ASU Interplanetary Lab
Lightcube Project

Optical light output measurements of LightCube

Dr. Michael Goryll, ASU ECEE

28 Jan 2022

Introduction

LightCube is being designed as a 1U Cube Sat which fulfills an educational mission by providing users access to satellite functions via HAM radio interaction and open-standard telemetry communication protocols. LightCube will provide “visual feedback” to users via a Xenon flash lamp which is part of the payload. The flash can be triggered remotely but will have to be “scheduled” as to not interfere with other scientific experiments. The target brightness of the flash is designed to be at 0 to -1 apparent magnitude, allowing unaided observation of the optical signal.

In order to be able to generate an intensity of light that corresponds to an apparent magnitude of -1 when viewed from a distance of 400 km, we decided to employ a Xenon flash lamp due to its high peak output power. Our initial calculations showed that a Xenon flash design that is commonly used for (Digital) Single Lens Reflex photographic cameras provides the required light output. Commercial designs, however, contain components that are not space-qualified, in particular electrolytic capacitors, inefficient high voltage power supplies as well as proprietary microcontrollers. Commercial Xenon flash units use glass flash tubes, which have a limited lifetime. The limitation is due to the high plasma temperatures, leading to local melting of the glass envelope. The subsequent re-crystallization during cool-down weakens the glass and can lead to micro-cracks. The absence of convective cooling in space exacerbates this problem. Using a Quartz envelope mitigates this issue. Since a modification of a commercial xenon flash unit did not seem feasible, we developed a xenon flash power supply and trigger circuit. The design specifications of the Xenon flash circuit are as follows:

- Linear Xenon flash tube with a Quartz envelope with 27 mm arc length and an inner diameter of 2 mm (Xenonflashtubes L-4040)
- 2x 400 uF polypropylene film capacitors, charged to 368 V, corresponding to a stored energy of 108 J.
- Voltage converter based on Linear Technology LT 3750, which features overvoltage and overcurrent limits as well as a charge inhibit input.
- Input power is supplied from lithium-based batteries with a nominal voltage of 3.7V, charging current is limited to 2.1 A, about 1/3 C
- Capacitive flash trigger circuit

The modifications in circuit components (flash tube, capacitors) pose a challenge for photometric measurements. Commercial photometers use filters, calibration constants or a combination of both to report a photometric illuminance in lux. This assumes that the spectrum of the light source is known and independent of operating power and circuit design. The emission spectrum of Xenon flash lamps depends on the discharge current density, which affects the plasma temperature. High current densities lead to higher plasma temperatures. Higher plasma temperatures cause the thermal radiation spectrum (black body spectrum) to shift its emission peak to shorter wavelengths. In addition, lower plasma temperatures favor the emission via characteristic lines in the infrared spectrum, while higher plasma temperatures lead to the excitation of lines in the blue spectral range. Thus, we decided to measure the emission spectrum of the flash tube under default operating conditions.

Another issue that influences photometric measurements is the peak intensity compared to the duration of the light emission. The polypropylene capacitors feature an equivalent series resistance that is ten times lower than that of electrolytic “photoflash” capacitors. This results in a faster rise time of the current, higher peak intensity, higher plasma temperatures and shorter emission duration.

Experimental Procedures

The equipment used for the photometric and spectrophotometric measurements is the following:

- 3M-Photodyne Model 22 XL Optical Multimeter with calibrated silicon sensors
- Thorlabs SM05PD1A mounted silicon photodiode
- Stanford Research Systems SR 570 Current Amplifier
- Tektronix TDS 7104 Oscilloscope
- Jobin-Yvon Horiba HR 320 monochromator with 1200 lines/mm holographic grating and stepper motor control
- Oriel lamp holder with 24V 150W Philips Halogen Bulb for calibration
- PTI constant current source for Halogen lamps
- Stanford Research Systems SR 830 DSP Lock-In Amplifier
- EG&G Optical Chopper Wheel
- Neutral density filters and narrow-band interference filters
- HP 8452A UV-VIS Spectrometer
- Sinton FCT-450 solar cell tester for silicon photodiode calibration

The issue we faced when using the 22 XL Optical Multimeter in connection with the Xenon flash was that the internal sample-and-hold circuit cannot be synchronized with the flash trigger. This results in poor repeatability of the light output measurements. Thus, we operated the silicon sensor independently from the Optical Multimeter by connecting it to the SR 570 Current amplifier, which in turn was connected to the Tektronix TDS 7104 oscilloscope. This allows for light output measurements that are synchronized with the Xenon flash discharge event and enables recording of the time evolution of the light intensity.

