León 05
CIE Midterm Meeting y
Congreso Internacional de Iluminación

CIE

Título del trabajo/
Title of paper

General Practice for the Measurement of Flashing Lights

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Introduction

Flashing lights are widely used in many applications including those for warning and control signals in transportation. In the 19th century the flashing lights were recognized as attracting more attention than steady lights of the same intensity and therefore were used in light houses. The measurement of flashing lights also dates back over a century, with the first well-known paper published in 1876.[1] However, the measurement of flashing lights is still far from satisfactory. Recently large measurement variations were reported on aircraft anti-collision lights, so NIST worked on establishing physical standards for flashing light measurements in 1997 and started a calibration service for flash photometers.[2] In 1999, a workshop "Photometry of Flashing Lights" was held as a part of Commission Internationale de l'Eclairage (CIE) Warsaw session, which articulated the urgency with which a guide for measurement of flashing lights and for standardization of effective intensity[3] was needed. As a result, CIE TC2-49 (Photometry of Flashing Lights) was established. The Technical Committee is working to produce a technical report for physical measurement of flashing lights including a standardized definition of effective intensity. In 2002, CIE hosted a symposium on Temporal and Spatial Aspects of Light and Color Perception and Measurement, where the issue of effective intensity was actively discussed. A consensus has not yet been reached, as many conditions, such as the measurement of the intensity of narrow beam fixtures, must be addressed to successfully assess real flashing light devices. In 2004, the National Cooperative Highway Research Program, USA, began Project 13-02 Guidelines for the Selection and Application of Warning Lights on Roadway Operations Equipment, and NIST is participating to provide measurement support. We are evaluating various flashing light devices used in highway traffic maintenance vehicles. In this paper, we report the current issues and work at NIST in photometry of flashing light devices ranging from physical measurement standards to visual evaluation of the intensity of flashing lights.

Product Survey

Flashing lights represent a significant number of the signaling devices in the transportation community including aircraft anti-collision lights, emergency vehicle warning lights and traffic control lights. A large variation in the measurements of flashing lights has been a problem and is evident in the product literature. A survey of products was done by reviewing brochures, catalogues, and websites of companies that produce flashing light products. The information gathered would be used by consumers as their initial selection process. The comparison of different product lines from different vendors is not possible due to a lack of information. According to the manufactures, three technologies of flashing light equipment are available: incandescent filament bulbs, xenon or HID flash tubes, and LEDs. Additionally, many 'philosophies' exist for presenting the source, such as rotating a mirror about the lamp, turning the lamp on and off, or grouping many pulses together to form a flash. Table 1 is an extraction of the specifications from flashing light product information.

Unfortunately, the units used are extremely confusing, and none of the information provided gives a clear indication of the amount of light that reaches the observer. The wattage of the bulbs indicates the amount of steady light available to the system, but the shape and efficiency of the reflector controls the pulse intensity and width. Candlepower (cp) is an outdated name for luminous intensity, which is a quantity, not a unit. The unit of candlepower was candela (cd). Beam candlepower, also an old name, is used to indicate the peak luminous intensity of the beam, but was never defined as a unit. More importantly, candlepower and beam candlepower are quantities for steady light and do not describe flashing lights. Many of the lamps list the

energy in joules, which is the total radiant energy the lamp produces. It is a radiometric quantity and is not useful to judge the amount of light perceived by an observer. Effective candlepower is an outdated name for effective intensity (of flashing lights) and is abbreviated "ecp." Therefore, "ecp" is not a unit. The unit of effective intensity is candela (cd). The unit "cd/s" makes no sense and may be an error for "cd·s". These examples demonstrate the great confusion in the use of quantities and units in the industry to specify flashing light sources. No LED-based lights are included in the table because no specifications are listed with in the LED-based lights' brochures.

