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EXPERIMENTAL EFFECTIVE INTENSITY OF STEADY AND FLASHING LIGHT EMITTING DIODES FOR AIRCRAFT ANTI-COLLISION LIGHTING

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Research was conducted to determine the effective intensity of flashing lights that incorporate light-emitting diodes (LEDs). LEDs require less power and have the ability to flash without the addition of moving parts. Compared with incandescent bulbs, however, LEDs yield a different spectral output and a different intensity profile when flashing. To determine the effect of these differences on a viewer's ability to detect the light, we examined LEDs to determine if they can successfully replace legacy technologies/assemblies on aircraft. The LED was displayed to naïve subjects to establish visibility thresholds using an automated system to drive the LED with variable intensity and duration. Experimental data were examined to determine which model for effective intensity (Allard, Modified Allard, or Blondel-Rey) is most appropriate for LEDs. Each of the methods was found to be applicable dependent upon the system being considered. Use of the Blondel-Rey method produced acceptable but conservative results.

In recent years, designs for aircraft anti-collision lights have incorporated LEDs because of their low power consumption, longer operating life, and the ability to flash without moving parts. However, the spectral output of an LED is significantly different than that of existing technologies. A white incandescent bulb produces a yellowish output and most white LEDs produce a white that has a much stronger blue component. Also, the intensity profile, or pulse shape of a flashing LED is rectangular and much longer compared with a xenon flash tube having very short pulses, and different from a rotating incandescent bulb producing some variation of a rounded pulse shape.

The research presented in this paper evaluated several formulae (the Blondel-Rey, the Allard, and the Modified Allard) to find an acceptable and practical measurement technique for describing the effective intensity of flashing LED lights, such as aircraft anti-collision light system, that incorporate LED technologies. The method incorporated in Title 14 of the Code of Federal Regulations (CFR) Part 25, §25.1401(e) has been adequate for use with xenon flash tube technology, but may be inappropriate for anti-collision lights using LED technology. According to existing standards, the effective intensity for an anti-collision light must be determined by the Blondel-Rey formula, specified in CFR §23.1401, 25.1401, 27.1401 and 29.1401. These new LED anti-collision lights use various pulse durations, pulse shapes, and groupings of pulses to generate the intensity and flashing characteristics required in §25.1401. Because data have indicated that the Blondel-Rey metric may underestimate the effective intensity of these flashing lights with complex pulse patterns, the Blondel-Rey equation may be inappropriate for determining the effective intensity of anti-collision lights using LEDs (Federal Aviation Administration, 2009).

Effective intensity is defined by International Commission on Illumination (CIE) as "luminous intensity of a fixed (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." The currently-used FAA standard for qualifying the effective intensity of flashing lights was first proposed by Blondel and Rey in 1911. That experiment involved subjects viewing a lamp housed in a contraption with a rotating disc that created a flashing light effect. Since then, the technology used to develop aircraft anti-collision lights has changed considerably, yet the equation proposed by Blondel and Rey is still used as the standard.

The Blondel-Rey equation has been evaluated both experimentally (1911) and analytically (Ohno & Couzin, 2002) for use with LEDs. In addition, other models have been proposed as alternatives for measuring the effective intensity of a pulsed light source such as the Allard method (Allard, 1876) and the form-factor method (Schmidt-Clausen, 1968). Ohno and Couzin (2002) conducted a theoretical study of these models and proposed the

Modified Allard method as a more accurate alternative for multi-pulse flashing lights. Multi-flash signals are advantageous, as they help the observer to better judge the distance and location of the light signal (Mandeler & Thacker, 1986). Experimental effective intensity of multi-flash signals is studied (Mandeler & Thacker, 1986) using very short xenon strobe pulses. Our previous work in this area used the same apparatus described below to determine experimental effective intensity of a single-pulsed LED (Yakopcic et al., 2012). Those results showed that using a randomized distribution of LED signals resulted in a stronger correlation to the Blondel-Rey equation than when presenting the signals using a method of limits approach.

