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TEST PROCEDURES FOR FLASH INTENSITY MEASUREMENTS IN THE VISIBLE AND INFRARED SPECTRUM FOR SMALL ARMS

Edition A, Version 1

AUGUST 2021

NORTH ATLANTIC TREATY ORGANIZATION

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NATO LETTER OF PROMULGATION

30 August 2021

1. The enclosed Allied ENGINEERING Publication AEP-4785, Volume II, Edition A, Version 1, TEST PROCEDURES FOR FLASH INTENSITY MEASUREMENTS IN THE VISIBLE AND INFRARED SPECTRUM FOR SMALL ARMS, which has been approved by the nations in the NATO ARMY ARMAMENTS GROUP (NAAG), is promulgated herewith. The recommendation of nations to use this publication is recorded in STANREC 4785.

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CHAPTER	RECORD OF RESERVATION BY NATIONS
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RECORD OF SPECIFIC RESERVATIONS

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CHAPTER - 1 INTRODUCTION

1.1. INTRODUCTION

1. The objective of this section is to provide a testing protocol for the quantitative characterization in multiple spectral bands of flash produced when small arms are fired. These procedures have been developed with an emphasis on suppressed weapons, but they are equally applicable for characterization of flash from unsuppressed weapons. This test method describes procedures for determining the luminous energy of a visible flash by integrating its luminous intensity over its duration. For non-visible spectral bands, radiant energies are similarly determined by integrating their in-band radiant intensity over their duration. Instrumentation, data collection procedures, calibration procedures, and data reporting requirements are described herein.

1.2. BACKGROUND

1. Weapon flash, or simply flash, is commonly defined as electromagnetic radiation emitted as hot propellant gases exit the weapon.

2. Flash is most commonly produced at the muzzle, though flash from the gas system, ejection port, or other parts of the weapon may also be apparent. In the simplest case, hot propellant gasses will emit a faint glow within a few centimeters of the barrel as the projectile exits the weapon. These emissions are referred to as primary or intermediate flashes. In other circumstances, the propellant gasses can be ignited after they have left the barrel and mixed with atmospheric oxygen. This is referred to as a "secondary" flash, and is typically much more intense than a primary or intermediate flash (Figure 1). Further discussions of flash mechanisms may be found in Annex A.

3. Flash may be measured for a variety of reasons, including but not limited to: location and/or identification of a weapon on the battlefield, assessment of the potential to temporarily inhibit sensor performance, assessment of suppressor designs, and performance assessment of ammunition-based flash suppression.

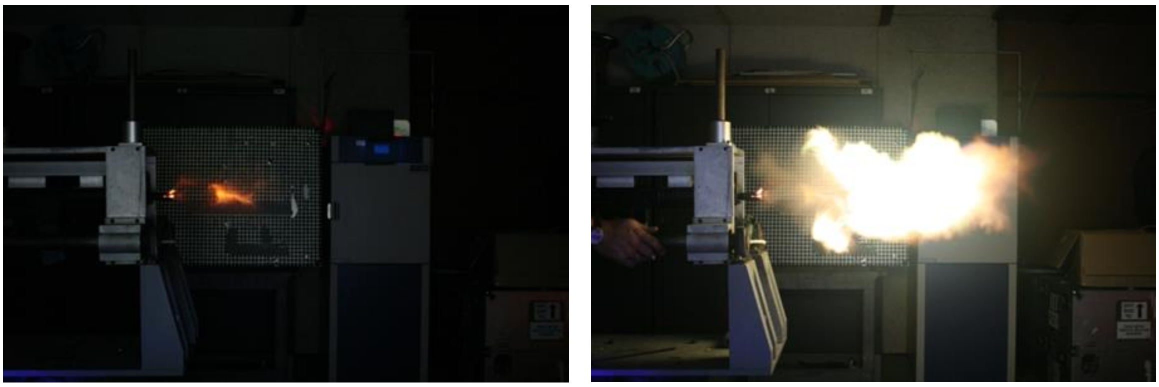

Figure 1 Visible flash intensity variability. Primary and intermediate flash (left) is typically less intense than secondary flash (right).

4. Both radiometric (pertaining to the measurement of electromagnetic radiation) and photometric (pertaining to the measurement of visible light) terms have been used throughout this document. Just as visible light is a subset of the electromagnetic radiation spectrum, photometry is a subset of radiometry, therefore most of the concepts and quantities in photometry have a radiometric counterpart. As a result, two different terms may be used to describe similar concepts or quantities depending on the spectral region of interest. Radiometric terms used herein will have a base of "radiant" or "radiance" and their symbols are denoted with a subscript "e" for "energetic". Photometric terms will have a base of "luminous" or "luminance" and their terms are denoted with a subscript "v" for "visible". The radiometric and photometric terms used in this document are listed in Annex B with their symbols and definitions.

5. This method determines the luminous energy (Q_v) and radiant energies (Q_e) that are emitted by a flash ~5° from the weapon's line of fire.

a. The detection angle of ~5° was selected to approximate the view of the flash as will be seen by an adversary without placing instrumentation at risk of accidental bullet impact.

b. Q_v and Q_e were selected as metrics of visible and invisible flash intensities for several reasons:

(1) Q_v is proportional to the brightness of a flash perceived by the eye. Primary and intermediate flashes are typically less than a millisecond in duration, and secondary flashes typically range from 1-10 milliseconds. Over these timeframes, the human eye will perceive brightness as being proportional to the total luminous energy of a flash[1]. As a result, the metric of luminous intensity (I_v, typically reported in candela) that is typically used to describe the intensity of steady-state light sources is not sufficient to describe perceived flash intensity since it does not include a time component. To illustrate this, Figure 2 shows two possible flashes: Flash 1 (blue, solid line) has twice the peak luminous intensity of Flash 2 (red, dashed line) but a shorter duration. By integrating luminous intensity with respect to time for the duration of the flashes, the luminous energy emitted during each event can be calculated. The results of these calculations (Table 1) show that Flash 2 has almost 10 times the energy of Flash 1, despite its lower peak intensity. If peak luminous intensity was used as a metric for flash intensity, it would incorrectly predict that Flash 1 would appear to be the "brighter" flash.

[1] The relative perceived brightness of photons having different colors or wavelengths is described by the photopic response function that is illustrated in Annex B.

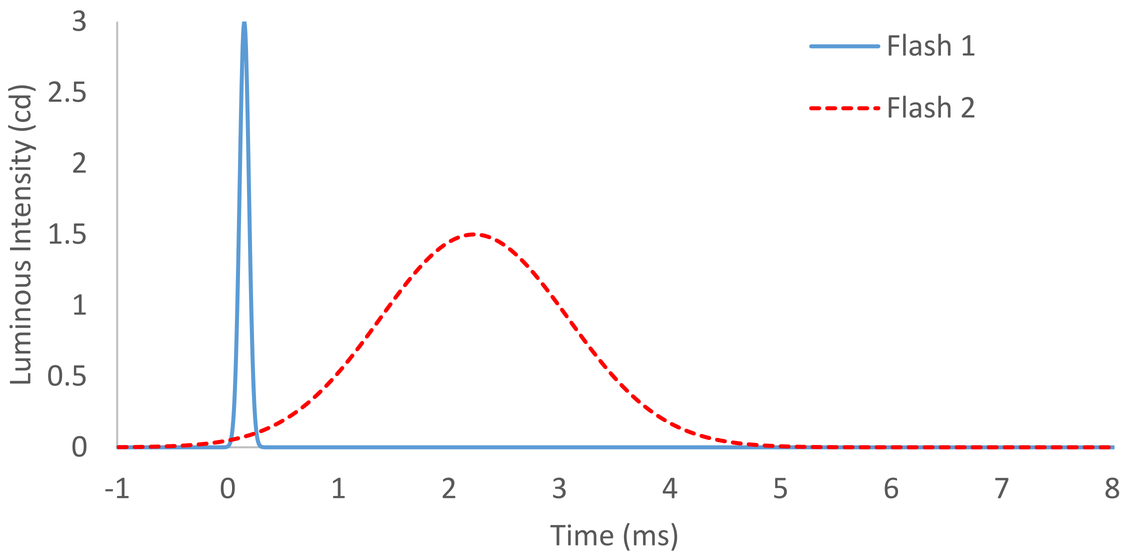

Figure 2 Illustration of two flashes with different peak luminous intensities and durations. The flash with the highest peak luminous intensity may not necessarily be easiest to see or detect.