Table 1 – Extraction of flashing light characteristics from product information

Product Number	Source	Specification
1	55 W halogen lamp	68,000 cd/flash
2	50 W lamp	70,000 beam candlepower
3	12 V lamp	50 candlepower
4	36 W lamp (12 V)	325 candlepower
5	20 W lamp	2839 cp
6	24 V (2.2 A) – Double flash	2,300,000 cp
7	12 V (2.4 A) – Quad flash	17 J or 720 ecp
8	12 V (3.5 A) – Quad flash	25 J or 2500 cd/s

The proper photometric quantities to describe flashing lamps are time-integrated luminous intensity and effective intensity. Time-integrated luminous intensity (unit: candela·second, symbol: J or J_v) is defined as the time integral of instantaneous luminous intensity $I_v(t)$ of a flash over the flash duration T as given by:

$$J_v = \int_0^T I_v(t)\mathrm{d}t \tag{1}$$

Effective intensity (unit: candela) is the luminous intensity of a fixed (steady) light, of the same relative spectral distribution as the flashing light, which would have the same luminous range as the flashing light under identical conditions of observation.[4] There are several formulae to calculate effective intensity, and the correct one has not been agreed upon internationally.

The other two important photometric quantities for flashing lights are luminous energy and luminous exposure. Luminous energy (unit: lm·s, symbol: Q or Q_v) is the total amount of light in a flash emitted from a source, and is defined as the time integral of instantaneous luminous flux $\Phi_v(t)$ of a flash over the flash duration T as given by:

$$Q_v = \int_0^T \Phi_v(t)\mathrm{d}t \tag{2}$$

Luminous exposure (unit: lux·second, symbol: H or H_v) is defined as the time integral of instantaneous illuminance $E_v(t)$ by:

$$H_v = \int_{\Delta t} E_v(\mathrm{t})\,\mathrm{d}t \tag{3}$$

More rigorous and official definitions of these quantities are given in the International Lighting Vocabulary.[4] The CIE Technical Committee 2-49, Photometry of Flashing Lights is currently preparing to write a technical report to give recommendations on the measurements of photometric quantities of flashing lights including effective intensity.

Issues on Physical Measurement of Flashing lights

Calibration standards and traceability

The units for flashing light, such as luminous exposure and time-integrated luminous intensity, are defined simply from corresponding photometric quantities for steady light. However, the time integration of detector signals for various of flashes (including those with very high peaks) can cause difficulties and instrumentation errors in flash photometers. Large variations of measurement of aircraft anti-collision lights in the industry were reported, so NIST established the unit of luminous exposure and a calibration service for flash photometers to measure anti-collision lights and other flash photometers, with support by U.S. Federal Aviation Administration.

The unit of luminous exposure (lx•s) has been realized using the detector-based method as previously employed in the realization of the candela.[5] Three flashing-light standard photometers equipped with current integrators were built and calibrated against the NIST illuminance standard photometers. They maintain the unit. Two different approaches were taken to calibrate these standard photometers; one based on electrical calibration of the current integrator, and the other based on electronic pulsing of a steady-state photometric standard. The units realized using the two independent methods were compared and agreed within 0.2 %. The uncertainty of the unit realization for both methods is ≈0.6 % (k=2). One component of uncertainty analyzed over the last eight years is the long-term stability of the standard photometers including the current-integration circuit units. The unit realization is performed every year as shown in Figure 1 and the average luminous exposure responsivity changed < 0.5 % over an eight year period.

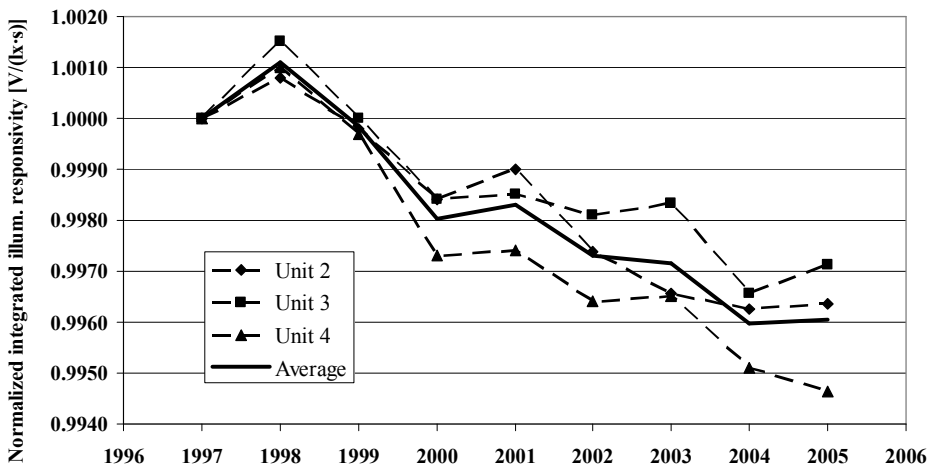

Figure 1 – The normalized luminous exposure responsivity [V/(lx·s)] of the three NIST flash photometers that maintain the unit for the last eight years.