Methods for Modeling Effective Intensity

The three models for effective intensity examined in this paper include the Blondel-Rey equation, the Allard Method, and the Modified Allard method. The Blondel-Rey equation is shown in Eq. (3), where $I(t)$ is the intensity profile of the pulse output from the LED, and a is the visual time constant that was experimentally determined to be 0.2s by Blondel and Rey. For a square pulse, t_1 and t_2 are the rising and falling edge of the pulse respectively. The value I_{eff} is the effective intensity of the light pulse in question.

$$I_{\text{eff}} = \frac{\int_{t_1}^{t_2} I(t) dt}{a + (t_2 - t_1)} \quad (1)$$

The Allard method is based on a convolution of the intensity profile of the pulsed LED with the visual impulse response function as defined by Allard. The equations for the Allard method are shown in Eqs. (2) and (3), where $I(t)$ again represents the intensity profile of the light pulse. The function $i(t)$ is the convolution of $I(t)$ and the visual impulse response $q(t)$ as defined in Eq. (3). Convolution refers to the mathematical operation denoted by the \otimes symbol in Eqs. (2) and (4). The visual time constant a is also set to 0.2s in this equation (Ohno & Couzin, 2002), and the effective intensity is defined as the maximum of $i(t)$.

$$i(t) = I(t) \otimes q(t) \quad (2)$$

$$q(t) = \frac{1}{a} e^{-\frac{t}{a}} \quad (3)$$

The Modified Allard method (Ohno & Couzin, 2002) was first developed by optimizing the constants in the visual impulse response function given in Eq. (5) so that the result of this method closely matched the Blondel-Rey equation for single rectangular pulses. Further theoretical analysis discovered the $q(t)$ function that perfectly matches the results of Blondel-Rey for rectangular pulses, shown in Eq. (6).

$$i(t) = I(t) \otimes q(t) \quad (4)$$

$$q(t) = \frac{w_1}{a_1} e^{-\frac{t}{a_1}} + \frac{w_2}{a_2} e^{-\frac{t}{a_2}} \quad (5)$$

$$q(t) = \frac{a}{(a+t)^2}; t \geq 0 \quad (6)$$

Experimental Method

Subjects

Participants were recruited through email lists of enrolled students and with posters hung in campus buildings. Prior approval for all procedures and use of human subjects was obtained from the University of Dayton (UD) Institutional Review Board. Informed consent was obtained prior to participation and subjects were free to withdraw from the project without consequence at any time. Three different experiments were conducted that differed in the pulse type displayed. These included (1) a single rectangular pulse, n=36; (2) a 2 pulse multi-flash signal, n=21; or (3) a 4-pulse multi-flash signal, n=15. In a one-hour testing session, only one of these three signal options was utilized. Each test subject completed a demographics form for general data regarding eyesight. A visual acuity test was administered and only subjects with 20/30 vision or better were utilized for the experiments. The subjects were mainly college students, and the subject age was in an 18-25 range with about 50% males and 50% females. Subjects were rewarded with a \$20 voucher for the UD Bookstore upon completing the experiment.

Apparatus and Procedure

A MATLAB (Mathworks) program was developed that automatically controlled the LED intensity and pulse width that was observed by the test subjects. The MATLAB script was capable of controlling the pulse width

to a resolution of 2 milliseconds. The MATLAB script fully automated the testing procedure for displaying the LED and collecting the user responses using input obtained from a “yes” button and a “no” button placed below the subject’s right and left hand respectively that corresponded to whether or not a light was seen. A single trial consisted of a 5-second presentation and answer interval and a 2-second between-trial interval. A total of 539 trials were presented at random. These trials consisted of 7 different pulse widths (see Figure 1) at 11 different intensities (see Table 1), each shown 7 times. Preceding the trials, a dark adaption and pretest was administered. This consisted of a 7-minute dark adaption period, followed by a 16-trial pre-test, and then another 8 minutes of dark adaption.