Table 1 Peak luminous intensities and luminous energies for flashes illustrated in Figure 2.

	Peak Luminous Intensity (cd)	Luminous Energy (cd × s)
Flash 1	3	0.32
Flash 2	1	3.19

(2) Q_e and Q_v are proportional to flash detectability by most sensors. Each image/frame recorded by a typical camera is generated by integrating the detector response over the duration of exposure. For a camera with an exposure time greater than a few milliseconds or a frame rate slower than 100 Hz, the flash will usually only be recorded by one frame. The practical result is that luminous or radiant energy values are proportional to the maximum signal that most sensors will detect from a single flash.

(3) Q_e and Q_v are independent of the distance at which measurements are made. Radiometers and photometers inherently respond to changes in irradiance (E_e) and illuminance (E_v) respectively at their detectors[2]; however, the values of E_e and E_v for a given flash will vary depending on the distance between the flash and the radiometer.

[2] This is the reason that most photometers are calibrated in units of Lux.

This is because E_e and E_v describe the power per unit area that an emissive source projects onto a surface. Since the area of a detector is fixed, the power projected onto the detector by a flash is inversely proportional to the square of the distance between the flash and detector. To illustrate this, consider that the number of photons (and therefore the power) projected within a solid angle θ is constant as those photons move away from a radiant source, but the area over which they are projected changes proportionally to the square of the distance between the source and the projection surface (Figure 3). Similarly, both E_e and E_v are inversely proportional to the square of the distance between the source and the surface (Equation 1).

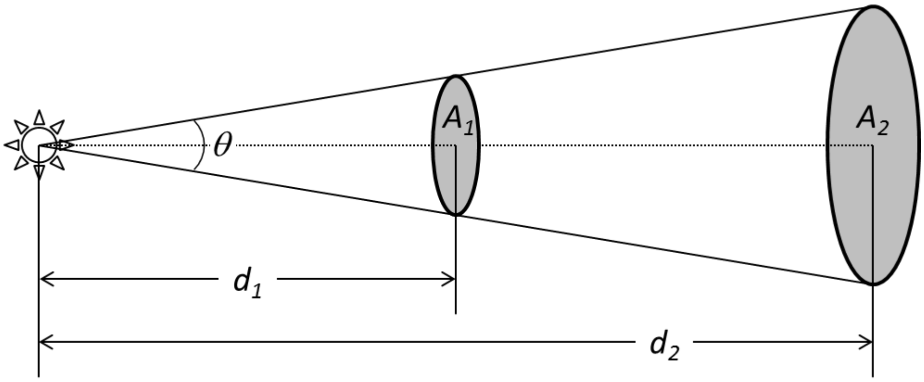

Figure 3 The area (A) over which photons within a solid angle θ are projected in proportional to the square of the distance (d) between the source and the projection surface.

$$E_2 = E_1 \times \frac{{d_1}^2}{{d_2}^2} \qquad \text{Eq 1.}$$

c. Units of millicandela seconds (mcd × s) and millijoules per steradian (mJ/sr) have been selected for reporting luminous and radiant energies respectively for two primary reasons:

(1) Flashes can act as highly directional emitters: their radiant intensities can change drastically as the angular position relative to the weapon changes. As a result, the more commonly used units for luminous and radiant energies of lumen seconds (lm × s) and Joules (J) were not used since these units describe the total energy emitted in all directions, and do not allow angular specificity.

(2) The luminous energies for most small arms flashes are on the order of mcd × s. Similarly, for most infrared bands of interest, small arms flashes are on the order of mJ/sr. For the NIR band, flashes are typically on the order of microjoules per steradian (μJ/sr), and should be reported as such.

d. For high-speed (>1000 kHz) cameras and sensors, luminous or radiant intensity may be the most appropriate metric for determining flash detectability.

Standard methods for reporting and comparing these values is beyond the scope of this document; however, the methodologies described herein for collection and calculation of luminous and radiant intensities during the process of calculating luminous and radiant energies may be used to collect these data.

6. A full explanation of photometry and radiometry is beyond the scope of this document. For additional information, the user is referred to one of the numerous reference works on these topics. The authors of this document have specifically verified that "Introduction to Radiometry and Photometry" by Ross McCluney (1994, ISBN: 0-89006-678-7) contains the pertinent background information related to the concepts referenced herein.

1.3. SCOPE

1. The following procedure is a balance between practicalities ('ease of use') and an acceptable level of error ('completeness').

2. The scope of this test procedure is to specify a method for measurement of the radiant and luminous intensities emitted during a flash as well as the calculations necessary to determine the radiant and luminous energies from those measurements.

3. These radiant and luminous energy values will facilitate quantitative analysis of variations in flash as a result of changes to small arms systems.

4. The procedures prescribed in this document will provide quantitative results which may be used for comparative purposes.

5. Determining visibility thresholds and/or detection metrics is of national interest, and is beyond the scope of this document.

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CHAPTER - 2 TESTING PROTOCOL

2.1. INSTRUMENTATION

1. **Radiometric Instrumentation:** Typical instrumentation used for measurement of luminous and radiant energies is illustrated as a block diagram in Figure 4 and described below:

a. A radiometer or photometer is used to collect photons emitted by the flash and to produce an electrical signal. A photometer is a special type of radiometer that has a spectral response proportional to the photopic response of the human eye, and is only used to measure visible light.

b. The output of the radiometer is amplified and converted from current to voltage using a transimpedance amplifier.

c. The amplified signal is converted into a machine-readable format using an analog-to-digital converter within a data acquisition system.

d. The digitized data is then stored on a computer for processing.

e. Finally, post-processing software is used to calculate luminous or radiant energies of the flash from the raw voltages output by the radiometers.

f. In parallel, long-exposure images of the flash are recorded using digital cameras and stored on the computer. These images are not used for quantitative data analysis, but their collection and reporting is required as part of this procedure.

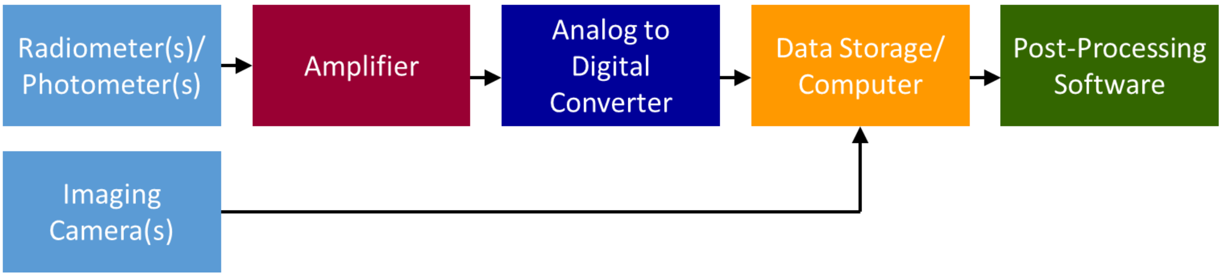

Figure 4 Flash measurement instrumentation block diagram.

2. **Spectral Bands:** The luminous energy (visible) emitted by a flash shall be measured and reported. Measurements and reporting of radiant energies in other bands is a matter of national interest, however, inclusion of near infrared (NIR, 600-900 nm) and short wavelength infrared (SWIR, 900-1700 nm) bands is highly encouraged. Measurements in the midwave infrared (MWIR, 1700-4800 nm) are also encouraged, but may be complicated by the bandwidth, sensitivity, and cooling requirements of many detectors used in this spectral region. These band

recommendations, as well as recommended detector materials and filters, are listed in Table 2. These recommendations are NOT requirements, but are intended to encourage data consistency between measurement laboratories.

Table 2 Recommended radiometer bands and configurations.

Spectral Band	***Wavelength Range (nm)***	***Detector Material***	***Filters***
Visible (Vis)	Photopic*	Silicon	Photopic* filter
Near Infrared (NIR)	600-900	Silicon	600 nm high-pass, 900 nm low-pass
Short Wavelength Infrared (SWIR)	900-1700	InGaAs	900 nm high-pass, 1700 nm low-pass
Mid Wavelength Infrared (MWIR)*	1700-4800**	PbSe, MCT	Various edge filters as appropriate

*The CIE 1931 spectral luminous efficiency function for photopic vision is assumed for photometric measurements unless otherwise indicated.
**MWIR detectors may present bandwidth and sensitivity challenges. The user is encouraged to evaluate their detection requirements and match the radiometric detection system to those requirements.

