AD

AD-E404 108

Technical Report ARMET-TR-17076

AN INTRODUCTION TO PYROTECHNIC LIGHT MEASUREMENTS

Jay C. Poret, Ph.D.

April 2019

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER

Munitions Engineering Technology Center

Picatinny Arsenal, New Jersey

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

The citation in this report of the names of commercial firms or commercially available products or services does not constitute official endorsement by or approval of the U.S. Government.

Destroy by any means possible to prevent disclosure of contents or reconstruction of the document. Do not return to the originator.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-01-0188*

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (*From - To*)
April 2019	Final	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
AN INTRODUCTION TO PYROTECHNIC LIGHT MEASUREMENTS	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHORS	5d. PROJECT NUMBER
Jay C. Poret, Ph.D.	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
U.S. Army CCDC Armaments Center, METC Energetics & Warheads Directorate (FCDD-ACM-ET) Picatinny Arsenal, NJ 07806-5000	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army CCDC Armaments Center, ESIC Knowledge & Process Management Office (FCDD-ACE-K) Picatinny Arsenal, NJ 07806-5000	11. SPONSOR/MONITOR'S REPORT NUMBER(S) Technical Report ARMET-TR-17076

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Over the past several decades, there have been dramatic changes in light measurement technology. For example, Weston cells were once used to make luminous intensity measurements but have been replaced by silicon detectors with photometric filters. Visible light spectral measurements (once made with single grating spectrometers) are now measured with silicon charge coupled devices for fast spectral measurements. To develop high-performance illuminants, the pyrotechnician not only needs to understand high-temperature combustion chemistry but also needs to understand the nature of light emission and how to accurately measure and quantify emitted light. In this paper, the basic theory and practical aspects of light measurements will be discussed. Examples of experimental setups and methodologies will be described for measuring physical quantities such as luminous intensity and emissive color.

15. SUBJECT TERMS

Optical light measurements Color measurements Optical equipment

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Jay C. Poret, Ph.D.
U	U	U	SAR	21	19b. TELEPHONE NUMBER (Include area code) (973) 724-3035

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

CONTENTS

FIGURES

INTRODUCTION

Mankind has always been fascinated with light. Some of the earliest records show that Peking man may have lit fires in caves as early as 400,000 BC (ref. 1). In 4500 BC, oil was placed in round man-made bowls and used to provide light. Candles, made from beeswax and tallow, were invented by the Egyptians around 3000 BC, and provided an alternative to oil-based lamps (ref. 2). The first street lamps appeared in the streets of Cordova, Spain in the year 1000 AD.

In 1666, Sir Isaac Newton used a prism to disperse white light into its component colors. This was a revolutionary discovery because people at the time thought light was a mixture of light and darkness. He also recombined colored light back into white light using the same prism further validating the idea that white light is a combination of different colors. Newton also hypothesized that luminous bodies radiate light as particles and that the particles radiate in straight lines. Later, Huygens and Young showed that some of light's properties are attributed to its wavelike properties.

The first practical light detector was developed by Nobile and Melloni around 1830 (ref. 3). They developed a thermopile sensor that detects light by the thermal energy imparted to an array of thermocouples. Even though thermopiles are not very sensitive to low levels of light, this detector was the first device to quantify the amount of light incident on a surface.

The silicon diode, the cornerstone of modern light measurements, was developed in 1954. In its simplest form, the silicon photodiode is composed of a P-N junction. A P-N junction is fabricated by combining two different semiconductors – a positively doped semiconductor (p-type) and a negatively doped semiconductor (n-type). When light strikes the surface of a p-n diode, an electron pair hole is produced within the material. Due to the internal electric field of the diode, the electron is swept toward the anode and the hole toward the cathode producing a photocurrent. When the detector is operated in the photovoltaic mode (no voltage bias), the photocurrent is linearly proportional to the level of light striking the detector. Silicon photodiodes are typically used for measuring visible light and near infrared light.

Photodetectors are useless without a way to collect the signal and process it. The first systems that could record signal produced by photodetectors were based on strip chart recorders. A strip chart recorder produced a paper record of the event that could be stored and analyzed. Even though this enabled users to store data, they were cumbersome and made it difficult to analyze data. In 1983, National Instruments released one of the first General Purpose Interface Bus data acquisition cards (ref. 4). This data card allowed users to digitize analog data and store it on a computer and allowed users to write computer code to analyze the data rapidly and quickly. As electronics and computer technology matured, digital data collection systems have become more sophisticated and widespread.

The intent of this paper is to give the reader a brief overview of how light is produced from pyrotechnic light sources and the basic theory of light measurements. The point source approximation is used to simplify the radiometric equations needed for describing the energy transfer from the source to the detector. Basic equations will be presented without complex mathematical derivations. For readers interested in a more in-depth description of both light emission and light measurement, references will be provided at end of this paper.

BASIC THEORY OF LIGHT EMISSION

Background

When a pyrotechnic item (i.e., signal flare or illuminant) undergoes combustion, there are several mechanisms by which light can be emitted. Depending on how the item is formulated, white light or colored light can be produced. Originally, light was thought to be composed of individual particles of energy, or corpuscles, which traveled from the source to the person's eyes in straight lines (ref. 5). Eventually, this concept was disproved, and light was then thought to be a wave. Upon further experimentation, the wave theory of light by itself could not explain other properties of light such as the spectral distribution of incandescent sources. Both of these concepts were inadequate for describing the newly discovered properties of light.