Subjects were seated 50 feet directly in front of the LED apparatus. The LED was white with chromaticity values of (x=0.301, y=0.293) on the 1931 CIE chromaticity diagram. Black Curtains were hung to remove the possibility of reflection from the walls. The LED was housed in a wooden, matte black box with circular baffles to reduce the scattering of the observed light. A headrest was used to ensure the subjects were looking in the direction of the LED. The LEDs required about 3mA to display a stable signal, which provided too much intensity for these experiments. To obtain appropriate intensity values considered to encompass each test subject’s threshold based on a priori testing, neutral density filters were used to reduce the light output from the LED to the order of micro-candelas (μcd). Our system was capable of driving the LEDs with a maximum current of about 30mA. Therefore, to maximize the range of intensities that could be presented, two identical LEDs were used side by side. Only one LED was presented within a single trial, although different neutral density filters were applied to each LED. For the single pulse test, the neutral density filters differed by a factor of 10. Given that each LED also has an output range of about a factor of 10, this allowed for a set of intensities where the strongest intensity was about 100 times that of the weakest (see Table 1, Single Pulse Test), hence permitting a wide range of brightness for a more accurate determination of each subject’s threshold.

Table 1.

The values in the table show the peak luminous intensity of each rectangular pulse after considering neutral density filters for each experiment. Reduction in transmission through filters is linear for all visible wavelengths.

Experiment 1 n=36 Single Pulse Test LED Intensities (μcd)		Experiment 2 n=21 2-Pulse Multi-Flash Test LED Intensities (μcd)		Experiment 3 n=15 4-Pulse Multi-Flash Test LED Intensities (μcd)	
LED 1	LED 2	LED 1 (Steady)	LED 2 (2 Flash)	LED 1 (Steady)	LED 2 (4 Flash)
0.00	0.00	0.00	0.00	0.00	0.00
0.02	LED Not Used	0.06	0.39	0.06	0.20
0.34		0.08	0.51	0.08	0.26
LED Not Used	0.38	0.10	0.60	0.10	0.30
	0.81	0.20	1.28	0.20	0.64
	1.23	0.31	1.94	0.31	0.97
	1.62	0.41	2.57	0.41	1.29
	2.00	0.50	3.17	0.50	1.59
	2.36	0.59	3.74	0.59	1.88
	2.72	0.68	4.32	0.68	2.16
3.06	0.77	4.85	0.77	2.43	

In addition to the variable intensities, 7 different pulse widths were used; 5s, 1s, 500ms, 250ms, 100ms, 50ms, and 20ms. The 5-second light represented a steady state signal because all methods for calculating effective intensity showed that at a pulse width of 5 seconds resulted in an effective intensity within 5% of the intensity of a true steady state light. The steady state (5-second) signal is required as the reference to accurately determine the effective intensity. Figure 1 shows the pulse width of the normalized LED signal and response interval for experiments 1 and 2. Experiment 3 has a similar pattern to experiment 2, although each trial width contains 4 pulses. The 5-second, steady state signal directly overlaps the response interval in each case. Each of the multi-flash tests (experiments 2 and 3) required a 5 second steady state signal for comparison, but the small multi-flash signals were significantly more difficult to detect when compared to the steady state signal. As a solution, the steady state and the multi-flash signal were each presented from a different LED. Each LED was identical but different neutral density filters were applied to each. The intensities for the 2-flash and 4-flash multi-pulse experiments (see Table 1).

Results

For each test subject, a visibility threshold was calculated for each of the 7 pulse widths. This was done by applying a logistic regression to collected data and determining the point where the probability of detection was at 50%. The plots in Figure 2 display a data set from a single subject. The visibility thresholds obtained from all test subjects were used to determine a mean visibility threshold for each pulse width in each of the three experiments. To determine the experimental effective intensity using these data, the mean steady state threshold was divided by the mean threshold for each of other six pulse widths. The results for the single pulse experiment were based on 36 subject datasets, the results for the 2 pulse experiment were based on 21 subject datasets, and the 4 pulse experiment was based on 15 subject datasets.

