PHYSICAL MEASUREMENT OF FLASHING LIGHTS – NOW AND THEN

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ABSTRACT

This paper begins with a historical review of flashing lights and physical measurement of flashing lights since the time the Blondel-Rey equation was developed. Then the recent work on the physical measurement standards for flashing lights, developed in 1997 at the National Institute of Standards and Technology, is introduced. The paper also discusses the physical requirements and practical aspects of measurements based on the four formulae (Blondel-Rey equation, Form Factor method, Allard method, and Modified Allard method) for effective intensity.

1. INTRODUCTION

Flashing lights are widely used in many signalling applications in aviation, marine, and land transportation. Flashing lights, such as aircraft anticollision lights, marine aids-to-navigation lights, obstruction lights, and emergency vehicle warning lights, are specified for effective intensity (cd). These lights need to be physically measured to assure that they meet specifications. Effective intensity is defined as luminous intensity (cd) of a steady light, of the same relative spectral distribution as the flashing light, which would have the same luminous range (or visual range in aviation terminology) as the flashing light under identical conditions of observation [1]. Several formulae, such as those by Allard in 1876 [2] and Blondel-Rey in 1911 [3], were developed to calculate effective intensity from the waveform of a flash pulse. This paper first gives a historical review on how the measurements of effective intensity of flashing lights were made in such early days when visual photometers, early photodetectors, and planimeters were used.

Then the latest work on the physical measurement standards for flashing lights, developed in 1997 at the National Institute of Standards and Technology (NIST), USA, [4] is introduced. The unit of luminous exposure (lx·s) has been realized on NIST reference standard photometers developed for flashing lights, and calibration capabilities have been established for effective intensity (xenon flash sources only) as well as luminous exposure (lx·s) of pulsed light and flash photometers to measure these quantities.

Finally, the physical requirements and practical aspects of the effective intensity formulae including those by Allard, Blondel-Rey, Schmidt-Clausen [5], and the Modified Allard method [6] are discussed. Possible ways to produce practical photometers based on these formulas are presented, and merits and demerits are discussed.

2. HISTORICAL REVIEW

2.1 Effective intensity formulae

In the 19th century, lighthouses started using flashing lights to provide their identification to mariners. Oil lamps were used as the light source in early lighthouses. Flashing lights were produced either by intermittently obscuring an omnidirectional light source with a hood or shutter driven by a clockwork mechanism, or by rotating collimating optics around the source. It was also recognized that intermittent light (flashing lights) produced higher visibility than the steady light of the same intensity, and efforts started to quantify the visibility as effective intensity.

Allard proposed in 1876 [2] that the visual sensation $i(t)$ in the eyes for a flashing light with instantaneous intensity $I(t)$ is given by

$$\frac{\mathrm{d}i(t)}{\mathrm{d}t} = \frac{I(t) - i(t)}{a}, \qquad (1)$$

where a is a visual time constant (0.2 s). This differential equation is solved as a mathematical convolution of $I(t)$ with a visual impulse function $q(t)$ as given by

$$i(t) = I(t) * q(t); \quad q(t) = \frac{1}{a}\,\mathrm{e}^{-\frac{t}{a}} \ (t \geq 0) \qquad (2)$$
$$q(t) = 0 \ (t < 0)$$

(*: convolution)

The effective intensity I_{eff} is given as the maximum value of $i(t)$. This method did not prevail widely, probably due to lack of publicity and difficulty of calculation in the old days.

In 1911, based on visual experiments for threshold detection of flashing lights, Blondel and Rey proposed that the effective intensity I_{eff} of flashing lights is described by the equation,

$$I_{\mathrm{eff}} = \frac{\int_{t_1}^{t_2} I(t)\mathrm{d}t}{a + (t_2 - t_1)} , \tag{3}$$

where $I(t)$ is the instantaneous luminous intensity of the flash, $(t_2\text{-}t_1)$ is the duration of the flash, and a is a visual time constant, 0.2 s, known as the Blondel-Rey constant [3]. This equation was straightforward for rectangular pulses, but they soon faced a question as to how t_1 and t_2 should be determined for non-rectangular pulses rising and diminishing slowly. Blondel and Rey proposed also in 1911 that, for nonrectangular pulses, t_1 and t_2 should be determined in such a way that

$$I_{\mathrm{eff}} = I(t_1) = I(t_2) \tag{4}$$

is satisfied in Eq. (3). This requires iterative solution. In spite of the difficulty with non-rectangular pulses, the simplicity of Eq. (3) gained wide acceptance, and the Blondel-Rey method has been commonly used worldwide until today. In 1957, Douglas prescribed a formula applying the Blondel-Rey equation for a train of pulses, known as Blondel-Rey-Douglas equation [7].