Calibration service is provided primarily for anti-collision light meters that measure effective intensity (cd) as well as for other flash meters to measure luminous exposure (lx·s) and time-integrated luminous intensity (cd·s). Calibration measurements are performed using real

white and red anti-collision lights with a xenon flash source. Effective intensity is calibrated as follows.

In the specification of aircraft anti-collision lights and other vehicle signals using flashing lights, the term effective intensity (cd) is widely used. Practically, effective intensity is calculated from the waveform of the flash pulse, and there are four formulae available.[1,6,7] The Blondel-Rey equation[8], developed in 1911, is most commonly used. All four methods give the same result for a very narrow, single pulse, as one emitted by a xenon flash tube. For such a very narrow single pulse, the effective intensity (cd) is five times the time-integrated luminous intensity (cd·s). In the NIST calibration, the effective intensity is calculated from the integrated luminous intensity (cd•s) based on this relationship so that it is independent of the formula used. The NIST calibration does not test effective intensity measurement for pulses of longer duration. The time-integrated luminous intensity is determined by the luminous exposure (lx•s) at the reference plane of the photometer and the photometer-to-source distance.

Addressing various pulse shapes of real flash devices

The measurement of flashing lamps is more difficult than steady lamps because of the time dependency and the spatial profile of flashing lights. Two types of flashing light instruments exist: single pulse integrators and multiple pulse averagers. With either instrument, it is important to collect the complete flash. For example, strobe lamps have single pulses that are ≈1 ms full width at half max (FWHM). However, a complete flash can be made of one main pulse followed by three pulses separated by 100 ms that are one quarter of the intensity of the main pulse. Single pulse integrators, that have collection windows of 50 ms, will neglect the three trailing pulses in a quad pulse system. Rotating beacon lamps, a lamp that has a focusing mirror rotate about it, has its own issues. A pulse from a rotating beacon lamp viewed from 20 m is shown in Figure 2. It appears to be a pulse that is 11 ms at FWHM. However, a rotating beacon lamp of this type is actually two pulses convolved in time. Figure 3 shows a magnification of the bottom part of the curve. The pulse starts when the lamp is visible to the observer but not focused by the mirror. A narrow, high peak comes when the mirror is focused. Trailing flux is caused by unfocussed light again, until the rotation of the mirror blocks the lamp.

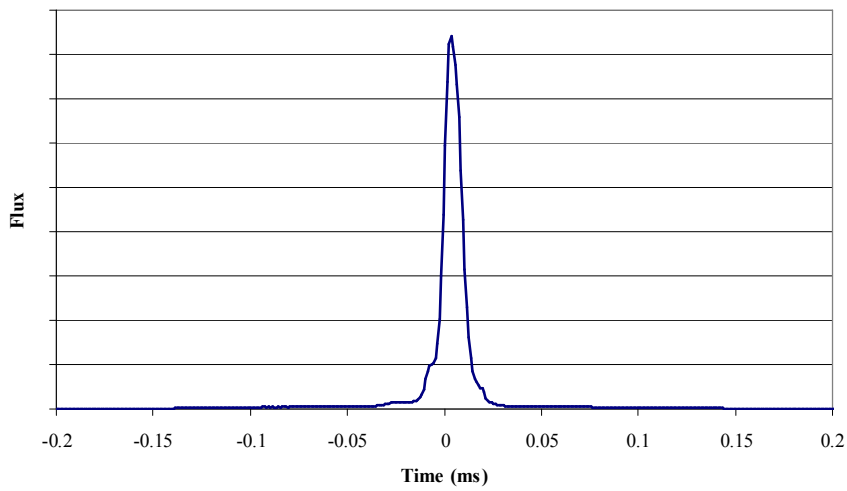

Figure 2 – The time dependent flux of a rotating beacon lamp.

The amount of energy in the square pulse or pedestal is not insignificant. The ratio of the pedestal to the total pulse energy remains constant at 12 % at any viewing distance.