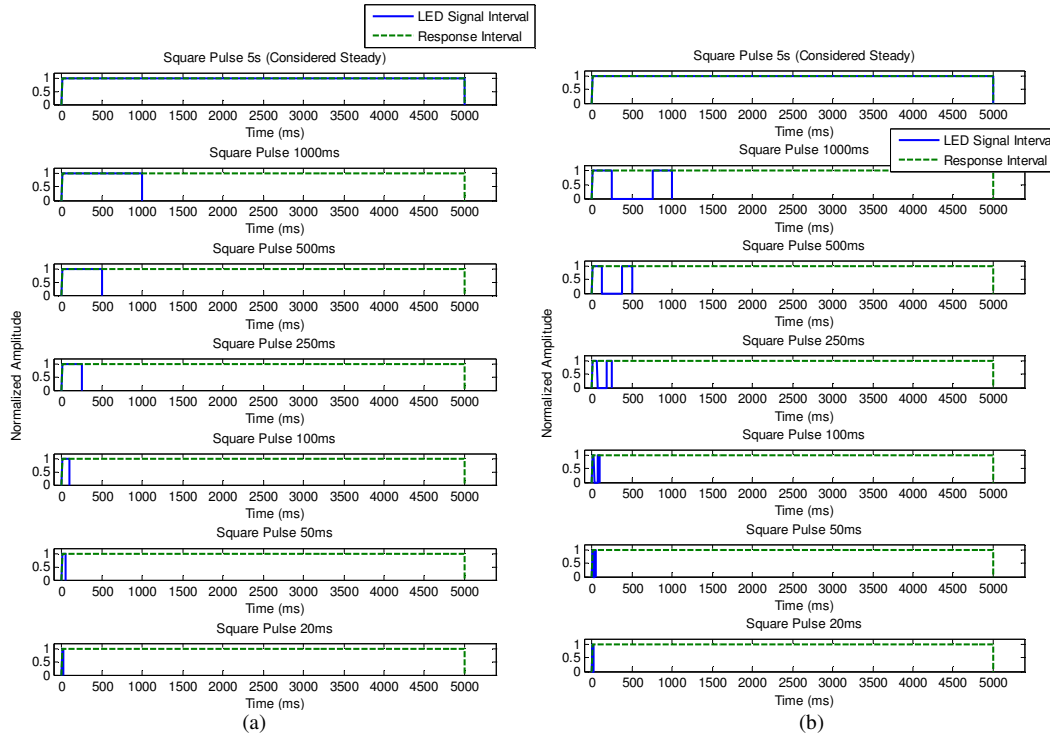


Figure 1. Normalized LED signals and response intervals for (a) the single pulse experiment and (b) the 2 pulse multi-flash experiment.

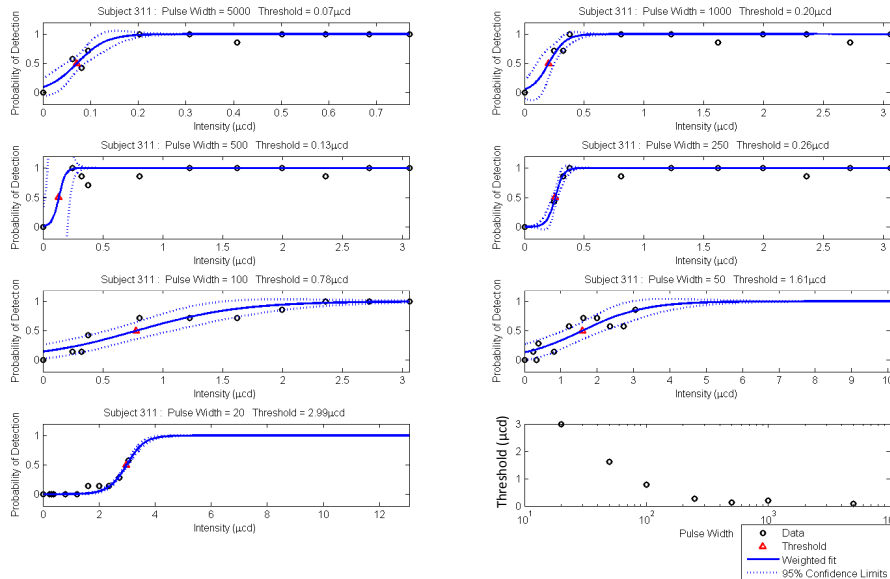


Figure 2. Sample of individual subject data.

Figures 3, 4, and 5 show how the experimentally determined effective intensities relate to the theoretical effective intensity equations including the Blondel-Rey, Allard, and Modified Allard methods. It should be noted that the multi-flash experiments were compared to the Blondel-Rey-Douglas equation (Douglas, 1957) as opposed to Blondel-Rey equation because the Blondel-Rey-Douglas equation (described by Ohno and Couzin (2002)) provides a slight modification to the Blondel-Rey equation that allows for more accurate modeling of multi-pulse signals. Figures 3, 4, and 5 correspond to the single pulse, 2-pulse, and 4-pulse experiments, respectively. Figure 3 shows that the best representation of the data collected would appear to be the Allard method. Although, Figures 4 and 5 both show that the multi-flash experimental data are more closely related to the Modified Allard method.