Spectrometer response function measurement

For our spectrophotometric analysis, we determined the instrument response function shown in Fig 1 using a continuum halogen light source, driven by a constant-current power supply, and recorded the output from the calibrated photodiode. We used an optical chopper wheel along with a Lock-In Amplifier to suppress ambient light interference and improve the signal-to-noise ratio.

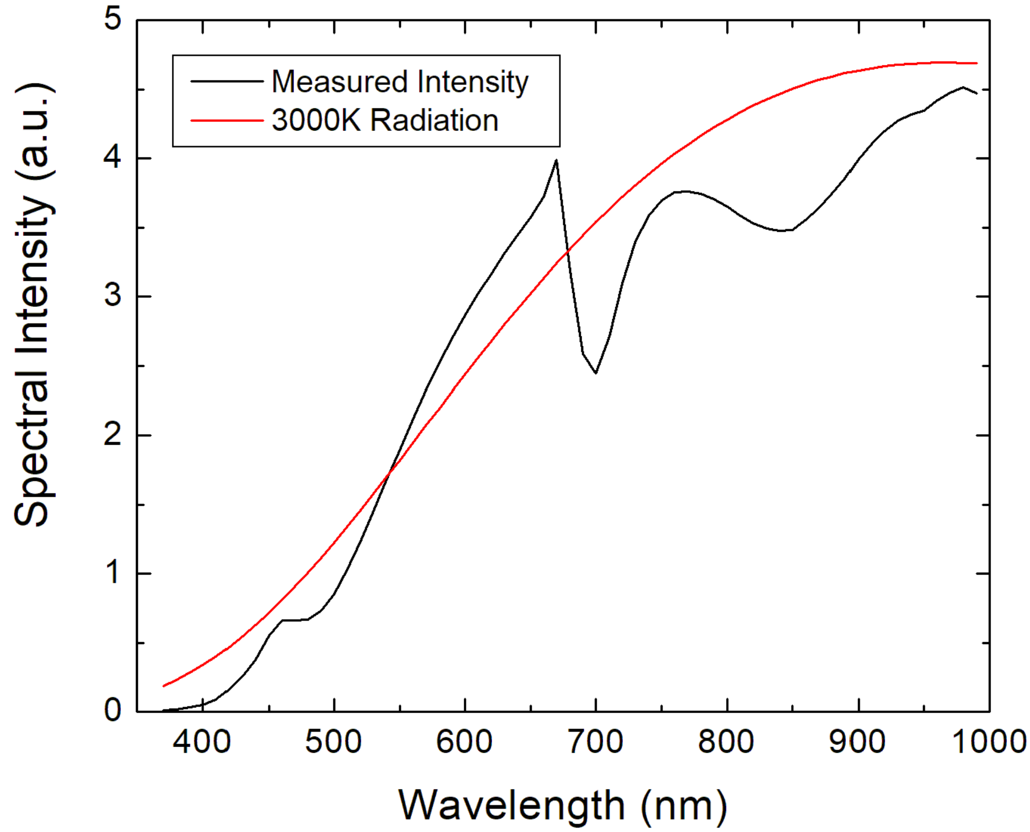

Fig 1: Halogen lamp spectrum measured using a Horiba HR 320 monochromator with a 1200 lines/mm holographic grating and a silicon diode. The red line shows the simulated spectrum of a black body radiator at 3000K temperature, scaled to match the experimental data at 550 nm.

Spectral Intensity distribution

For the tests with the xenon flash, we replaced the halogen light source with the Xenon flash, driven by the payload supply. Due to the intermittent nature of the Xenon flash emission, we removed the chopper wheel and replaced the lock-in amplifier with the oscilloscope. For every wavelength setting of the monochromator in 10 nm increments, we triggered the flash and recorded the light output curve. The peak voltage values were tabulated, converted from Volts to Watts based on the amplification factor of the current amplifier (in A/V) and the wavelength -dependent quantum efficiency of the silicon detector (in A/W). The emission spectrum we obtained is similar to spectra reported in literature for linear Xenon flash tubes with current densities above 4000 A/mm^2, which is consistent with the current density of 9300 A/mm^2 we measured experimentally on the payload.