3. **Bandwidth:** The combined bandwidth of radiometers, amplifiers, and data acquisition hardware should be >10 kHz. Bandwidths >100 kHz are generally achievable, and are preferred when possible.

4. **Data Resolution:** Analog signal recording shall be performed using a digital to analog converter with 16 bit or higher resolution.

5. **Field of View:** The field of view of the radiometer(s) and imager(s) shall be sufficient to encompass the entire flash event. (A basic discussion of field of view calculations is contained in Annex C.)

6. **Calibration:** Radiometers shall be calibrated in accordance with section 2.3 of this document. Calibration shall be valid for 12 months.

2.2. INSTRUMENTATION ORIENTATION

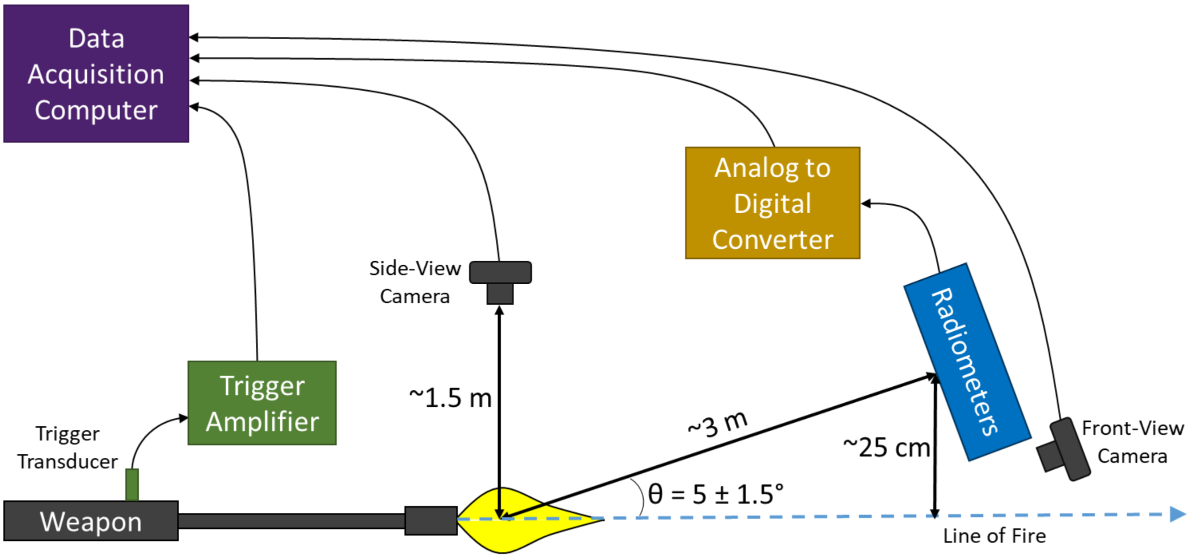

Figure 5 Recommended flash measurement instrumentation configuration for suppressed weapons.

1. Radiometers shall be placed 5±1.5° from the line of fire and approximately 3 m from the center of the expected flash (Figure 5). This position was selected to approximate the view of the flash as will be seen by an adversary without placing the instrumentation at risk of accidental projectile impact.

a. Varying the distance between the flash and the radiometers is acceptable[3] as long as the following conditions are met:

(1) The entire flash event is within the field of view of the radiometers.

(2) The radiometers are 5±1.5° from the line of fire.

b. This distance shall be measured from the expected center of the flash to the front surface of the lens of the radiometer, or the surface of the detector if no lens is used.

(1) An image of the flash taken perpendicular to the line of fire may be used to determine the location of the center of the flash.

(2) For suppressed weapons, no visible flash may be apparent perpendicular to the line of fire. In this case, the location of the flash shall be assumed to be the front surface of the suppressor.

[3] Examples of when changing this distance may be necessary include: 1) placing radiometers close to a weapon that produces extremely dim flashes to increase the signal to noise ratio of the measurement, and 2) moving the radiometers far from a weapon that produces large secondary flashes to ensure that the entire event is within the radiometers' fields of view.

2. The field of view of the radiometers shall be centered on the expected center of the flash event.

3. A visible light camera shall be placed close to the radiometers such that recorded images encompass the field of view of the radiometers. A second visible light camera may be placed perpendicular to the direction of fire to record images for informational purposes.[4]

4. Surfaces within the field of view of the detectors should be non-reflective within the spectral regions of interest to the greatest extent practically possible. A number of commonly available paints and coatings that are effective at minimizing visible and infrared reflections have been identified in the scientific literature.[5]

a. Common sources of visible reflections include metallic surfaces, glossy painted surfaces, and some white paints.

b. Some surfaces that appear to be non-reflective in the visible spectrum may be good reflectors in infrared bands. For critical measurements, using infrared imagers that are sensitive in the spectral regions of interest to help identify reflective surfaces is recommended.

c. If reflective surfaces cannot be minimized, then calibration-in-place using an unhoused source is recommended so that any reflections can be accounted for within the calibration procedures. For this procedure, the radiometers and test weapon shall be in their respective test positions, and the calibration source shall be placed in the expected center of the flash.

5. Though not required, use of an instrumented trigger to start data acquisition is recommended. Contact microphones and accelerometers attached to the weapon or mount have proven useful for this application, though any method which reliably signals the start of the flash event will be appropriate.

2.3. CALIBRATION

1. Calibration of the radiometer, amplifier, and digital-to-analog converter as a single system is recommended over calibration of components individually.

a. If the detector, amplifier(s), and data acquisition system are calibrated as a system in accordance with the following procedures, then independent

[4] Though not used for data collection, still photographs of the flash event may be useful in determining correlation of physical phenomena with recorded flash measurements. Additionally, since side-view photographs have been historically used for flash analysis, these images may provide continuity in interpretation of test results even though they are not necessarily representative of the shape or intensity of the flash from the perspective of an adversary.

[5] See, for example, Persky and Szczesniak, 1 April 2008, Vol. 47, No. 10, Applied Optics, p 1389-96, https://doi.org/10.1364/AO.47.001389.

calibration of the instrumentation components (notwithstanding the illumination source) will not be required.

b. Amplifiers, data acquisition systems, and any other instrumentation components within the measurement system that are not calibrated as a system shall be calibrated in accordance with their manufacturer's recommendations.

2. An illumination source with a known spectral radiant intensity or luminous intensity (depending on the detector to be calibrated) shall be placed at a known distance (d) from the detector(s) to be calibrated.

a. The detector(s) shall be oriented such that the illumination source is in the center of the detector's field of view.

b. If an un-housed lamp is used, the distance shall be measured from the filament of the lamp to the front surface of the collection optics of the detector, or to the surface of the detector if no collection optics are used.

c. If an integrating sphere or a hollow black body source is used, the distance shall be measured from the exit aperture of the source to the front surface of the collection optics of the detector, or to the surface of the detector if no collection optics are used.

(1) The plane containing the exit aperture of a cavity source shall be orthogonal to the optical axis of the radiometer.

3. The detector response shall be measured in a manner representative of the configuration to be used during testing. (For example, if a bias voltage or amplifier gain will be applied to the detector during testing, that bias &/or gain should be applied to the detector during calibration.)

4. The responsivity (R_e) of each radiometer shall be calculated by multiplying the measured system response to irradiation by the reference source[6] (ΔV) by the distance from the source to the detector (d) squared, and dividing the resulting value by the in-band radiant intensity (I_e) as shown in Equation 2.

$$R_e = \frac{\Delta V \times d^2}{I_e} \qquad \text{Eq 2}$$

5. The in-band radiant intensity (I_e) shall be calculated by integrating the known spectral radiant intensity ($I_{e\lambda}$) of the calibration illumination source within the spectral band defined by the 50% response bandpass wavelengths of the sensor system (Equation 3). This 50% response point is typically defined by bandpass filters, edge filters, or the intrinsic response function of the detector.