One of the first modern breakthroughs in understanding the nature of light was by Max Plank. Plank developed an empirical equation for describing the spectral distribution of radiation emitted by a blackbody radiator. This equation is shown in equation1 (ref. 6):

$$L = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda kT}}-1\right)} \quad (1)$$

Where L is the radiance, h is Plank's constant, c is the speed of light, T is the temperature, λ is the wavelength, and k is the Boltzman constant. This equation can be used to show the spectral distribution of energy for a given wavelength and temperature. In developing this equation, Plank had to make some radical assumptions (for that time). For energy to be emitted from a blackbody radiator, the atoms (treated as oscillators) could only emit energy in multiple of nh*f*, where n is a quantum number, and *f* is the frequency of the oscillator. The energies of the oscillator are quantized and can only emit energy when moving from one quantum state to another. The oscillators can only emit or absorb energy in discrete quanta (photons). This lead to the radical thought that the photons can only have energies of h*f* when the oscillators move between two quantum states. Plank found this concept difficult and did not fully accept the concept of quantization of photons and searched for a different explanation. Physicists during this time continued their research on light emission, as quantum theory was the only way to explain these effects at the atomic level.

The photoelectric effect, originally discovered by Hertz, is a classic experiment that finally showed the energy of a photon is not only quantized, but that the energy of a photon is related to its frequency and not to its intensity. In this experiment, a metal cathode is placed within an evacuated tube together with an anode, and a potential voltage is applied between the two electrodes. When light strikes the metal plate (with the correct frequency), photoelectrons are ejected from the metal surface and collected by the positively charged anode. Photoelectrons are only ejected from the photocathode when the energy of the incident light exceeds the cutoff frequency of the metal[1]. If the intensity of light is increased, the number of photoelectrons increases but not the energy of the photoelectron.

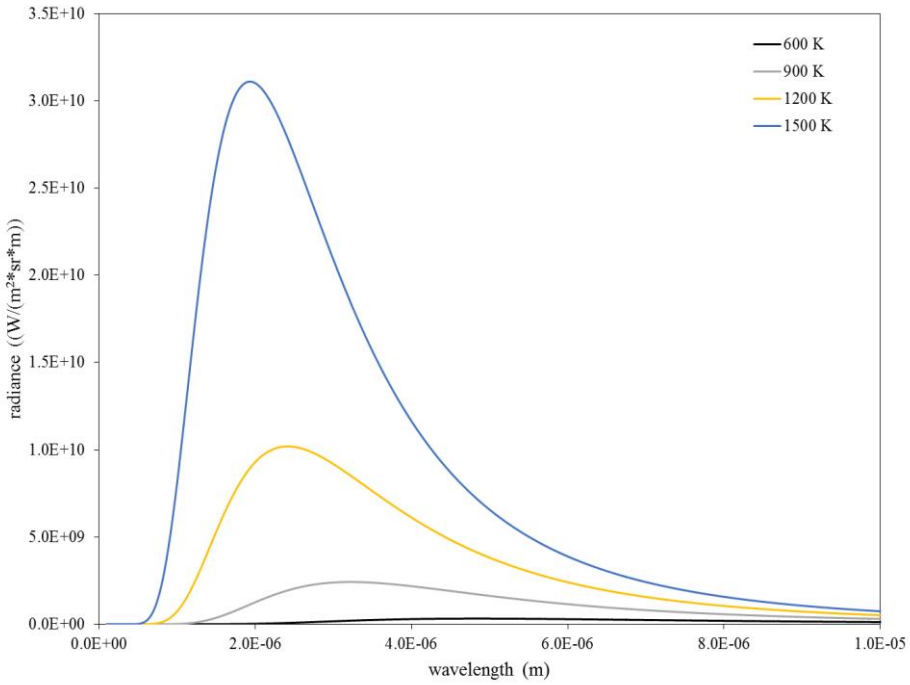
Einstein's paper (written in 1905) finally explained the reason for these observations. He used the concepts originally developed by Plank and applied them to electromagnetic waves and hypothesized that light is composed of quantized energy packets (called photons) with energy E=h*f* (h is Plank's constant and *f* is frequency). He reasoned that the energy of the ejected photoelectron must be equal to the energy of the incoming photon. If the energy of the photon is less than the cut-off frequency of the metal, then a photoelectron is not emitted from the metal cathode.

[1] Actually, the kinetic energy of the ejected photoelectron is slightly less due to the energy needed to overcome the surface energy of the metal (called the work function).

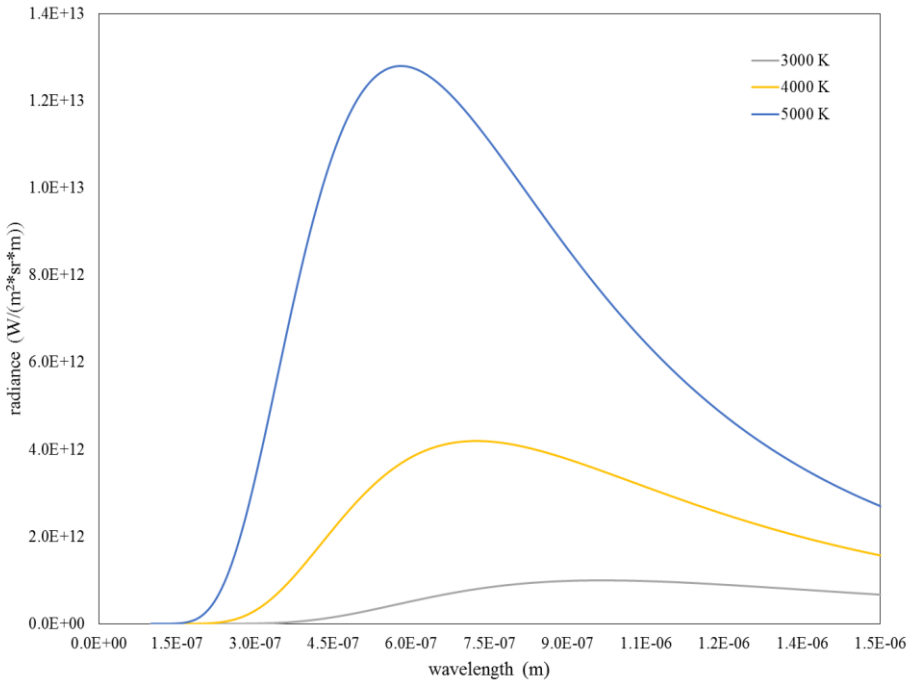
How does this relate to light produced during high temperature chemical reactions? Plank's law will be used to show how white light is produced for high temperature combustion reactions. Colored light emission is controlled by discrete atomic and/or molecular transitions. Depending on the reaction temperature and formulation, one can produce either white light or colored light. In the next section, how light is produced in pyrotechnic formulations will be covered.