In 1968, Schmidt-Clausen introduced a concept of Form Factor, and proposed a method that simplified the calculation of effective intensity for non-rectangular pulses [5]. The effective intensity I_{eff} of a flash pulse $I(t)$ is given by

$$I_{\mathrm{eff}} = \frac{I_{\max}}{1 + \frac{a}{F \cdot T}} ; \quad F = \frac{\int_0^T I(t)\mathrm{d}t}{I_{\max} \cdot T} \tag{5}$$

where F is called Form Factor, and $I_{\max}$ is the maximum of the instantaneous luminous intensity $I(t)$. This equation can be transformed into a form

$$I_{\mathrm{eff}} = \frac{\int_0^T I(t)\mathrm{d}t}{a + \Delta T} ; \qquad \Delta T = \frac{\int_0^T I(t)\mathrm{d}t}{I_{\max}} = F \cdot T \tag{6}$$

which gives an interpretation that this method is an extension of the Blondel-Rey equation with a new way of determining the duration of the flash. With its simplicity in dealing with non-rectangular pulses, the Form Factor method is gaining acceptance.

There is an effort being made to compare these formulae for measurement of various forms of pulses and possibly to standardize the definition of effective intensity [8]. In this effort, the Modified Allard Method is proposed, in which the visual impulse response function - $q(t)$ in Eq. (2) - is modified so that the results for rectangular pulses match the results by the widely-accepted Blondel-Rey equation; the function $q(t)$ is approximated by a sum of two exponential functions [6].

2.2 Physical measurement of effective intensity

Until around the 1940s, there were no physical photodetectors available, and photometry was made with a visual photometer, matching the brightness of two light sources positioned at varied distances using human eyes [9]. Only steady light could be physically measured using such a technique. How was the effective intensity of flashing lights measured around that time?

Flashing warning lights in the early days were comprised of either a rotating light or an incandescent lamp operated intermittently, both of which were rather slowly-changing pulses. Such rotating lights are still commonly used for lighthouses, railroad crossings, and many other applications. The effective intensity of rotating lights can be calculated (rather than directly measured) using the luminous intensity distribution of the light in steady state and its rotation speed. Therefore, it can be handled as a measurement of steady light in laboratories. An intermittent

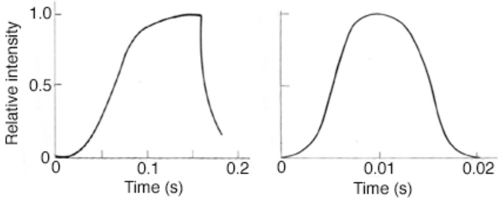


Figure 1. An example of pulse waveforms of warning lights with an incandescent lamp intermittently turned on and off (left) and rotating beacon (right) – from Ref. [10]

incandescent lamp had to be roughly approximated as a rectangular pulse.

The pulsed signal from an intermittent incandescent lamp signal, or rotating beacon in the field, however, needs to be measured directly. Figure 1 shows an example of such pulses. In that case, for the Blondel-Rey equation, the instantaneous luminous intensity must be measured and recorded. Such physical measurements had to wait until the advent of photodetectors. One means to accomplish this in the early days (~1950s) was the use of a phototube and an oscilloscope to measure the light pulse. A photograph of the oscilloscope screen was taken to record the waveform. The integration of the pulse was performed using an area-measuring instrument called a planimeter, tracing the waveform on the photograph, or by counting graph paper squares under the waveform curve [11]. It took hours, if not days, to obtain the results.