[6] The system response to irradiation (□V) is typically found by subtracting the instrument's "dark" output (typically voltage) when no illumination is applied from the instrument's output when it is illuminated.

$$I_e = \int_{\lambda_1}^{\lambda_2} I_{e\lambda} d\lambda \qquad \text{Eq 3.}$$

6. The responsivity of photometers (Rv) shall be calculated relative to the luminous intensity in candela (Iv) of a calibration source according to Equation 4.

$$R_v = \frac{\Delta V \times d^2}{I_v} \qquad \text{Eq 4.}$$

7. Recalibration shall be performed at least every 12 months, or after any hardware changes are made to the radiometric instrumentation.

8. Additional calibration considerations:

a. When possible, the intensity of the illumination source and/or the distance between the source and detectors should be chosen so that the system response values measured during calibration approximate the system response values measured during testing.

b. It is highly recommended that detectors and instrumentation should be selected and configured so that the detector response is linear with respect to radiant intensity over the ranges which will be measured. For detectors that exhibit a non-linear response, an appropriate detector response function should be determined which encompasses the measured range of radiant intensity values that will be reported.

c. For detectors that exhibit a linear response over the range of radiant intensity values, the test operator should ensure that the measured values fall within the instruments' linear response range.

2.4. DATA ACQUISITION AND PROCESSING

1. The response of a radiometer to flash (typically a change in voltage) shall be recorded at a minimum of 100,000 samples per second. (Faster sampling rates may be used.) Data recording shall start a minimum of 1 ms prior to the start of the flash event and shall continue until the radiometer response returns to baseline. The measured photometer voltage response of an example flash is shown in Figure 6.

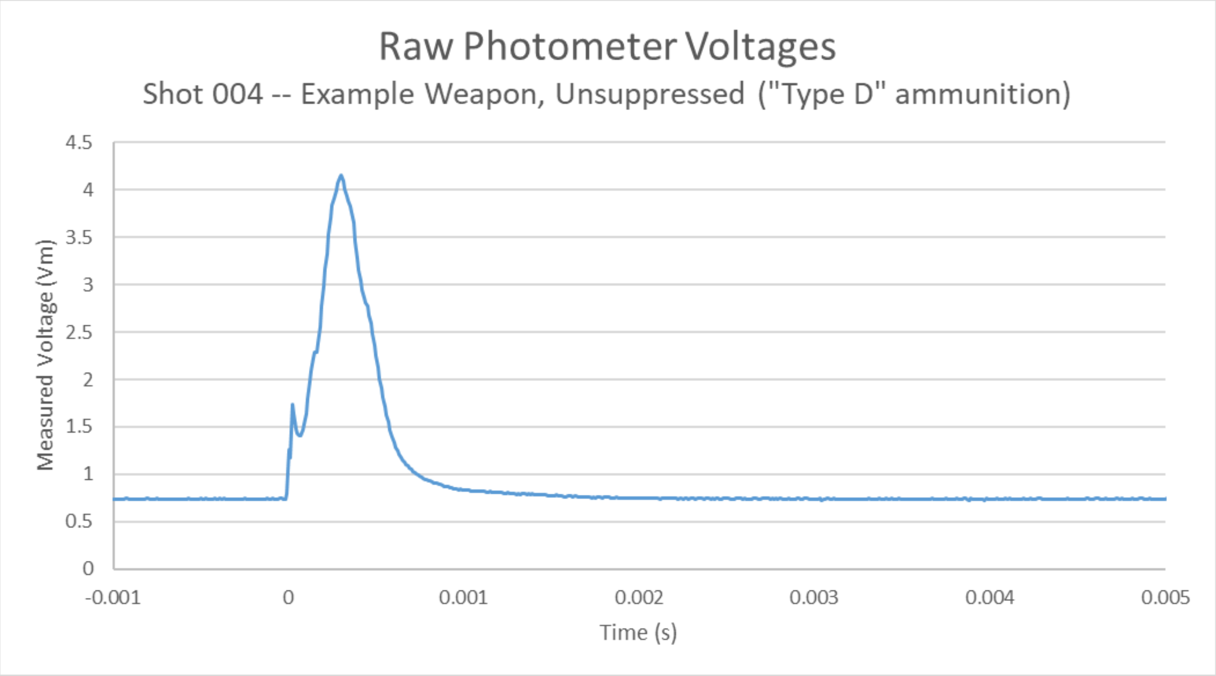

Figure 6 Measured photometer voltage during an example flash.

2. For still photographs, the camera shutter shall open before any light is emitted from the muzzle, and the shutter shall remain open until the flash event is complete such that the exposure time fully encompasses the flash event.

3. Any background response or detector offset voltage shall be subtracted from the measured detector response prior to calculation of in-band radiant intensity. This will correct for any ambient light present in the test area that is measured by the radiometers as well as any electronic offset in the amplifiers or data acquisition system. In most scenarios, this offset voltage (V_o) can be calculated by averaging 0.5 ms of the radiometer response measured immediately prior to the flash event. Subtracting this value from the measured response (V_m) will provide the detector response (ΔV) as shown in Equation 5. Figure 7 shows the detector response (ΔV) over the duration of the example flash after a V_o of 0.7386 V was subtracted from each of the measured voltages (V_m).

$$\Delta V = V_m - V_o \quad \text{Eq 5.}$$

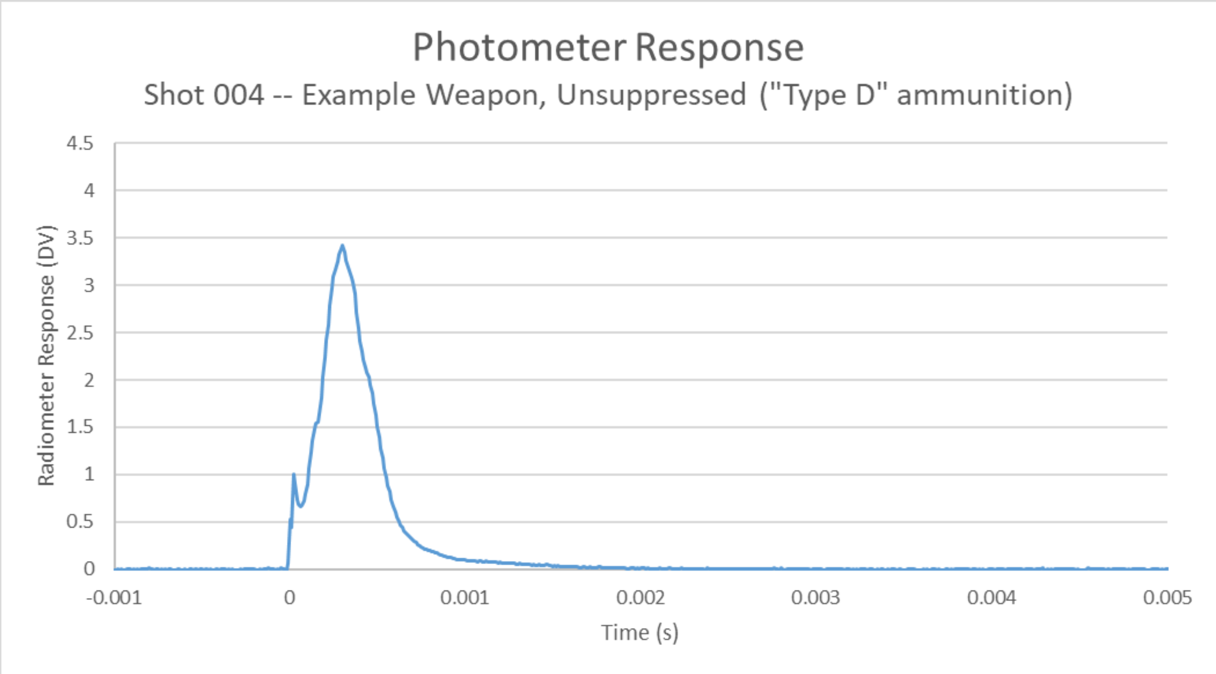

Figure 7 Response of a photometer to an example flash.