Colored and White Light Production in Pyrotechnics

In general, pyrotechnic systems can emit light by two different mechanisms: broadband emissions and atomic/molecular emissions. Broadband light emissions are produced when hot particles are rapidly heated to high temperatures. As particles are heated, they first begin to produce infrared light (low temperature) followed by visible light (high temperatures). The spectral emission emanating from hot particles (as a function of temperature) can be predicted with Plank's law (eq. 1). For example, figures 1a and 1b show the spectral radiance for low temperature sources (fig. 1a) and high temperature sources (fig. 1b). As can be seen from figure 1, as the temperature increases, the maximum emission wavelength shifts to shorter wavelengths. The intensity (or radiance) will exponentially increase as the temperature increases.



(a)
Radiance of low temperatures

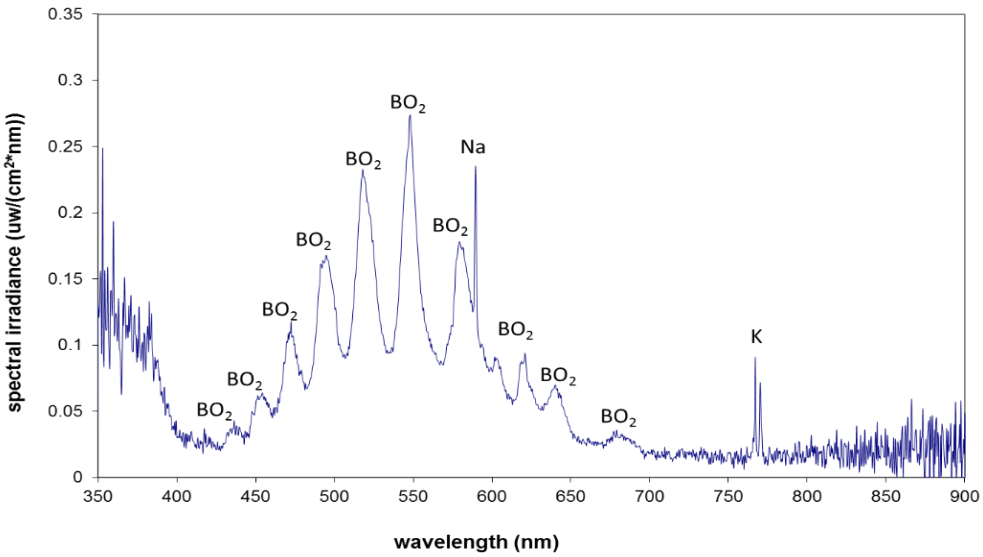


(b)
Radiance of high temperatures

Figure 1
Radiance calculated with Plank's law

Incandescent particles produced during combustion are broadband emitters and can be used to produce white light. For example, pyrotechnic compositions containing magnesium can be used to produce white light since the oxidation of magnesium to magnesium oxide (MgO) liberates a considerable amount of energy, helping to increase the overall temperature of the reaction. To produce white light, adiabatic flame temperatures in excess of 3,000°C are required (ref. 7). When zirconium metals are combined with oxidizers, brilliant white light can be produced with adiabatic temperatures around 5,000°C.

However, colored light emission is more complicated. In combustion reactions, there are essentially two ways to produce colored light: atomic emitters and molecular emitters. Atomic emitters have very sharp spectral emissions that are due to distinct atomic transitions between energy states. When an electron drops from a high energy state to a lower energy state, a photon is emitted. A good example of an elemental emitter is sodium, which is commonly found as an impurity in pyrotechnic oxidizers (i.e., KNO_3 and $BaNO_3$) and also as the oxidizer $NaNO_3$ (yellow light emitters). Sodium has a sharp spectral emission line at 589 nm. The more common colored emitters in pyrotechnics are molecular emitters. These emitters are more complex due to overlapping rotational and vibrational bands created when the molecular emitters are “energized” during combustion. The spectral emission lines from these emitters are significantly broader than the atomic emitters. In figure 2, a spectral emission curve is shown for MgB_2 based green light emitting composition (ref. 8). The molecular emitter BO_2 has broader spectral lines than both the elemental Na and K atomic emitters. Other common molecular emitters are SrCl (red) and BaCl (green).



Note: The width difference between the BO_2 lines and the Na and K lines.

Figure 2
Spectral emissions produced by an MgB_2 based green light emitting composition

The production of colored light generally requires high temperatures to energize the system and to produce the emitting species in sufficient quantity. Incandescent emission must be minimized since broadband light emission can “poison” colored light production by making the resulting color appear washed out. Control of impurities, such as sodium, is also critical for producing vibrant colors since unwanted light emission can alter the desired emitted color by the introduction of unwanted emission lines.