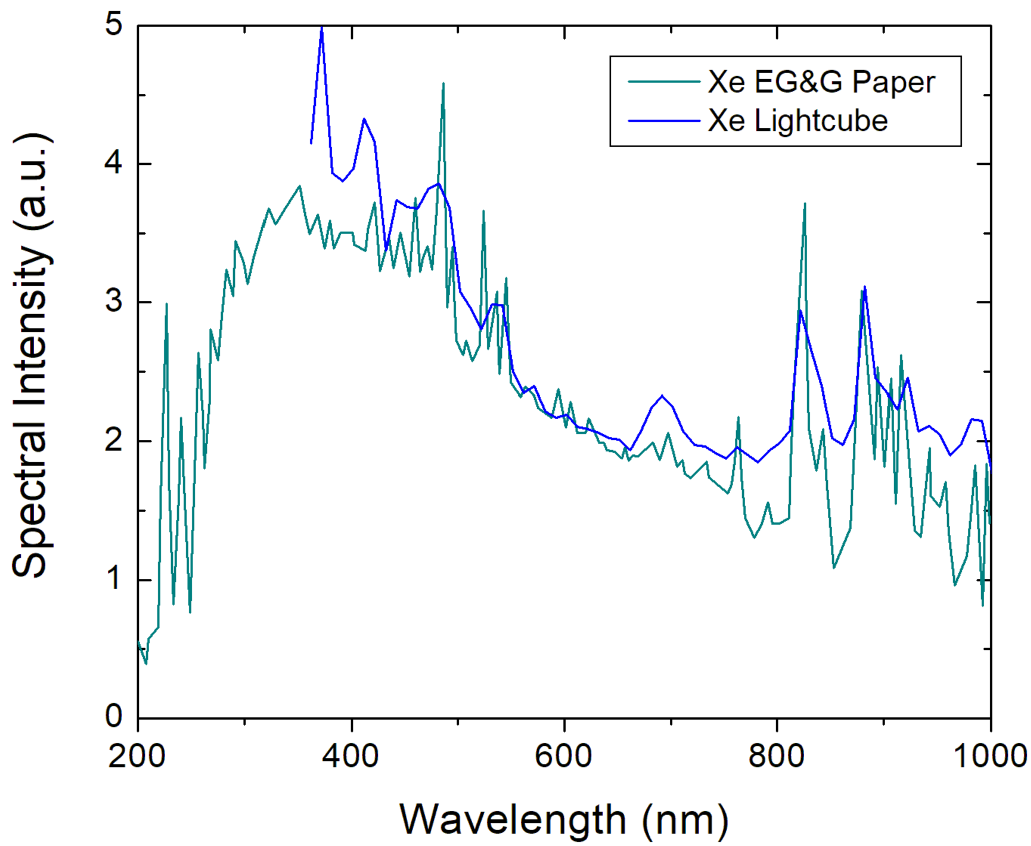

Fig 2: Comparison between the spectral intensity distribution of a linear Xenon flash lamp operating at or above 4000 A/mm^2 reported in a datasheet and the intensity distribution measured on the Lightcube Payload flash.

The spectral irradiance distribution of the light output of the Xenon flash tube allows us to generate calibration constants to map integral spectroscopic intensity data from silicon photodiodes to photometric data, for photopic and scotopic response curves as well as Apparent Magnitude (V) filter curves.