4. In-band radiant intensity (I_e) or luminous intensity (I_v) shall be calculated by multiplying the detector response in volts (ΔV) by the distance from the source to the detector (d) squared, and dividing the product by the detector responsivity (R_e or R_v) as shown in Equation 6. Procedures for determining a radiometer's responsivity are documented in Section 2.3. Figure 8 shows the luminous intensity of the example flash calculated from the photometer response shown in Figure 7 where d = 3.1 m and $R_v = 0.2357\frac{V \times m^2}{cd}$.

$$I_e = \frac{\Delta V \times d^2}{R_e} \qquad \text{Eq 6.}$$

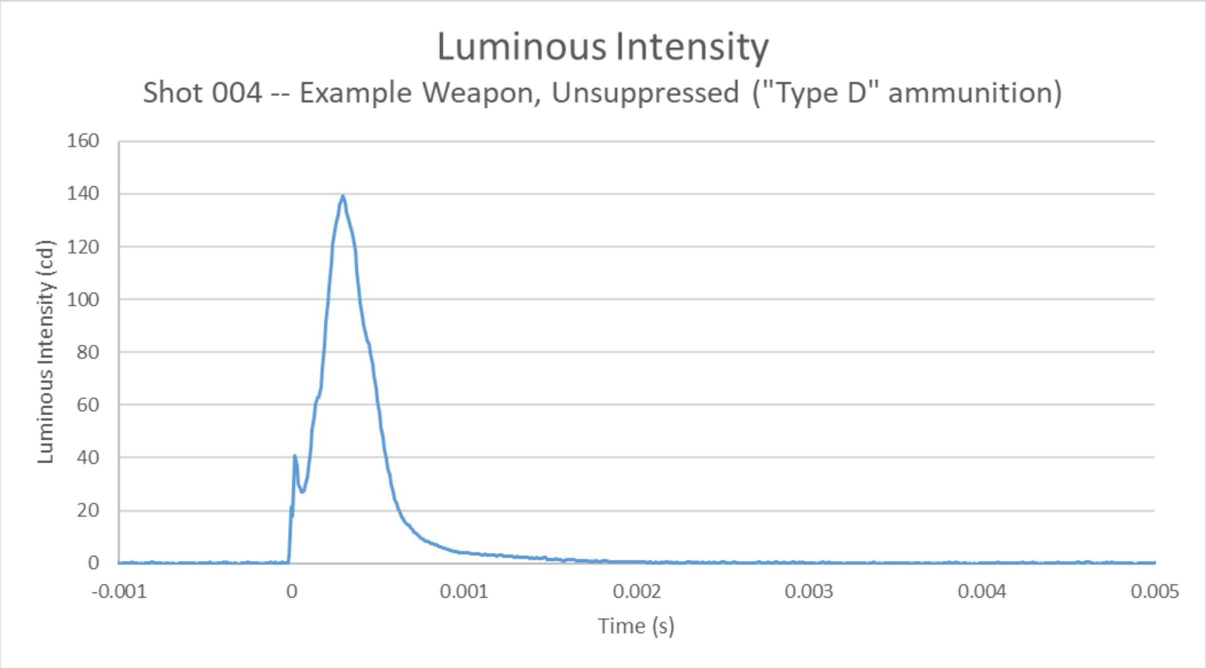

Figure 8 Luminous intensity of an example flash calculated from the measured photometer response.

5. Radiant energy (Q_e) shall be calculated by integrating I_e from the start of the flash event (t_0) until the flash event has concluded (t_f) as shown in Equation 7. The time over which the flash event occurs may vary between bands, and the integration times may be varied accordingly to capture the entire in-band energy emitted by each flash event.

$$Q_e = \int_{t_0}^{t_f} I_e(t)\, dt \qquad \text{Eq 7.}$$

6. Luminous energy (Q_v) shall be calculated by integrating I_v from prior to the start of the flash event (t_0) until after the flash event has concluded (t_f) as shown in Equation 8. Integration of Iv for the example flash from t_0 = -0.0001 s to t_f = 0.003 s (Figure 9) results in a value of Q_v = 51.8 mcd × s.

$$Q_v = \int_{t_0}^{t_f} I_v(t)\, dt \qquad \text{Eq 8.}$$

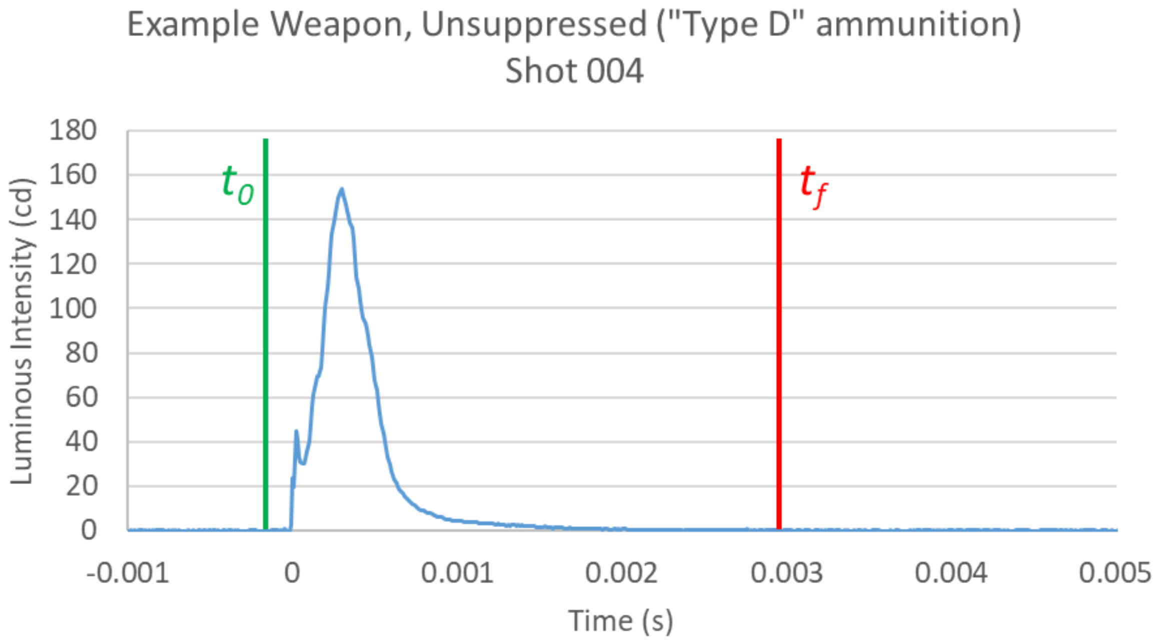

Figure 9 Recommend integration bounraries t_0 and t_f for calculation of luminous energy.

7. Luminous energy (Q_v) shall be reported in units of millicandela seconds (mcd × s) for visible emission, and radiant energy (Q_e) in SWIR and MWIR bands shall be reported in units of millijoules per steradian (mJ/sr). NIR radiant energies shall be reported in units of microjoules per steradian (μJ/sr).

2.5. DATA REPORTING

1. At a minimum, the following data shall be included when reporting measured flash intensities:

a. In-band flash energies. Recommended bands include visible (photopic), near infrared (NIR, 600-900 nm), short-wave infrared (SWIR, 900-1700 nm), and mid-wave infrared (MWIR, 1700-4800 nm).

b. Long-exposure visible photographs of each flash event from the perspective of the radiometers (required) and perpendicular to the firing axis (optional)[7].

c. Firing schedule.

[7] Historical flash measurements have frequently relied on long exposure photographs taken orthogonally to the firing axis. It is recommended that long-exposure photographs from this position be recorded & reported in addition to those from the perspective of the radiometers to assist in comparison of modern and historical results.

d. Any special weapon preparation considerations (such as whether warmer shots were fired, if the weapon was purged with air between shots, etc.) as available.

e. Range environmental conditions to include, at a minimum, temperature and humidity.

f. Physical orientation of the instrumentation to include, at a minimum, location of radiometers and camera(s) relative to the muzzle or the suppressor.

g. Description of the instrumentation used to include, at a minimum, model numbers and vendors/sources of any detectors, optics, amplifiers, data acquisition systems, triggering devices, still cameras/lenses, and any other devices within the data acquisition chain.

h. Radiometer/photometer calibration information.

(1) If a calibration service was used, include the name of the vendor, date of calibration, and sufficient information to allow traceability to a primary reference.

(2) If calibration was performed by the test operators, include the date of calibration of the radiometers, a description of the reference source (vendor, model number, etc.), date of calibration of the reference source, and traceable calibration certification information (e.g. NIST for North America).

i. Additional information related to the identification, configuration, and condition of the test weapons should be reported as available (such as how many shots have been fired through the barrel, when it was last cleaned, etc.). Similarly relevant ammunition information should be reported.