RADIOMETRY

Introduction

One of the most critical aspects in making good light measurements is an understanding of radiometry. Radiometry is defined as the measurement of optical radiant energy (ref. 3). Knowing 5the difference between radiometric units and being able to relate this to the fundamental equation of radiometry makes setting up measurements simple and will enable the user to make quality measurements. Some important concepts should be considered before getting to the fundamental equation of radiometry.

The first concept is the solid angle. The solid angle is defined as the angle that is located at the center of the sphere, and its area is equal to the square of the radius. The area of the sphere that is subtended by the angle is a hemispherical cap of a sphere (ref. 9). Because most pyrotechnic light measurements involve detector-source distances that are far enough to enable the use of the point source approximation, the planar surface area is safely used instead of the spherical surface area (ref. 10). The equation for the solid angle (using the point source approximation) is defined as:

$$\omega = \frac{A}{d^2} \tag{2}$$

where ω is the solid angle, A is the area of the source (or detector), and d is the distance between the detector and the source. The unit of the solid angle is the steradian, and it is unitless. When calculating the solid angle, make sure that the area and distance are in the same units.

The most basic optical measurement that a person can make is an irradiance measurement. Irradiance is defined as the power per unit area striking a surface and is defined as:

$$E = \frac{\vartheta}{A} \tag{3}$$

where E is irradiance (W/m^2), ϑ is the power, and A is the area. One of the key aspects of irradiance is that its value falls off with the distance squared (if the distance is large enough). This statement leads to an important point. In order to use the inverse square approximation, the distance must be at least 10 times the maximum radius of the source (ref. 10). Irradiance measurements are usually converted into other units such as radiant intensity or radiance. If given the irradiance of a pyrotechnic light source, it is important to obtain the distance the measurement was taken. Otherwise, making irradiance measurements at different distances will lead to different answers.

Another way to describe a light source is its radiant intensity. Radiant intensity is defined as the power per unit solid angle (in a specific direction). The equation that describes the radiant intensity is given as:

$$I = Ed^2 \tag{4}$$

where I is the radiant intensity (W/sr), E is the irradiance as defined in equation 3, and d is the distance between the source and the detector. Upon inspection, it becomes apparent as to why radiant intensity is the preferred way to report the level of light emitted by a source. If one measures the same light source at two different distances, they will get the same radiant intensity. Most pyrotechnic light measurements call for measuring the radiant intensity of a source. But this measurement still lacks one physical characteristic of the source: flame area.

The radiance of a source is defined as the flux per unit solid angle per unit area. This is perhaps the most descriptive measurement of a source but also the most difficult to measure since

one has to measure both the source area and the detector irradiance at the same time. Radiance is a fairly descriptive measurement of the source since it incorporates the area of the source as well as the distance from the detector[2]. Often when measuring the radiant intensity, there are small perturbations, or fluctuations, in the area of the flame that manifest themselves as oscillations in radiant intensity. This is caused by small changes in the area of the flame that become apparent in the radiant intensity measurement but not in the radiance measurement. The formula for radiance is:

$$L = \frac{I}{A} \tag{5}$$

where L is the radiance [W/(m^2*sr)], I is the intensity, and A is the area. Table 1 shows the major radiometric quantity units with their base equations and units.

Table 1
List of radiometric quantities and their units

Radiometric unit	Equation	Units
Irradiance	$E = \frac{\vartheta}{A}$	W/m^2
Radiant intensity	$I = Ed^2$	W/sr
Radiance	$L = \frac{I}{A}$	W/(sr$*$m^2)

One of the most important equations is the fundamental equation of radiometry. The equation is defined as:

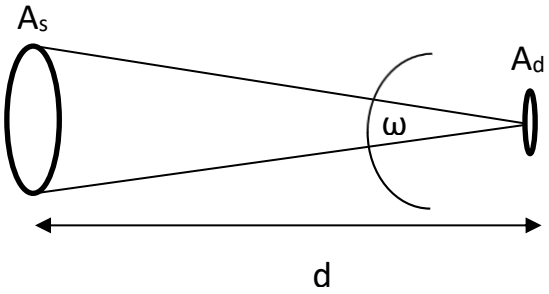
$$\vartheta = LA\omega \tag{6}$$

where the variables have been described in equations 3 through 5. The use of this equation assumes that the source is a point source and that the distance is large enough that the inverse square law applies to the measurement. This equation also assumes that the source and detector are perpendicular to each other. If the detector, or source, are at an angle, then angular effects must be considered.

Figure 3 shows a radiometric diagram that describes most pyrotechnic measurements. The source (area is A_s) subtends a solid angle with the detector, represented by ω, of A_s/d^2. Using equation 5 and inserting the constants from Figure 3:

$$\vartheta_d = L_s A_d \frac{A_s}{d^2} \tag{7}$$

[2] There are optical detectors that are designed to measure radiance directly. These detectors have very narrow field of view (FOV) optics that are basically overfilled by the source. This kind of measurement is limited to measuring the light output from a small area relative to the entire event.



Note: Subscript s represents the source, and d represents the detector.

Figure 3
Radiometric diagram showing the relationship between the source (A_s), detector (A_d), distance between the source and detector (d), and the solid angle (ω)

For example, using equation 2, the irradiance at the detector is given by equation 8:

$$E_d = L_s \frac{A_s}{d^2} \tag{8}$$

where E_d is given as ϑ_d / A_d. Using equation 6, one can easily calculate different radiometric quantities. For example, a distance can be calculated to ensure that source-detector distance is adequate to prevent bright sources from saturating the measurement system. Working backward with equation 6, one can calculate the radiance of a source from a given detector irradiance.