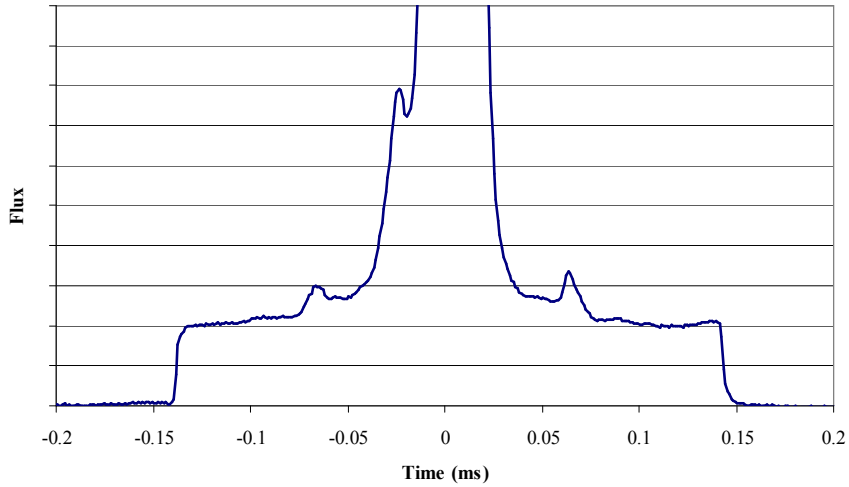

Figure 3 – The time dependent flux of a rotating beacon lamp with the scale expanded.

Measurement of flashes from LED-based systems may even be more difficult. Solid state systems can turn on and off in less than 1 μs and can have any waveform. Some new LED devices have waveforms with a 70 % duty cycle; therefore the flashes occur when the device turns off rather than on.

Measurement of narrow beam flashing lights

Another significant factor in the measurement of flashing lights is the distance required to enter the far field, where the system obeys the inverse square law. This minimum distance point is called the beam crossover point.[9] For a projector apparatus using either a shallow or deep-dish parabolic mirror, the beam crossover distance can be calculated by:

$$L_{\mathrm{O}} = \left(\frac{R}{r} \times \left(f + \frac{R^2}{4f} \right) \right) \times \frac{1}{1000} \qquad (4)$$

where R is the radius of the projector aperture (mm), r is the radius of the smallest element of the light source (mm), and f is the focal length of the reflector. For the rotating beacon lamp studied, the beam crossover distance was calculated to be 6.5 m. Figure 4 shows that the beam crossover distance is 15 m. This is true because Eq. 4 is only appropriate for on-axis measurements. As the rotating beacon operates the observer samples not only the on-axis, but also the off-axis, light from the reflector. The off-axis beam crossover point is much longer than the on-axis beam.

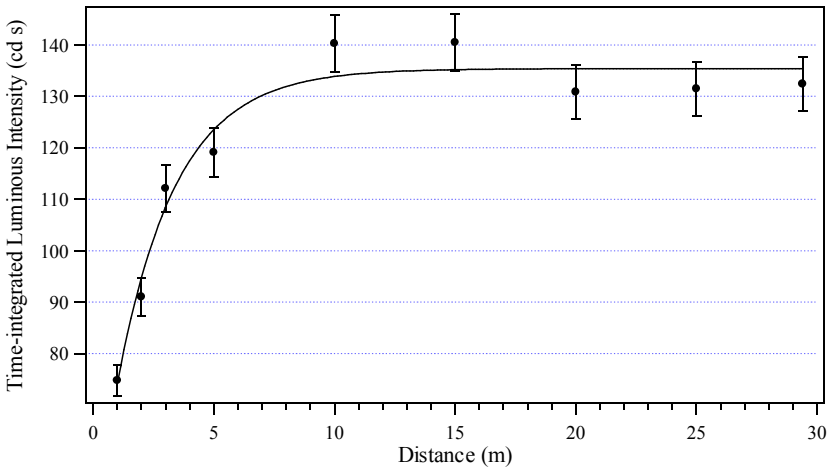

Figure 4 – The measured time-integrated luminous intensity of a rotating beacon lamp as a function of distance.