2. An example flash test report is included in Annex D.

2.6. ERROR CONSIDERATIONS

1. Though a full error calculation for flash measurements is beyond the scope of this document, some sources of error include the calibration error of the reference source, physical alignment errors, geometric errors resulting from the size of the flash event and deviation from a point-source approximation, and reflections off of objects within the detectors' fields of view. Practically, these errors limit the fidelity with which data collected during different tests or at different facilities can be compared. The absolute radiant/luminous power values measured using this method are expected to be within 20% of the absolute true value. Given that the variability in flash intensity from one shot to another using the same weapon and ammunition can vary by several percent (and by orders of magnitude if a secondary flash is observed), relatively large standard deviations within data sets are not atypical. As a general recommendation, differences of flash intensity of less than 20% should not be considered meaningful

unless extreme care was taken to control experimental variables and reliable standard deviation/error calculations have been performed.

Annex - A FLASH BACKGROUND

1. Flash is often broken into five components: pre-flash, primary flash, muzzle glow, intermediate flash, and secondary flash.

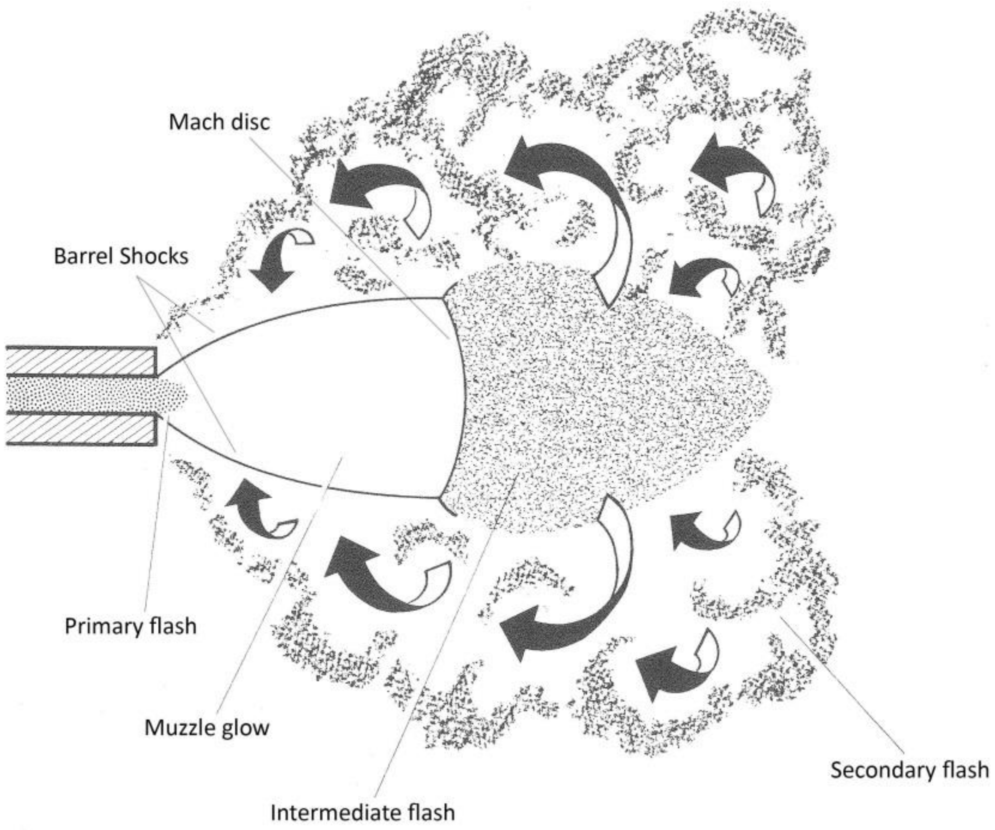

Figure 10 Illustration of various components of muzzle flash. Pre-flash is not depicted.

a. **Pre-Flash:** Propellant gases blowing by the projectile and exiting the muzzle before the projectile cause pre-flash.

b. **Primary Flash & Muzzle Glow:** Upon muzzle exit, the temperature of the propellant gases is high enough to emit visible radiation. This is known as primary flash. As the gases rapidly expand and cool, they continue to emit a relatively faint muzzle glow.

c. **Intermediate Flash:** As the propellant gases exit the barrel, a bottle shock is formed at the muzzle. The bottle shock consists of two shockwaves; the sides are called barrel shocks and the nearly flat base is called the Mach disc. When some of the propellant gases pass through the Mach disc the temperature rises as the gases are compressed. If the compression is large enough, and the consequent gas temperature is high enough, the radiation emitted by the gases appears as intermediate flash. Intermediate flash occurs roughly 20 to 50 calibres from the muzzle. Intermediate flash is geometrically larger than primary flash, but also has a low intensity.

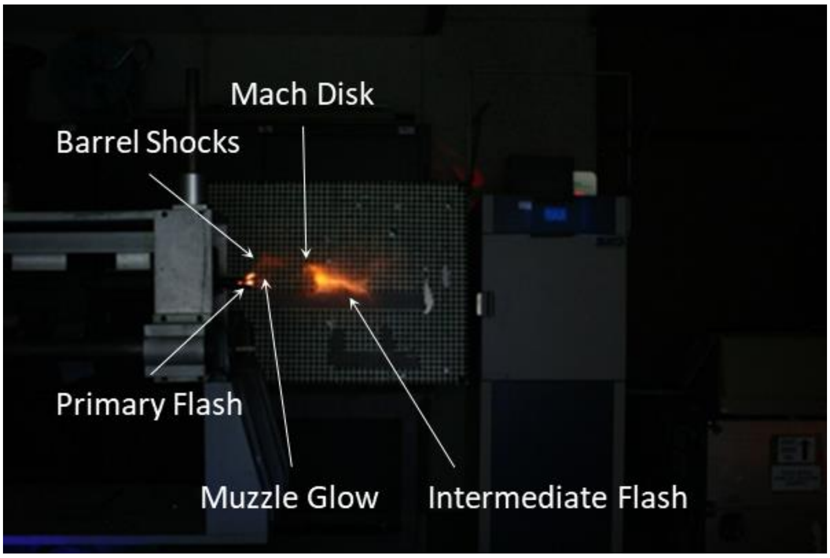

Figure 11 Primary and intermediate flash from a 5.56 mm rifle. Note: there is a total absence of secondary flash.

d. **Secondary Flash:** Ignition of the hot combustible gases, mainly hydrogen and carbon monoxide, may follow as they mix with oxygen in the surrounding air if the temperature in the gases is higher than the ignition temperature for the fuel-air mix. Secondary flash is produced by the ensuing large flame. Due to the small amount of propellant gases, secondary flash may or may not develop in small arms. The increased visible emission is largely produced by atomic emission from the sodium and/or potassium ions used in the oxidizers of many propellants. Since the primary flash event still occurs when a secondary flash is generated, infrared emission is still apparent and measurable.

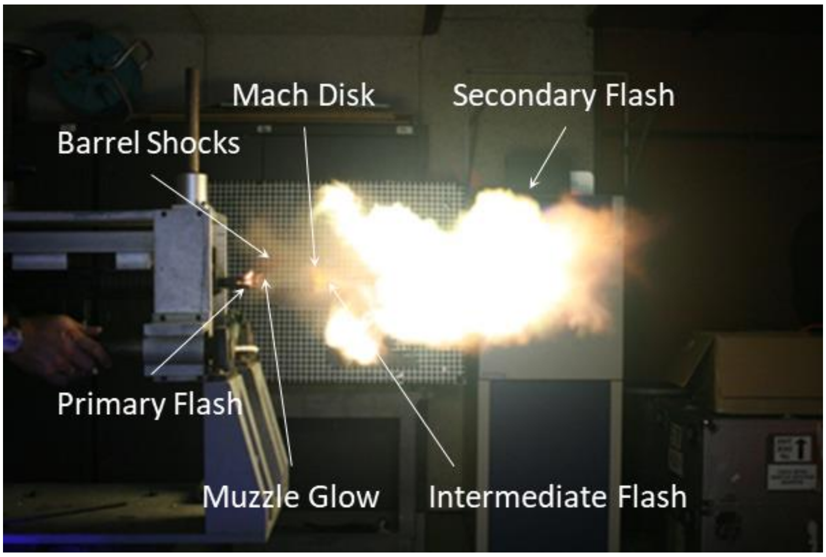

Figure 12 Secondary flash from a 5.56 mm rifle. Note: Primary and intermediate flash can still be identified in the presence of secondary flash.