Photometry

The eye, which is composed of many intricate parts, dynamically adapts to the light level, thus enabling the ability to see both during the day and at night. By use of the different parts of the eye and its refractive properties, the eye is able to focus the light coming from different distances onto the retina. Color and light sensitivity is controlled by the rod and cone cells that reside on the retina. The eye has about 6.8 million cones that are primarily active during the daytime and are responsible for color acuity (ref. 11). There are three different kinds of cone cells, each active over a specific range of wavelengths[3]. The cones reside primarily in the center of the eye and enable people to see color during the day. The eye contains 115 million rod cells that enable low light peripheral nighttime vision. Due to the off-center location of the rod cells, objects viewed at night are best viewed peripherally and not viewed directly. At low light levels (night), it is not possible to sense color since the rods contain a single pigment that is only sensitive to relative light levels.

While radiometric measurements measure absolute power (either at specific wavelengths or over a range of wavelengths), photometry is focused on how the human eye interacts with light. Depending on the relative light level, the spectral sensitivity of the eye changes due the chemical activity of the cones and rods. The eye's daytime response to light is described by the photopic luminosity function, and the nighttime response is described by the scotopic luminosity function. The eye's peak spectral response in daytime occurs at 555 nm, while the peak response shifts to the blue and peaks at 507 nm at night. Both luminosity functions are shown in figure 4.

[3] The cone cells are classified as short wavelength sensitivity, mid-wavelength sensitivity, and long wavelength sensitivity.

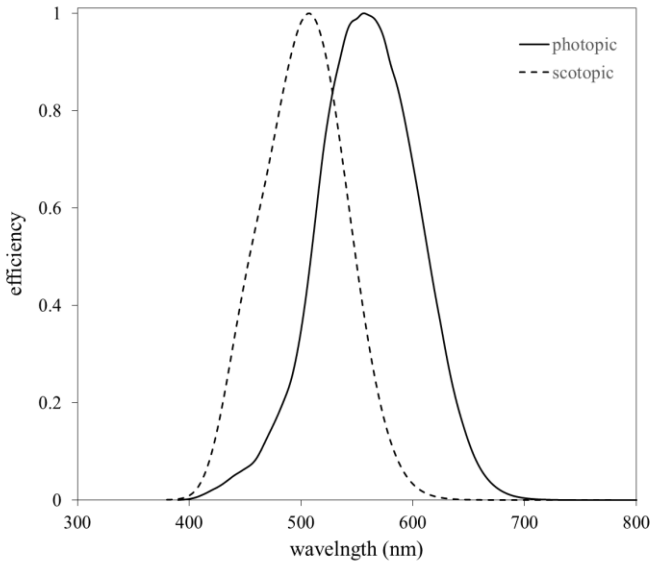


Figure 4
Efficiency versus wavelength for photopic and scotopic luminosity functions

To convert radiometric spectral measurements to photometric measurements, the following equation is used[4]:

$$\emptyset = 683 \frac{lm}{w} \int_{380}^{780} V(\lambda)\, \vartheta(\lambda) d\lambda \tag{9}$$

where V(λ) is the weighing function (photopic or scotopic) and $\vartheta(\lambda)$ is the radiant power. A new unit, luminous power ($\emptyset$), is defined to distinguish it from radiometric power[5]. The geometric definitions that were discussed for radiometric quantities are exactly the same for photometry, except they have new units to distinguish from their radiometric counterparts. Table 2 shows the new photometric units alongside their corresponding radiometric units.

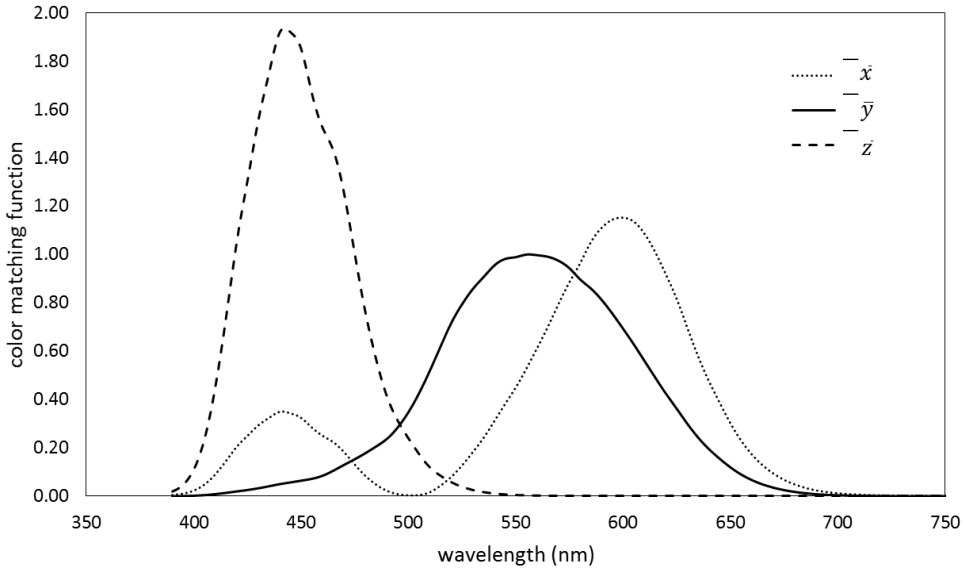
Table 2
Comparison of radiometric units to photometric units

	Radiometric		*Photometric*	
Quantity	Term	Unit	Term	Unit
Power	Radiant power	W	Luminous power	lm
Power per unit area	Irradiance	W/m^2	Illuminance	lm/m^2
Power per unit solid angle	Radiant intensity	W/sr	Luminous intensity	lm/sr
Power per unit solid angle per unit area	Radiance	$W/(m^2{*}sr)$	Luminance	$lm/(m^2{*}sr)$

[4] The limits of the integral are the photopic wavelength range of 380 to 780 nm.
[5] To calculate scotopic power, replace the photometric constant of 683 lm/w with 1,700 lm/watt and substitute the scotopic weighting function in equation 9.