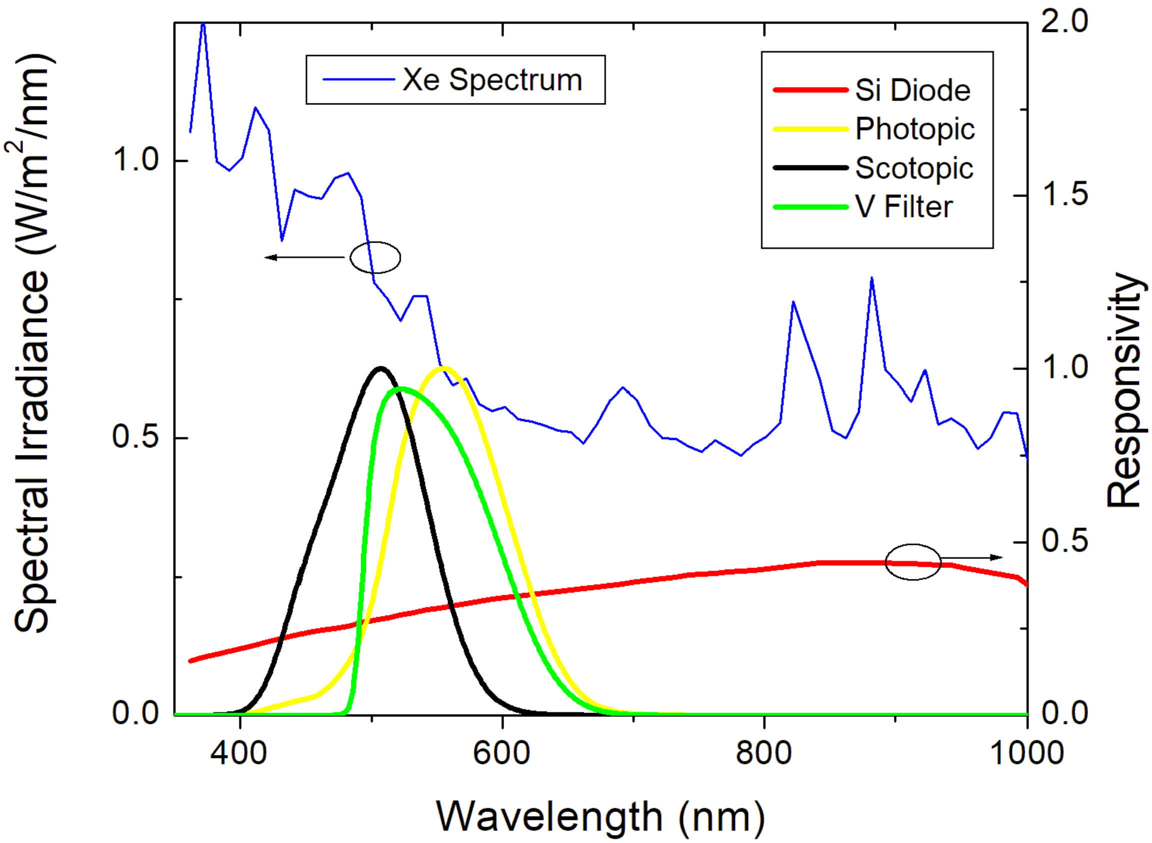

Fig 3: Measured Xenon flash tube spectrum (blue), recorded with a Horiba HR-320 grating monochromator and a silicon photodiode. The spectral irradiance was calibrated by measuring the transfer function of the spectrometer using a Halogen lamp as a standard as shown in Fig 1. The absolute unit calibration was based on the responsivity of the silicon photodiode. Various filter responses are included for reference.

Absolute intensity calibration

The absolute intensity calibration was performed by removing the spectrometer and positioning the calibrated silicon sensor at a defined distance from the flash tube. Either a neutral density filter with a response according to ISO-12312-2 (D = 5) or a narrow-band spectral filter (12nm @ 500 nm) was used. The transmittance of the mylar neutral density filter was verified using the 22 XL Optical Multimeter with a halogen light source. The transmittance of the narrow-band spectral filters was checked using a commercial HP 8452A UV-VIS Spectrophotometer with a Deuterium source. The broad-band sensitivity of the photodiode in A/W has been verified using a Sinton WCT-450 Solar simulator with a calibrated photodiode. The Sinton solar simulator uses a Xenon flash lamp (Quantum 800 Ws flash) to obtain a 1000 W/m^2 integrated intensity at the measurement location. Since the flash tube is operated at a lower current density, the spectral irradiance tapers off at longer wavelengths and the lines in the infrared are more prominent.