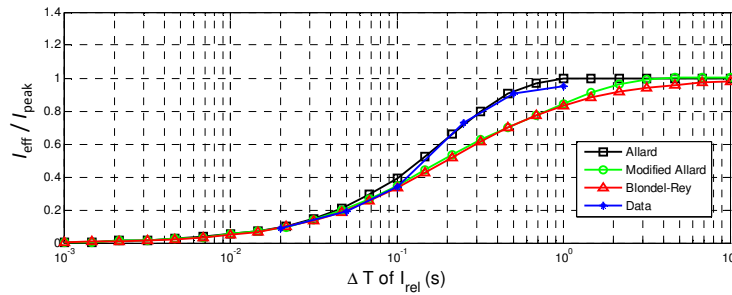


Figure 3. Experiment 1: Comparison of data from the single pulse experiment and the models for determining effective intensity (I_{peak} =Peak signal intensity).

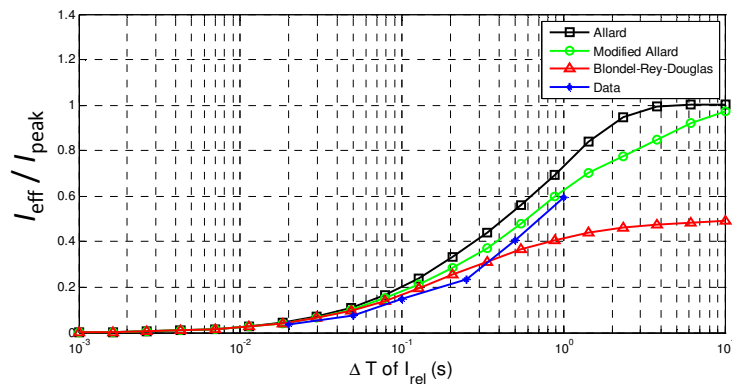


Figure 4. Experiment 2: Comparison of the 2-pulse experimental data and predicted results.

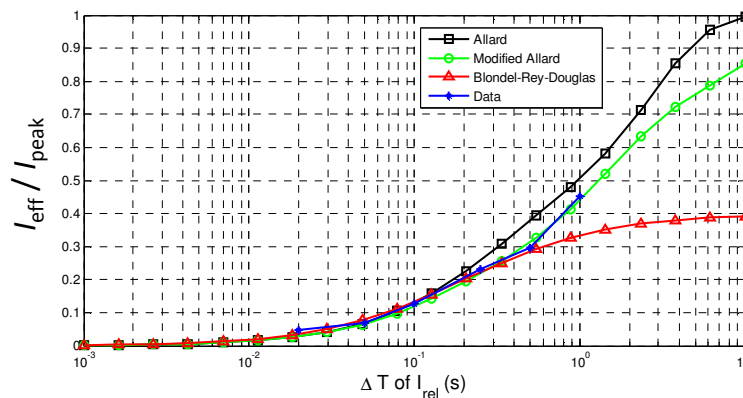


Figure 5. Experiment 3: Comparison of the 4-pulse experimental data and predicted results.

Conclusion

These results suggest that different models for effective intensity are required when using different LED signal patterns. When a single pulse flash is being used, it would appear that the Allard method is most appropriate to model effective intensity, although the data collected from the multi-flash experiments seems to suggest that the Modified Allard method is the best choice to match experimental results. In all cases, use of the Blondel-Rey method requires a higher actual intensity to produce a calculated effective intensity to be perceived as equivalent to the experimental results. Therefore, continued use of the Blondel-Rey method can be considered a conservative approach, but use of Modified Allard and Allard methods, as appropriate, could result in reductions in lighting component mass and/or energy while ensuring performance equivalently. Changes to the visual time constant of 0.2s could possibly make the Blondel-Rey method more appropriate for multiple flash cases when using LEDs, and this could be evaluated in future research.

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