Color Measurements

In the early 1920s, attempts were made to understand how humans perceive color. In 1931, the Commission International de L'Eclairage (CIE) developed standards by which color can be measured and defined. Three different tristimulus curves (X, Y, and Z), based on the relative response of the eye's cones (known at that time), were devised. The chromaticity coordinates were then developed so all visible colors can be represented by two coordinates (x,y). In the 1970s, researchers found that the 1931 CIE system biased the eye response to green and less to red, so attempts were made to correct the issues with this system, and a new standard, the 1976 CIE standard, was developed but was never adopted. The 1931 CIE standard remains the methodology to which emissive colors are quantified (ref. 12). Figure 5 shows the functions that will be used to setup the integrals for the tristimulus equations and used to form the expressions for both the dominant wavelength and spectral purity.



Note: Data taken from the Color Vision Research Laboratory (ref. 13).

Figure 5
Comparison of the three color matching function

For self-luminous light sources (i.e., pyrotechnics), the equations that are used to define the three different tristimulus value (capital X, Y, and Z) are given as:

$$\mathrm{X} = k \int_{380}^{780} \vartheta(\lambda)\bar{x}(\lambda)d\lambda \tag{10}$$

$$\mathrm{Y} = k \int_{380}^{780} \vartheta(\lambda)\bar{y}(\lambda)d\lambda \tag{11}$$

$$\mathrm{Z} = k \int_{380}^{780} \vartheta(\lambda)\bar{z}(\lambda)d\lambda \tag{12}$$

where $\bar{x}, \bar{y}, \text{and } \bar{z}$ are the color matching functions, k is the radiant to luminous conversion factor (683 lm/w), and $\vartheta(\lambda)$ is the radiometric power. The equations for the chromaticity coordinates (lower case x, y, and z) are given in equations 13 to 15.

$$x = \frac{\mathrm{X}}{\mathrm{X+Y+Z}} \tag{13}$$

$$y = \frac{\mathrm{Y}}{\mathrm{X+Y+Z}} \tag{14}$$

$$z = \frac{\mathrm{Z}}{\mathrm{X+Y+Z}} \tag{15}$$

The CIE developed the chromaticity curve that is currently used to determine the dominant wavelength and spectral purity of luminous sources (fig. 6). The colors represent the luminous colors for given combinations of x and y. For illustrative purposes, the white reference point is located at point A, and the chromaticity coordinates of a hypothetical light source is located at point B. The white reference at point A can be one of a number of white reference points such as Illuminant B or C, depending on the objective of the measurement.

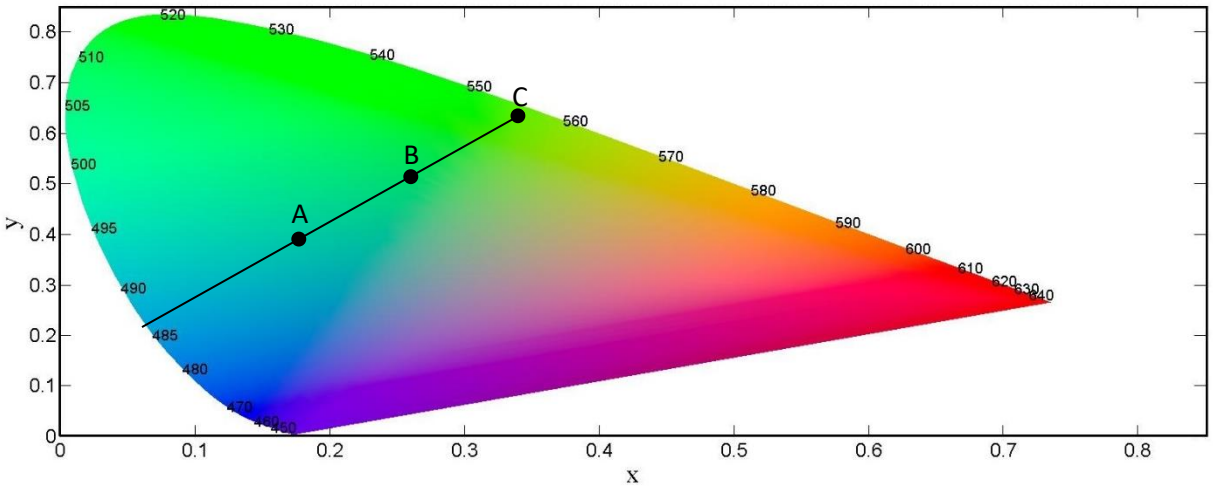


Figure 6
Chromaticity diagram showing dominant wavelengths

When defining the emissive color of a source, there must always be a white reference point in the chromaticity diagram. There are many white reference points, and one selects an appropriate reference point for their intended application. For example, comparison of a light source to a tungsten filament is best represented by illuminant A since it is modeled to resemble a Planckian radiator at 2856 K (ref. 11). To compare light sources to natural daylight, illuminants B and C are used[6].

Luminous light sources often emit over a range of wavelengths. The dominant wavelength is the single wavelength that gives the same visual response as this wavelength combined with an achromatic light source emitting over a range of wavelengths. The spectral purity is a measure of how close the dominant wavelength is to its monochromatic equivalent. For example, a red light emitter with a spectral purity of 90% will appear very pure as compared to a red light source with a spectral purity of 40%. Light sources with high levels of incandescent emitters typically have low spectral purities and appear washed out or faded to the eye.