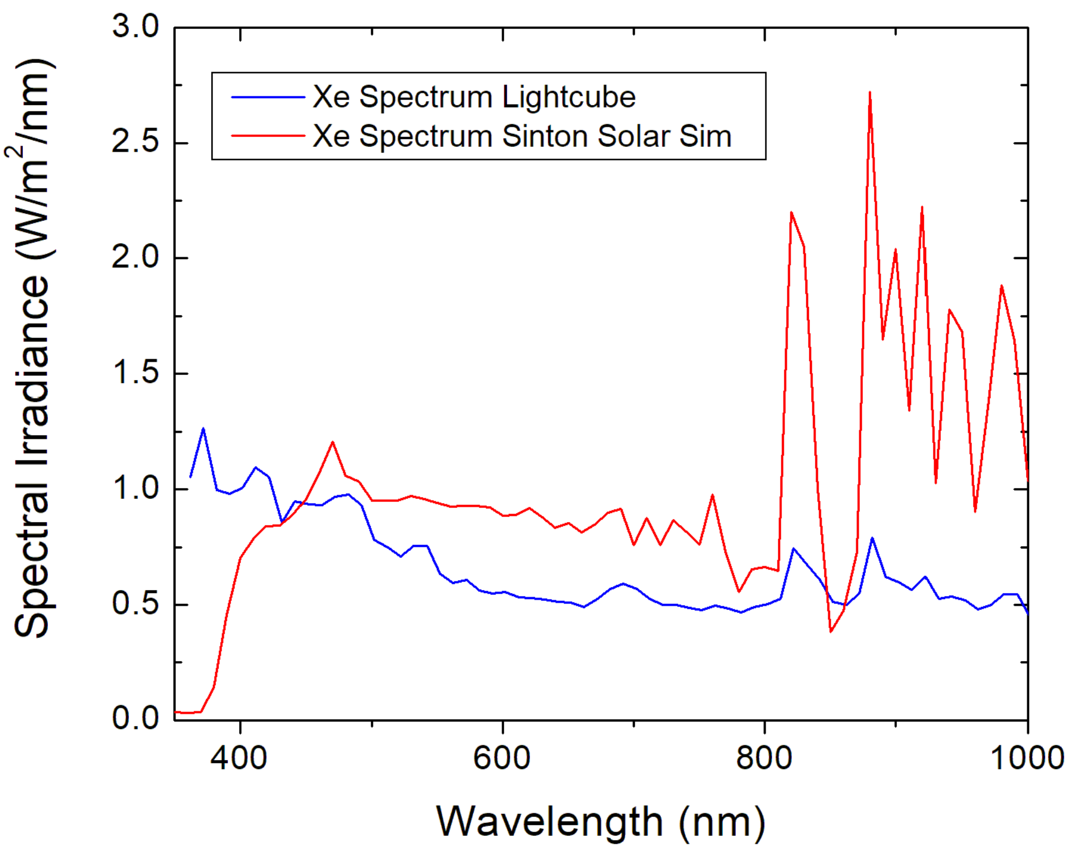

Fig 4: Comparison between the spectral irradiance of the Lightcube Payload flash and the Quantum flash used in the Sinton WCT-450 Solar Simulator.

The raw data based on this approach is shown in Table 1, with the first line corresponding to the broadband and the subsequent line corresponding to a 500 nm filter measurement, respectively:

					photopic			V filter curve		
Pcurrent	A/W	W	Wintegal	W/m^2	lux	**lux@1m**	**lumen**	Jy@detector	Jy@400km	m@400km
0.408	0.304	1.3421	1.3421	34029.04	3.34E+06	**4.95E+05**	**6.22E+06**	5.16955E+15	4789.1078	-0.297883
4.24E-03	0.267	1.59E-02	2.260501	57314.94	5.62E+06	**8.34E+05**	**1.05E+07**	8.85184E+15	8200.4	-0.881834

All values refer to the photocurrent at the maximum oscilloscope signal point. The discrepancy between the values can be due to the non-uniformity in filter characteristic for the neutral density filter as well as differences in the relative intensity for the specific wavelengths. Light leakage around the filter is another contributing factor to the higher intensity recorded with the narrow-band filter.

Conversion from Lumens to watts

We measure 6.22e6lm / (330V * 300A) = 63 lm/W. This is high but we are pushing our flash tube to the limit of what it is able to handle. Manufacturers typically recommend 50 lm/W as a value that ensures a longer lifetime of the xenon lamp.
https://www.phoxene.com/wp-content/uploads/2018/09/05-Traffic-Enforcement-XENON-FLASH-VS-LED.pdf

