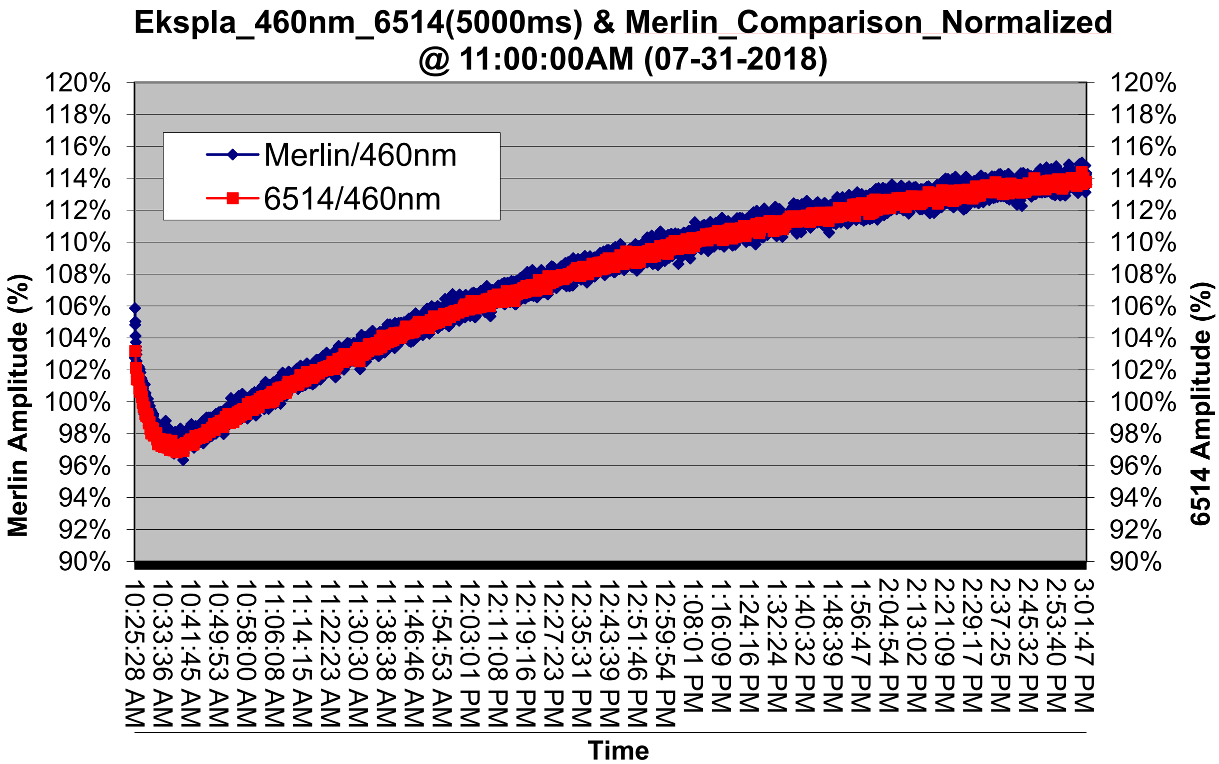


Figure 17 Ekspla laser warm-up: 6514 vs. Oriel Merlin

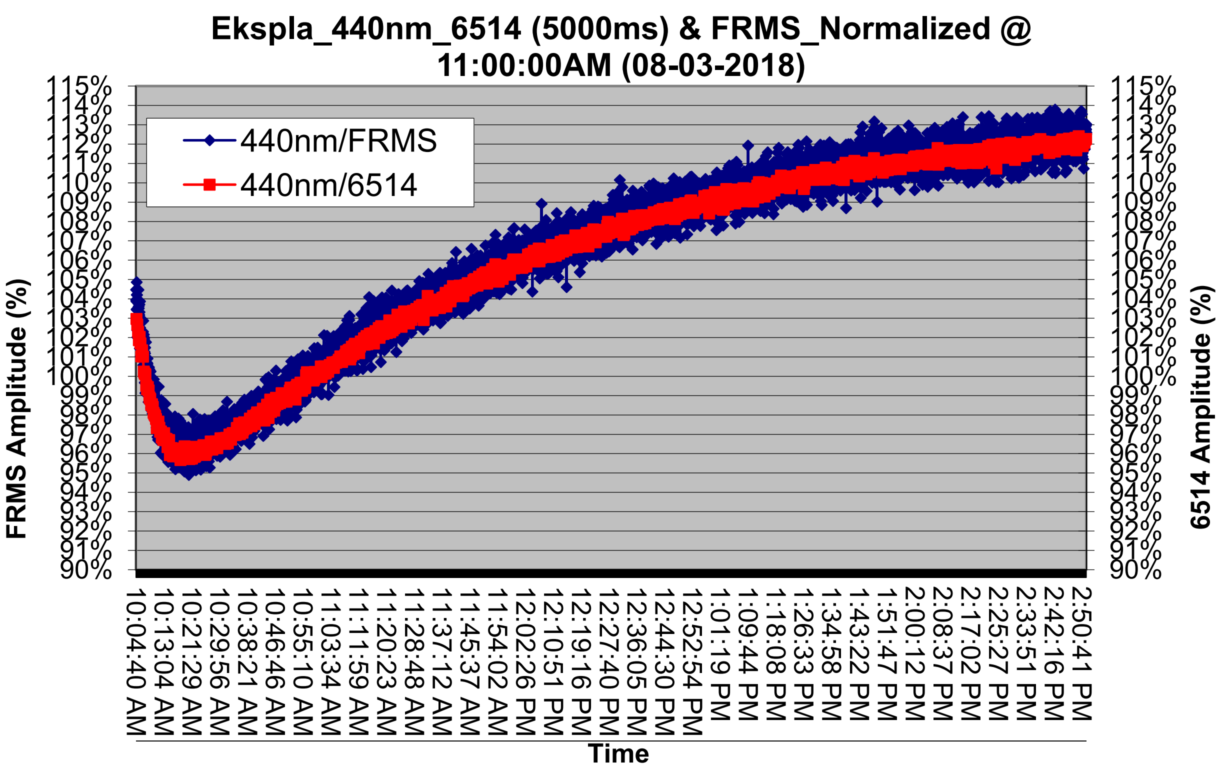


Figure 18 Ekspla laser warm-up: 6514 vs. FRMS

All three measurements show that the pulsed laser detection system and the other three participating instruments responded consistently to signal changes; but the three participating instruments did have differing noise performance. The trap detector had the best noise performance among those three participating instruments similar to the pulsed laser detection system with Window Time 5000 ms. The FRMS had the worst noise performance; and the Oriel Merlin was in the middle.

Quantitative measurements for responsivity linearity were performed by using two ND filters, 50%, 25% and their combination, to provide three levels of signal change. When we worked with the Oriel Merlin, two pre-amp gain settings (10^{+5} and 10^{+6}) were used to make the measurements. Table 3 ~ 6 show the measurement results.

460 nm	6514	6485A (Trap)
Open 460 nm	**1**	**1**
ND50 460 nm	**52.48%**	**52.40%**
ND25 460 nm	**27.86%**	**27.85%**
ND50+25 460nm	**14.55%**	**14.55%**

Table 3 6514 and 6485A

440 nm	6514	FRMS
Open 440 nm	**1**	**1**
ND50 440 nm	**52.17%**	**52.03%**
ND25 440 nm	**27.83%**	**27.74%**
ND50+25 440 nm	**14.47%**	**14.42%**

Table 4 6514 and FRMS

460 nm	6514	Merlin 10^{+5}
Open 460 nm	**1**	**1**
ND50 460 nm	**52.44%**	**52.29%**
ND25 460 nm	**28.34%**	**28.34%**
ND50+25 460 nm	**14.73%**	**14.80%**

Table 5 6514 and Merlin

460 nm	6514	Merlin 10^{+6}
Open 460 nm	**1**	**1**
ND50 460 nm	**52.375%**	**52.255%**
ND25 460 nm	**27.919%**	**27.820%**
ND50+25 460 nm	**14.515%**	**14.494%**

Table 6 6514 and Merlin