In figure 6, the white reference point is located at A. To calculate the dominant wavelength, a line is drawn through the white point and through the measured light source. The intersection of the line with the outer part of the curve is the dominant wavelength. In this example, the intersection is indicated by point C and is located at 555 nm. The spectral purity is calculated by taking the length of

[6] The U.S. Army color specifications specify illuminant C as the white reference point.

the line segment from the white point to the coordinates of the light source at B and dividing it by the entire line segment AC. The spectral purity is calculated by the following expression:

$$spectral\ purity = \frac{length\ of\ AB}{length\ of\ AC} \tag{16}$$

Spectral purity can be reported either as a fraction or a percentage.

PERFORMING A MEASUREMENT

Equipment Considerations

The final part of this paper will discuss selecting equipment and setting up an actual measurement. Selecting the proper detector(s) for the desired wavelength range is very important. Considerations such as expected signal levels, cooled versus uncooled detectors (critical for infrared measurements), optics for controlling the field of view (FOV), and data acquisition systems are all variables that need to be considered when designing a measurement system. One of the first design considerations is what part of the spectrum is to be measured? Table 3 shows the wavelength range for several commercially available detectors. One interesting point to make is that infrared detectors almost always require external cooling to reduce thermal noise and to enhance performance. Another consideration is photovoltaic versus photoconductive detectors (ref. 14). Photovoltaic detectors are unbiased and generate a linear change in output current with incident light[7]. Photoconductive detectors are reversed biased (voltage applied across the cathode and anode), and the incident light changes the detector's resistance.

Table 3
List of several commercially available photodetectors and their mode of operation and wavelength range

Detector	Wavelength range (μm)	Cooled or uncooled	Photovoltaic or photoconductive
Silicon (Si)	0.190 to 1.1	Uncooled	Photovoltaic
Indium gallium arsenide (InGaAs)	0.8 to 2.6	Either	Photovoltaic
Lead selenide (PbSe) and lead sulfide (PbS)	1.0 to 4.8	Cooled	Photoconductive
Mercury cadmium telluride (HgCdTe)	0.4 to 14	Cooled	Either[8]
Indium antimonide (InSb)	1.0 to 5.0	Cooled	Photovoltaic

Measurement systems based on photovoltaic detectors are easy to set up. A simple photovoltaic-based measurement system consists of a detector connected to an amplifier that converts current to voltage (i.e., transimpedance amplifier). This enables the user to select the

[7] Photoconductive detectors are biased by applying a reverse voltage across the P-N junction of the detector.
[8] HgCdTe detectors can be doped to modify their bandgap, changing their spectral response and mode of operation from photoconductive to photovoltaic. Photoconductive and photovoltaic HgCdTe detectors are commercially available.

appropriate gain level for the desired measurement. Photoconductive detectors require the use of a light chopper (to modulate the incident light) and lock-in amplifier to extract the light level from the chopped light signal[9]. These measurement systems are more difficult to set up and are more expensive due to the extra electronics. Extra care is needed to select the correct chopping frequency to match the desired data collection rate.

The type of measurement will dictate if a banded measurement or a spectroscopic measurement will be needed. Banded measurements involve putting a filter in front of the single element detector to select the bandpass of the desired region of interest. For example, if the photometric response of a light source is desired, then a photometric filter will be placed in front of the detector. Both the filter and detector are calibrated as a single unit. If a spectrum is desired (energy versus wavelength), then a grating-based charge coupled device (CCD) spectrometer can be used for this measurement. Typical universal serial bus (USB) powered units are available with 2048 or 3648 pixels. Care must be taken to select CCDs that are linear with light level for the desired integration time. Some CCDs exhibit nonlinear behavior with low integration times (for fast measurements).

Another aspect to selecting a detector is the FOV. The FOV can be defined as the angular extent to which a luminous object can be measured by the detector. For example, if the FOV of a detector is 30 deg, then the FOV of the detector at 50 ft is ~27 ft in diameter. A schematic of this is shown in figure 7 for a hypothetical InSb detector with a 30-deg FOV. The FOV definition brings up an important point. When designing a measurement, the luminous object to be measured must be smaller than the detector's FOV. If the object exceeds the FOV, then part of the energy being emitted by the object is not being captured by the optical detector and is lost.

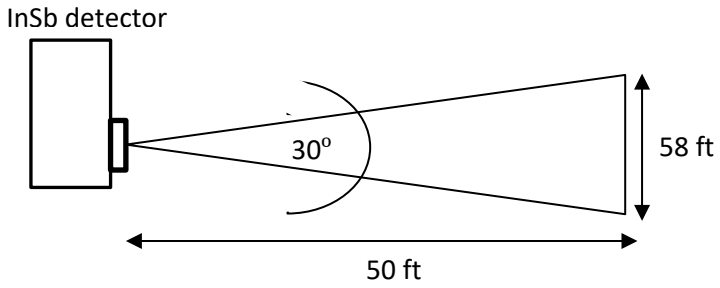


Figure 7
Schematic of the FOV for a hypothetical InSb detector

The method of data collection is yet another important aspect in the design of a measurement system. Almost all modern measurement systems are designed to take an analog signal and digitize it for collection and processing by a computer. Data acquisition cards are available with different data collection rates and different levels of precision. For example, 12 and 16-bit data cards with a wide range of data collection rates are commercially available. In general, the length of the event will dictate the data rate needed to capture the measurement. If one is measuring an illuminant candle that burns for 50 sec, then selecting a very high data collection rate is unnecessary since this will result in an extremely large data file. Conversely, measuring a fast event, like a flash, will require a fast data rate to capture the event. The voltage resolution of the signal is important because the higher the resolution, the greater the fidelity of the signal. For example, if a 16-bit data card with a voltage range ±10V is used to collect a signal, then the smallest change that can be detected is 305 μV (20/65,536). For a 12-bit data card, the minimum variation will be 5 mV.