Annex - B ABBREVIATIONS AND DEFINITIONS

B-1. ABBREVIATIONS

°C	degrees Celsius
cd	candela (cd = lm/sr)
Ge	germanium
InGaAs	Indium gallium arsenide
J	Joules (J = W/s)
K	Kelvin[8], the base International System of Units temperature unit
m	metre
lm	lumen
lx	lux
mcd	millicandela (1 x 10^{-3} cd)
MCT	mercury cadmium telluride
ms:	millisecond (1 x 10^{-3} s)
MWIR	mid-wavelength infrared
NIR	near infrared
nm	nanometre (1 x 10^{-9} m)
PbSe	lead selenide
QTH	quartz tungsten halogen
Si	silicon
s	second
sr	steradian
SWIR	short wavelength infrared
V	voltage or volts
W	Watts (J/s)
λ	wavelength, typically in reference to photons
µJ	micro Joule (1 x 10^{-6} m)

B-2. DEFINITIONS

1. Radiometers & photometers: Radiometers are devices that produce an electrical response when stimulated with electromagnetic radiation. Photometers are a specific subset of radiometers with response curves that approximate the wavelength sensitivity of the human eye.

2. Luminosity Function: The sensitivity of an average human eye to photons of different wavelengths. These functions are empirically derived based on human response studies, and many different functions have been published. The photopic and scotopic luminosity functions are most commonly used.

3. Photopic Luminosity Function: The sensitivity of an average human eye to photons of different wavelengths under well-lit (typically luminance conditions ranging from 10 to 10^8 cd/m^2). One of the more commonly used models is the CIE 1931

[8] Kelvin heat units.

Photopic Luminosity Function which is illustrated in Figure 13. Use of photopic intensities were recommended for this measurement since they are most commonly used for radiometric measurements, and will allow the easiest comparison with other light measurements despite the fact that a flash may be more easily seen under scotopic conditions.

4. Scotopic Luminosity Function: The sensitivity of an average human eye to photons of different wavelengths under low-light conditions (typically 10^{-6} to 10^{-3} lm/m^2). These conditions do not provide enough light for cone cells to provide a perceptible response; therefore, scotopic vision relies predominantly on the response of rod cells. The difference in the spectral sensitivity of rod vs. cone cells accounts for the shift in the scotopic and photopic luminosity functions. One of the more commonly used models is the CIE 1951 Scotopic Luminosity Function which is illustrated in Figure 13.

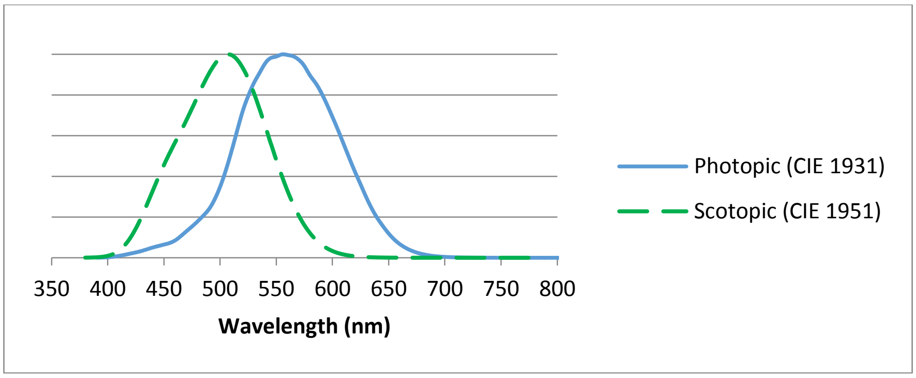

Figure 13 Normalized photopic and scotopic luminosity functions.

5. Radiometric and Photometric Terms, Symbols, and Units:

Table 3 Radiometric and photometric units. Radiometric terms are listed first within a group, and their symbols are denoted with a subscript "e". Photometric terms are listed second, and their terms are denoted with a subscript "v".

Term	***Symbol***	***Units***	***Notes***
Radiant Energy	Q_e	J/sr	Energy of electromagnetic radiation emitted by a source within a solid angle
Luminous Energy	Q_v	cd × s	
Radiant Intensity	I_e	W/sr	Power of electromagnetic radiation emitted by a source within a solid angle
Luminous Intensity	I_v	cd (= lm/sr)	
Irradiance	E_e	W/m^2	Electromagnetic power received by surface per unit area
Illuminance	E_v	lx (= lm/m^2)	
Radiant Exposure	H_e	J/m^2	Integrated irradiance or illuminance per unit area of a surface over time
Luminous Exposure	H_v	lx × s	

Annex - C RADIOMETRIC CONSIDERATIONS

1. A detector's field of view is generally defined as the area over which a sensor will detect radiation. For lensed radiometers and imaging cameras, *FOV* is often defined in terms of "angular field of view" (*AFOV*), which is the angle through which light will be projected onto a detector by a lens (Figure 14). The *AFOV* is equal to twice the arctangent of the ratio of the "height" of the detector (h_d) to twice the focal length of the imaging lens (f).

$$AFOV = 2 \times tan^{-1}\left(\frac{h}{2f}\right) \qquad \text{Eq 9.}$$

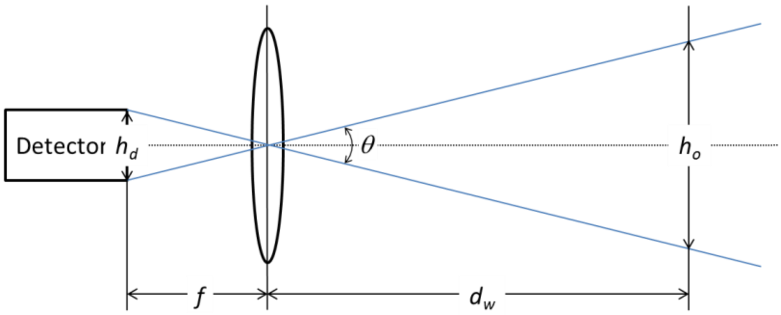

Figure 14 The angular field of view (AFOV) of a detector (θ) is dependent on the focal length of the imaging lens (f) and the size of the detector (h_d). The minimum AFOV required for an application can be calculated if the desired working distance and object height are known.

2. For example, if a 10 mm diameter circular photodiode was fitted with a 60 mm collecting lens, then the calculated angular field of view of the radiometer would be 9.5°. In order for it to accurately measure a 1 m diameter flash, this radiometer would have to be placed at least 6 m away from the event. (Practically, the radiometer should be placed further from the event to minimize the risk that alignment errors would cause part of the flash to be outside of the detector's field of view.)

3. Alternately, if the height of the object of interest (h_o) and the working distance (d_w) are known, then the minimum *AFOV* required to fully image the object can be calculated according to the following equation:

$$AFOV = 2 \times tan\left(\frac{h_o}{2d_w}\right) \qquad \text{Eq 10.}$$

4. For rectangular sensors with different horizontal and vertical dimensions, the angular field of view of the horizontal and vertical axes will obviously be different since h_d will be different along each axis. Within real systems, there may also be some clipping or vignetting, so it is advised that the user measure the angular response of a radiometer to validate *FOV* calculations if flashes larger than half of the *AFOV* are to be measured.

5. For radiometers with no lenses, the *AFOV* is effectively 180° since any light source placed in front of the detector will project photons onto the detector, regardless of its position relative to the normal axis of the detector. However, the irradiance projected onto the detector of the radiometer, and thus the calculated radiant intensity of the source, will vary as a cosine function of the radiometer's "viewing angle", which is defined here as the angle formed by the illumination axis (a line passing through the illumination source and the center of the detector) and the detector's optical axis (defined in this instance as the line passing through the center of the detector that is orthogonal to the detector's surface.) The reason for this lies in the change of the effective area that the illumination source "sees" as the detector is rotated - the area of the detector projected along the illumination axis varies as a function of the cosine of the viewing angle (Figure 15).