All three participating instruments responded to signal changes proportionally to the pulsed laser detection system. The expected saturation problems were not observed, and conventional measurement instruments seem to work responsively with Ekspla laser light source, with relatively higher noise level, compared to with CW light sources. The Ekspla laser can be used as a handy calibration light source with conventional measurement instruments, but the measurement uncertainty is dependent on wavelength and instrument type. If it is a picoammeter based instrument, the measurement uncertainty is expected to be 0.25% ~ 1%; if it is a lock-in amplifier based instrument, a 0.5% ~ 1% measurement uncertainty is possible; a DVM based instrument can reach a 1% ~ 2% measurement uncertainty. Also, a monitoring system is required as the Ekspla laser exhibits the instability over time.

Summary

The pulsed laser detection system was characterized by using a CW light source and a KHz OPO based Ekspla laser. The pulsed laser detection system demonstrated a solid performance in all measurements. The pulsed laser detection system (with a longer integration time, e.g. ≥5000 ms) and the Ekspla laser can be used in BRDF measurements, in-band and out-band characterizations, etc. The Ekspla laser alone can be used as light source to provide characterizations for conventional measurement instruments, with slightly higher uncertainties. This work can be extended by using a standard InGaAs detector so that the responsive spectral range can be extended to 1700 nm for this pulsed laser detection system.

Note: All notations of instrument manufacture names or model numbers in the figures, charts or text of this paper do not constitute an endorsement on the part of the NASA/GSFC for these products.

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