[9] A light chopper is a spoked wheel that spins at a preset frequency. The incident light is modulated at this spin frequency, and the lock-in amplifier extracts the light level at this frequency.

Setting up a Measurement

When setting up a measurement, it is critical that certain aspects of the measurement be understood to best select the proper equipment and measurement distance. Having an idea of the source intensity is always a good idea since this can be used to initially select the amplifier gain level (or integration time for spectrometers) so that the signal stays within the measurement (voltage) range of system. If the signal exceeds the upper voltage limit of the system, then it is saturated, and the data is effectively "lost" since the true intensity of the source is not known. Likewise, if the signal is too low, it will be dominated by noise and contain very little information. Knowing the diameter of the flame (or fireball) helps to set the correct distance to ensure the measurement meets the requirement of the inverse square law. Knowing the fireball diameter is also critical to ensure that the entire flame front is being measured and does not exceed the FOV of the detector at the measurement distance.

Another very important point is to ensure that the detector is perpendicular to the source. If the detector is placed on an angle to the source, then the signal will be decreased by the cosine of the angle. Not being aware of the angle of the detector relative to the source will also introduce errors since the angle will not be able to be reproduced when the equipment needs to be set up for additional measurements.

CONCLUSIONS

Performing good repeatable light measurements is not difficult if one understands the basics of radiometry and how to set up a good measurement. A working knowledge of the emission source (output and flame front diameter), measurement equipment, and intent of the measurement is critical to getting good measurements. In this paper, the basics of radiometry, photometry, color measurements, and equipment selection were discussed. Several references are included in this paper for readers who are interested in learning more about light emission and optical measurements.

REFERENCES

1. Williams, B., A history of light and lighting, Retrieved from http://www.mts.net/~william5/history/hol.htm, 1999.

2. History of Candles, Retrieved from National Candle Association, http://candles.org/history/, n.d.

3. Palmer, J., “Introduction to Radiometry,” in J. Palmer, The Art of Radiometry, pp. 4 to 5, SPIE Press, 2010.

4. National Instruments Corporation, Retrieved from Wikipedia, https://en.m.wikipedia.org/wiki/National_Instruments#Electronics_Workbench_Group, 2016.

5. Serway, R., “Physics for Scientist and Engineers,” New York: CBS College Publishing, 1983.

6. Woan, G., “The Cambridge Handbook of Physics Formulas,” Cambridge: Cambridge University Press, 2000.

7. Conkling, J.A., “Chemistry of Pyrotechnics,” Boca Raton: CRC Press, 2011.

8. Brusnahan, J.S., “Use of Magnesium Diboride as a ‘Green’ Fuel for Green Illuminants,” ACS Sustainable Chem. Eng., 1827–1833, 2016.

9. Moller, K.D., “Optics,” Mill Vallay: University Science Books, 1988.

10. Ryder, A., “Light Measurement Handbook,” Newburyport: International Light, 1998.

11. Schanda, J., “Colormetry,” In C. DeCusatis, Handbook of Applied Photometry, pp. 327-406, Woodbury: Amician Institute of Physics, 1997.

12. Some Color History, Retrieved from Hyperphysics, http://hyperphysics.phyastr.gsu.edu/hbase/vision/colhist.html, 2016.

13. London, U.C., “Color Matching Functions,” Retrieved from Color and Vision Research Laboratory, http://cvrl.ioo.ucl.ac.uk/, 2016.

14. Saleh, B., “Fundamentals of Photonics,” New York: John Wiley and Sons, 1994.

DISTRIBUTION LIST

U.S. Army CCDC Armaments Center
ATTN: FCDD-ACE-K
FCDD-ACM-ET, J. Poret
Picatinny Arsenal, NJ 07806-5000

Defense Technical Information Center (DTIC)
ATTN: Accessions Division
8725 John J. Kingman Road, Ste 0944
Fort Belvoir, VA 22060-6218

GIDEP Operations Center
P.O. Box 8000
Corona, CA 91718-8000
gidep@gidep.org

REVIEW AND APPROVAL OF ARDEC TECHNICAL REPORTS

Introduction to Pyrotechnic Light Measurements
Title

Date received by LCSD

Dr. Jay C. Poret
Author/Project Engineer

Report number (to be assigned by LCSD)

3035 Extension | 3124 Building

RDAR-MEE-T
Author's/Project Engineers Office (Division, Laboratory, Symbol)

PART 1. **Must be signed before the report can be edited.**

a. The draft copy of this report has been reviewed for technical accuracy and is approved for editing.

b. Use Distribution Statement A_X_, B____, C____, D____, E____, F____ or X____ for the reason checked on the continuation of this form. REASON_____

1. If Statement A is selected, the report will be released to the National Technical Information Service (NTIS) for sale to the general public. Only unclassified reports whose distribution is not limited or controlled in any way are released to NTIS.

2. If Statement B, C, D, E, F, or X is selected, the report will be released to the Defense Technical Information Center (DTIC) which will limit distribution according to the conditions indicated in the statement.

c. The distribution list for this report has been reviewed for accuracy and completeness.

James L. Wejsa 7/31/17
Division Chief (Date)

PART 2. To be signed either when draft report is submitted or after review of reproduction copy.

This report is approved for publication.

James L. Wejsa 7/31/17
Division Chief (Date)

RDAR-CIS (Date)

LCSD Form 49, supersedes SMCAR Form 49, 20 Dec 06.