More recently, since around 1960s, condenser-discharge lamps, such as xenon lamps, have become common for flashing warning lights. Xenon lamps produce light pulses with a duration of only about 1 ms or less (Fig. 2), and the duration t_2-t_1 becomes practically negligible in the Blondel-Rey equation. Then there is no need to measure the waveform. The effective intensity can be obtained only from the time integral of the pulse (in cd·s) divided by the Blondel-Rey constant. However, historically the physical measurement of the time integral of pulsed light was not easy. The National Bureau of Standards (now NIST) in 1958 used a $V(\lambda)$-filtered phototube connected to a resistor-capacitor filter with a long time constant to measure the averaged luminous intensity of repeated flashes, which was converted to an integrated luminous intensity (cd·s) and then to effective intensity [11]. The photometer system was calibrated with a rotating chopper disc with known sector ratios.

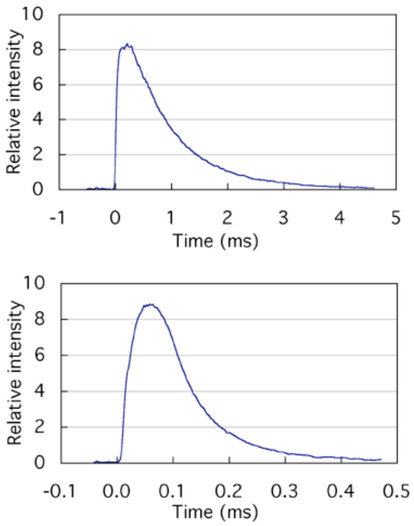


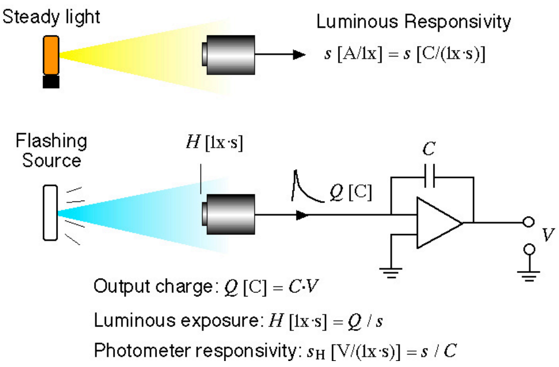
Figure 2. An example of waveforms of xenon flash pulses.

3. NIST REALIZATION OF PHOTOMETRIC UNITS FOR FLASHING LIGHTS

With modern electronics technology, a time integral of detector signals can be measured much more easily, and commercial instruments have been made available to measure integrated luminous intensity (cd·s) or luminous exposure (lx·s). However, calibration of these instruments has not been trivial. Around 1995, a large variation in the measurements of effective intensity of aircraft anticollision lights (mostly using xenon flash lamps) became a problem for enforcing the federal regulations in the United States. NIST undertook a task, upon a request by Federal Aviation Administration, to establish standards for these units and calibration services for flash photometers.

Two different approaches were taken to calibrate flashing-light standard photometers: 1) based on electrical

(a) Electrical method



(b) Pulsed photometry method

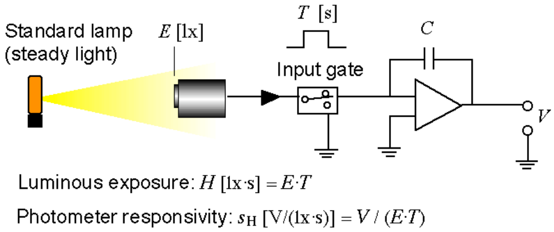


Figure 3. Derivation of photometric units for flashing light.

calibration of the current integrator (Electrical method), 2) based on electronic pulsing of a steady-state photometric standard (Pulsed photometry method). The principles of these two methods are illustrated in Fig. 3.

In the Electrical method shown in Fig.3 (a), A flashing-light standard photometer is first calibrated for illuminance responsivity s [A/ lx] with a steady light illuminance standard, and then, the same value holds for the luminous exposure responsivity s in coulomb / (lux·second). With the photometer combined with a current integrator using a calibrated capacitor C [farad], the luminous exposure responsivity s_H [V/(lx·s)] of the photometer including the current integrator is given by

$$s_H = s \,/\, C. \tag{7}$$

The pulsed photometry method, shown in Fig. 3 (b), works similar to the well-known chopper method. Instead of using a mechanical light chopper, an electronic gate is used for much higher accuracy in time. The standard photometer is connected to a current integrator which has an input gate controlled by an accurate time base. The photometer head is placed at a point of known illuminance E [lx] under steady light illumination, and the input gate opens for T [s], and the output voltage V [V] is measured. The luminous exposure responsivity s_H [V/(lx·s)] of the photometer is given by