Strobe lamps, which use Fresnel lenses, and LED devices, which use individual optics per LED, are more difficult to calculate. They typically require empirical measurements. Figure 5 shows an example of an LED device. When the measurements are made close to the device

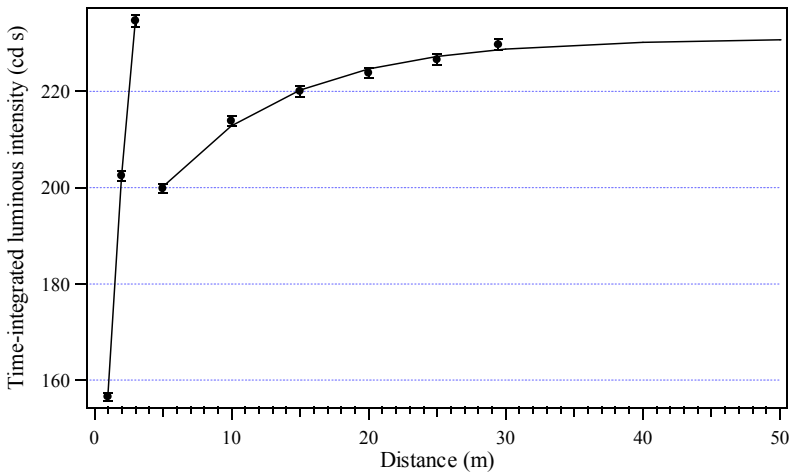

Figure 5 – The measured time-integrated luminous intensity of an LED-cluster based device as a function of distance.

(1 to 3 m), the results are significantly influenced by individual LEDs. For this particular case the individual LED optics creates a situation where the individual LED light converges before diverging. At short distances, the system appears to have a much larger time-integrated luminous intensity. As measurements are made at longer distance, the influence of all the LEDs in a far field region is measured. The beam crossover point for this device is almost 50 m.

Effective Intensity and Future Work

Effective intensity is used to specify the intensity of flashing lights as perceived by the human visual system. Effective intensity is calculated from the pulse shape of time dependent luminous intensity $I_v(t)$ of a flash. There are several different formulae available: Blondel-Rey, Allard, and Form Factor methods. Additionally, an improvement of the Allard method was proposed recently. Different methods are used in different countries and different applications, so the reported values of products cannot be compared. Table 2 shows an example of variation of results using the different methods, for four flashing lights: a single square pulse from an LED device (duration 320 ms), a rotating beacon (data in Figure 2), the pedestal of the rotating beacon (data in Figure 3), and a quadruple flash from a xenon amber strobe light (four pulses at 100 ms apart).

Table 2 – Effective intensity calculations of various pulses

Method	LED single	Beacon	Pedestal	Quad Pulse
Form Factor	285 cd	631 cd	40 cd	331 cd
Allard	334 cd	580 cd	43 cd	183 cd
Modified Allard	266 cd	547 cd	33 cd	152 cd
Blondel-Rey	266 cd	513 cd	34 cd	134 cd

The differences between these methods have been presented previously. The results for the quadruple flash have the largest differences. The experimental data available in the literature[10] indicates that Modified Allard method seems to give results most accurately for trains of pulses. However, more questions arise, such as whether the effective intensity of the pedestal is additive to the effective intensity of the beacon, when calculated with a method that forces selection of the pulse width (Blondel-Rey). Additionally, LED systems on the market work by turning the system off briefly (50 ms), as is done with the 70 % duty cycle LED system shown in Figure 6. The current models do not apply to negative pulses. CIE TC2-49, in corporation with CIE Division 1, is making an effort to standardize the definition of effective intensity as a part of their TC work.