Commercial flash units are often characterized by their guide number according to the American Standards Association PH 2.4-1953 publication. The relation between the guide number and the luminous flux in lumen is given by

$$GN = \sqrt{0.005 \cdot L \cdot t \cdot S \cdot M}$$

With GN being the guide number, L the luminous flux in lumen, t the duration of the flash in seconds, S the ISO film sensitivity and M the reflector factor (polished 3 inch = 7, polished 4 - 5 inch = 6, polished 6 - 7 inch = 4).With GN being the guide number, L the luminous flux in lumen, t the duration of the flash in seconds, S the ISO film sensitivity and M the reflector factor (polished 3 inch = 7, polished 4 - 5 inch = 6, polished 6 - 7 inch = 4). Unfortunately, the reflector factor of commercial flash units is not known. It is also not clear which solid angle is to be considered to refer the illumination values back to the luminous flux. Kodak has published an equation based on the ASA guide number equation, but refers to the illuminance E_v in lux at a distance of 1m instead, using an ISO sensitivity of 400:

$$GN = \sqrt{0.0478 \cdot E_v \cdot t \cdot 400}$$

Using the peak lux@1m value from the table (4.95E+5) and a peak duration (t.5) of 400 us, we arrive at a guide number of 19.5. A numeric integration of the lumen-vs-time signal results in a guide number of 21.6. Using the same optical measurement setup, a Canon 580EXII flash, set to manual mode and 105 mm Zoom, delivers 1.24E+6 peak lux@1m and the numeric integration results in a guide number of 62.9, which is 8.4% higher than the nominal value of 58. The discrepancy is related to differences in spectral output, affecting the W to lumen conversion as well as distance measurement uncertainties and light inhomogeneity due to the Fresnel lens present in the commercial unit.

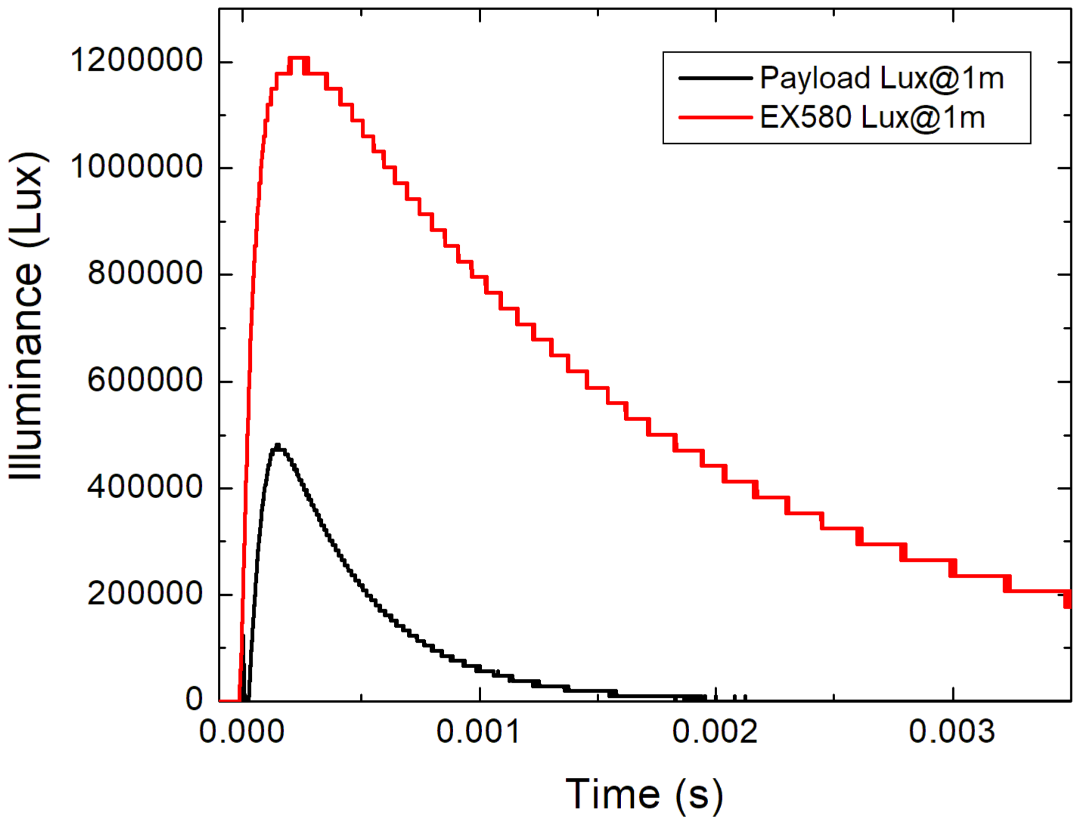

Fig 5: Light output versus time graph for the Lightcube payload without reflector and a commercial Canon EX580 II SLR flash.