$$s_H = V \,/\, (\, E \cdot T\,). \tag{8}$$

The scales realized using these two independent methods agreed to within 0.2 % [4]. The unit (lx·s) has been realized on the NIST standard photometers (Fig. 4) with an uncertainty of less than 1 % (*k*=2) in the range of 1 lx·s to 1000 lx·s, and is maintained at NIST by annual realization. Figure 5 shows the calibration history of one of the NIST flashing light standard photometers using the pulsed-photometry method. The stability of the photometer is shown to be within a few tenths of a percent over a period of five years. The other three photometers show similar stability. A calibration service (NIST Test No. 37110S [12]) has been established for flashing-light photometers.

Typical flash photometers for aircraft anticollision lights measure effective intensity I_{eff} [cd] at a specified distance d [m] using the Blondel-Rey equation but ignoring the pulse duration (for xenon pulses only). To calibrate such meters, the effective intensity readings are converted to luminous exposure H [lx·s] using Eq. (3) and the inverse square law, as

$$H = 0.2 \cdot I_{\mathrm{eff}} / d^2 \tag{9}$$

so that the flash photometers can be compared directly to the luminous exposure readings of the NIST standard photometer. Therefore, the test photometers need not be calibrated at the specified distance d but at any distances to produce required illuminance levels. If flashing lights of longer duration are to be calibrated, another fast response photometer with a current-to-voltage

Figure 4. NIST flashing-light standard photometers (below) and the current integrator units (above).

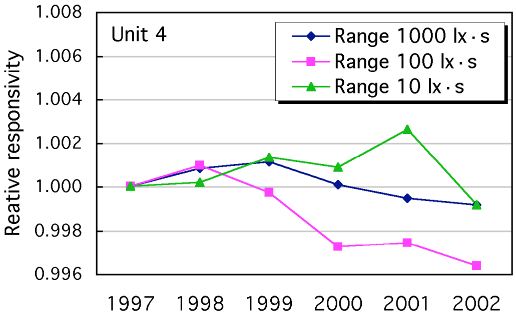


Figure 5. History of the annual calibration of one of NIST flashing-light standard photometers.

converter and a digital oscilloscope are used to measure the waveform of the pulse and the effective intensity is calculated using a specified formula.

4. PRACTICAL MEASUREMENT OF EFFECTIVE INTENSITY

4.1 Need for field measurement

Field measurements are essential for maintenance of various warning lights installed in various transportation facilities. Commercial hand-held flashing-light photometers are now available from several manufacturers. Most of these photometers, however, measure only the integral of the flash and do not measure the waveforms or durations of the pulse. Thus, these meters are useful only for measurement of luminous exposure (lx·s), integrated luminous intensity (cd·s), and/or effective intensity of xenon flash sources, for which the flash duration can be neglected. Therefore, these photometers cannot be used to measure effective intensity of rotating beacons or LED flashing lights having much longer pulse durations, unless their waveforms are known. The Blondel-Rey equation requires iterative solutions by a computer, which has hindered development of hand-held photometers. It is desired that effective intensity be defined in such a way that it can be applied easily into practical photometers.

4.1 Practical Aspects of the Effective Intensity formulae

Figs. 6 to 9 show examples of possible electronic configurations of photometers based on Blondel-Rey equation, Form Factor method, Allard method, and Modified Allard method, respectively. In all cases, the first stage is a current-to-voltage converter (I-V converter) with low input impedance in order to maintain linearity of the photodiode while converting its signal into voltage. The photodiode may be reverse-biased, if increased response speed is required.

With the Blondel-Rey equation, instantaneous luminous intensity of the pulse needs to be measured as a function of time, and the waveform data are processed by a computer for iterative solution (Fig.6). The need for a computer makes it difficult to realize a compact, hand-held photometer. The A/D conversion rate must be fast enough to be able to measure the integral and peak of very fast pulses (e.g., xenon flash) accurately, and the rate probably needs to be lowered for slower pulses.