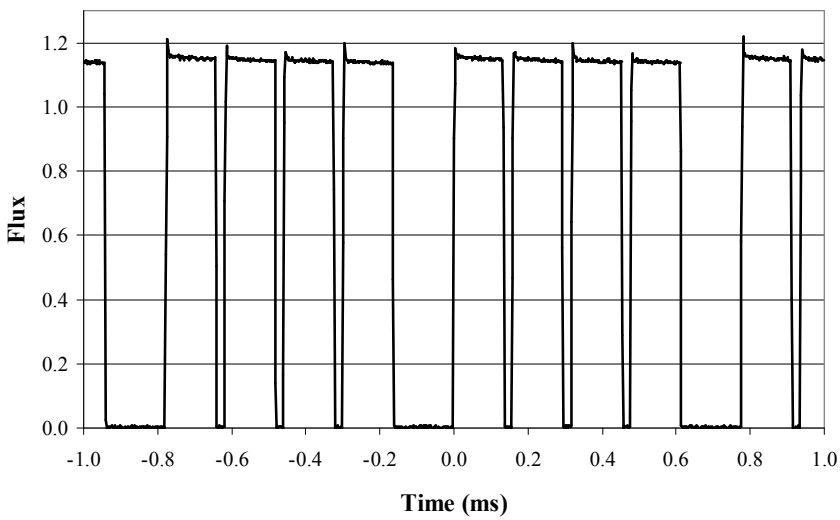

Figure 6 – The flux of a 70% duty cycle LED system.

All of these models are for achromatic sources only. Previous work has shown that the Blondel-Rey constant is not a constant for different chromatic sources[6] and varies significantly for colored sources. These findings indicate that the temporal response has a different spectral sensitivity than $V(\lambda)$. Figure 7 shows that amber lights produced by different lamp technologies have significantly different (time-integrated) spectral power distributions. This should be studied and taken into account by a new method of determining effective intensity.

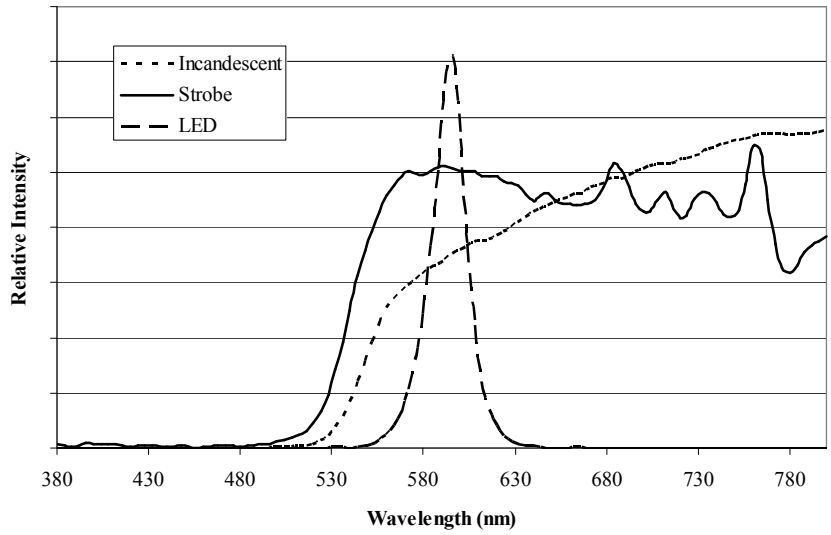

Figure 7 – The time-integrated spectral power distributions of three different amber flashing light technologies.

NIST has plans to perform vision experiments to establish a complete description of effective intensity. Fourier's theorem states that any periodic waveform may be analyzed as the sum of a series of sine waves with frequencies in a harmonic series. In other words, all periodic waveforms can be broken down into a collection of sine waves of specific amplitudes and frequencies. The human visual system has been characterized as approximating a Fourier analyzer on temporally modulated stimuli.[11,12,13] This means that the response of the visual system to a stimulus modulated over time by a complex waveform can be approximated by a sum of the responses to the sine-wave components of the waveform. Because of this property, a photometric system for sinusoidal temporal variations, of a broad range of frequencies, can be established and linear combinations can be used for any novel waveform.

To make the photometric system of flashing lights closely resemble the already-established photometric system for steady lights, the structure of the CIE photopic luminous efficiency function (V_λ) can be mimicked. The new photometric system for flashing lights will be based on a series of spectral sensitivity functions, each for stimuli at a different temporal frequency (sinusoidal modulation). These will be combined, resulting in a three-dimensional function, relating sensitivity, wavelength, and temporal frequency. By Fourier transforming the flash into frequency space as a function of wavelength, convolving this function with the new photometric system for flashing lights (which will be based on vision experiments), and integrating the resultant function, the effective intensity can be determined much like the luminous intensity is currently determined. From this data, models such as Ohno and Couzin's[7], which is much

simpler to implement instrumentally, can be thoroughly validated and expanded to include response to wavelength.

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