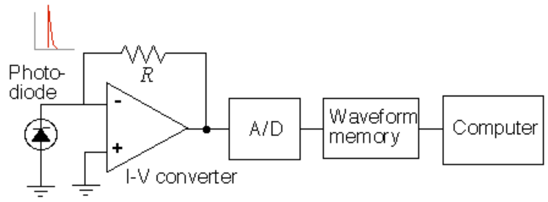


Fig.6 Configuration example for an effective-intensity photometer with Blondel-Rey equation.

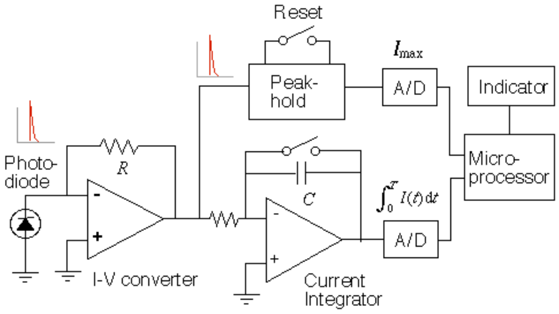


Fig.7 Configuration example for an effective-intensity photometer with the Form Factor method.

With the Form Factor method, the pulse waveform is not required, and only the maximum instantaneous luminous intensity (I_{max}) and the time integral of the pulse need to be measured. A photometer can be realized with analog circuits and a simple microprocessor as shown in Fig. 7. A difficulty is expected, however, in the circuit design where it needs to cope with a large range of the detector peak signal depending on the pulse duration. For example, the peak signal for a 0.1 ms xenon flash pulse is 10^3 times higher than a 0.1 s pulse having the same energy. The gain of the I-V converter must be changed to avoid amplifier saturation, and the gain of the current integrator must also be changed accordingly depending on the pulse duration.

The Allard method has a great advantage in that neither the waveform nor the time integral of the pulse is needed. It requires only the peak of the signal after a low-pass filter, as shown in Fig. 8. Since high peaks of the detector signal are absorbed by the capacitor C, the peak signal level at the I-V converter output is fairly constant regardless of the pulse duration, for short pulses having the

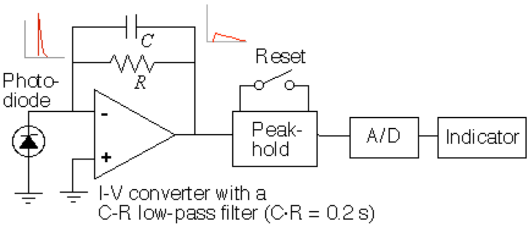


Fig.8 Configuration example for an effective-intensity photometer with Allard method.

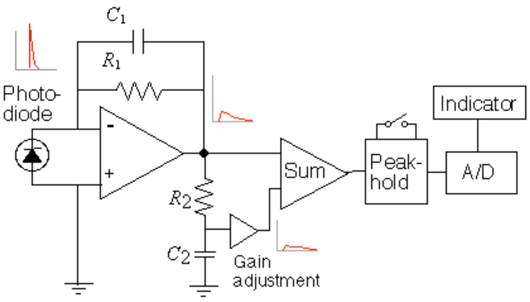


Fig.9 Configuration example for an effective-intensity photometer with Modified Allard method.

same energy. The output, as a result of low-pass filtering, is a slowly changing signal, which makes the subsequent peak measurement easy and robust. This significantly simplifies the requirements for the circuit design.

The Modified Allard method [6] can be realized with an additional intermediate stage added to the circuit for the Allard method, as shown in Fig. 9, still having the benefits of the Allard method in the ease of circuit design.

Conclusions

The effective intensity has been *calculated* rather than directly measured in the past (except xenon flash sources). The industry now needs field measurements of various warning lights to maintain and assure safety of traffic. Hand-held flash photometers that can be used for any forms of flashing lights are in need. While the standards and traceability for physical measurement of flashing lights (in lx·s, cd·s) has been established, there has been a difficulty in producing hand-held flash photometers for effective intensity. The formulae for the definition of effective intensity needs to be standardized, with consideration not only on the accuracy to visual perception but also on the circuit requirements in realizing practical photometers. Work is in progress at CIE Technical Committee 2-49 to produce recommendations on photometry of flashing lights.

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