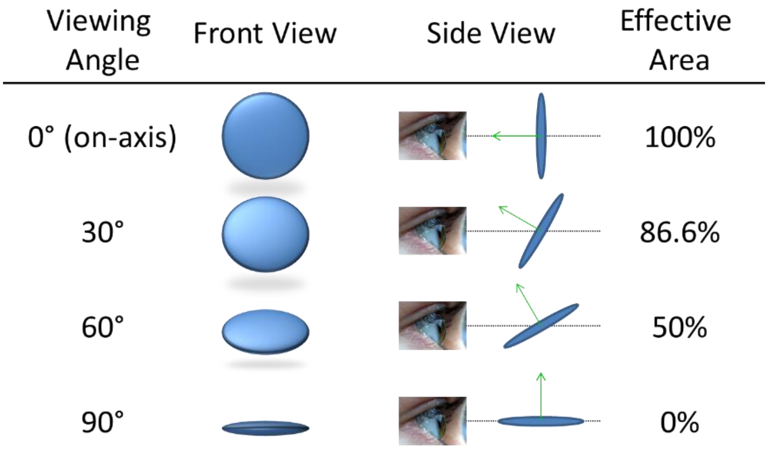

Figure 15 The area of a detector "seen" by a light source is a cosine function of the angle formed by the detector's normal axis (green arrow) and the projection axis.

6. Since the irradiance (E_e) or illuminance (E_v) of a surface at a given distance from an emissive source will be constant, the change in viewing angle will change the radiometer response since the effective detection area is being changed. This is commonly referred to as the "cosine response" of a detector when it is rotated relative to an illumination source.

7. The practical impact of this is twofold; 1) the detector should be oriented such that the center of the flash will be as close to the detector's normal axis as possible, and 2) the detectors should be placed a sufficient distance from the flash such that it can be effectively treated as a point source. If the detectors are not oriented correctly, or if the flash is "large" within the *FOV*, then measurement errors can be introduced. As a practical consideration, if un-lensed radiometers are placed 3 times further away from a flash event than the expected diameter of the event, then the error introduced due to geometric effects will be expected to be less than 1.5% of the total expected intensity. The primary problem with placing the detectors this close to a flash is that any distance measurement errors between the flash and the detectors will be compounded at short ranges. As the detectors are moved further from the flash, those

measurement errors will produce proportionally smaller errors into the radiant intensity calculations.

8. The wide field of view of a radiometer also introduces the possibility that stray light from reflections or other light sources within the test area will be detected by the radiometer. In order to limit the *AFOV* of an un-lensed radiometer, a Gershun tube (Figure 16) may be used. This simple device consists of a tube with an aperture on one end which is mounted to the radiometer. Additional internal baffles may be added to improve off-axis light rejection by minimizing internal surface reflections, though they should be sized such that they will not act as an aperture.

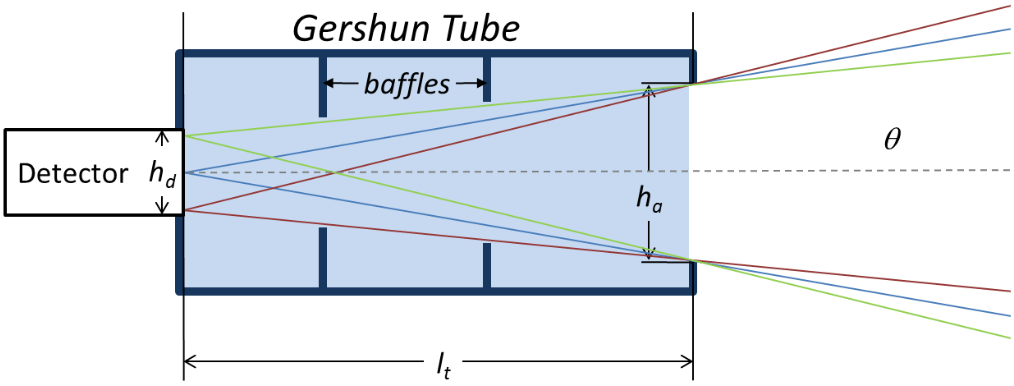

Figure 16 A Gershun tube may be used to limit the field of view of a radiometer to improve stray light rejection.

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Annex - D SAMPLE FLASH TEST REPORT

Flash Signature Measurements – Imaginary Weapon 1

1. The intensity of the flash produced by the weapon was measured using radiometers in the visible (photopic), near-infrared (NIR, 600-900 nm), short-wavelength infrared (SWIR, 900-1600 nm), and mid-wavelength infrared (MWIR, 1700-4800 nm) spectral bands. A long-exposure visible image of each flash event was also recorded from the perspective of the radiometers using a digital camera to allow comparison of flash with results from legacy test methodologies. Detailed descriptions of the instrumentation and experimental configurations are included below.

Table 4 Average flash intensities[9] of the test weapon with and without a suppressor.

	Visible (mcd × s)	NIR (μJ/sr)	SWIR (mJ/sr)	MWIR (mJ/sr)
Bare Muzzle	351	752	531	125
Suppressed – First Shots	35.1	75.2	53.0	12.5
Suppressed – Shots 2-5	3.51	7.52	5.31	1.25

2. The unsuppressed test weapon produced a radially symmetric muzzle flash (Figure 17) which was fairly uniform for all of the test shots with no evidence of secondary flash. Shots 4 and 5 were slightly more intense than the other shots in all bands except for the MWIR (Table 5). No incandescent sparks were ejected during any of the shots.

3. The suppressed weapon produced higher flash energies for the first shot vs. subsequent shots, which is typical of many suppressors, but this flash was still less energetic than that of the unsuppressed weapon by a factor a 10 (Table 4). Subsequent suppressed shots were less energetic still, and were not readily apparent to observers standing behind and to the side of the weapon. Photographs taken from the side of the weapon (Figure 17) showed no apparent light being emitted from the weapon, suggesting that the baffles mostly contained the flash. As a result, the visible flash may only be seen when looking into the suppressor baffles from in-front of the weapon when it is fired.

4. To contextualize these results, the flash emitted by the unsuppressed weapon is about 5 times less than an unsuppressed AR15[10] in the visible, NIR, and SWIR, but is similar to the MWIR intensity. In summary, the visible and infrared flash produced by the unsuppressed weapon is appreciably lower than an unsuppressed AR15, and

[9] These data are fabricated, and are used for illustration only.
[10] These data are not included in the document, but including a "baseline" weapon flash may help the audience contextualize the data more effectively.

addition of the suppressor further reduces the flash intensity below levels that are easily seen with the un-aided human eye.

Table 5 Individual flash intensities of the test weapon without a suppressor.

	Visible (mcd × s)	NIR (μJ/sr)	SWIR (mJ/sr)	MWIR 1 (mJ/sr)
Unsuppressed Shot 1	xx.x	xx.x	xx.x	xx.x
Unsuppressed Shot 2	xx.x	xx.x	xx.x	xx.x
Unsuppressed Shot 3	xx.x	xx.x	xx.x	xx.x
Unsuppressed Shot 4	xx.x	xx.x	xx.x	xx.x
Unsuppressed Shot 5	xx.x	xx.x	xx.x	xx.x

Flash 1 Picture:
View from Radiometers

Flash 1 Picture:
Side view

Flash 2 Picture:
View from Radiometers

Flash 2 Picture:
Side view

Flash 3 Picture:
View from Radiometers

Flash 3 Picture:
Side view

Flash 4 Picture:
View from Radiometers

Flash 4 Picture:
Side view

Flash 5 Picture:
View from Radiometers

Flash 5 Picture:
Side view

Figure 17 Photographs of unsuppressed flashes.

These tables and figures should be repeated for all shots.

Weapon details: Weapon model number and condition description here

Ammunition details: Ammunition type, lot number, any special notes here

Firing Schedule: For unsuppressed weapons, 30 shots were fired with approximately 5 seconds of wait time between each shot. For suppressed weapons, 6 sets of five shots were fired with approximately 5 seconds of wait time between each shot within the set. Between each set, compressed air was blown through the weapon via a flexible air hose placed into the chamber for approximately 1 minute. The compressed air was passed through a drier and a filter prior to use to ensure that condensation and/or oil were not introduced into the weapon.

Temperature & humidity: Temperature and relative humidity were measured to be 25 °C & 75% respectively at the start of the test using a BRAND & MODEL relative humidity gauge which was calibrated on DATE by the manufacturer.

Instrumentation Locations: Radiometers were placed approximately 26 cm to the left of the firing axis and 3 m from the expected center of the flash event to mimic a “head on” view of the firing event. The weapon was fired from a bipod which was placed in the same location for each shot. The DSLR was placed approximately 1.5 m to the left of the weapon’s muzzle.

Radiometers: See Table 6 for a summary of the radiometer hardware configuration.

Table 6 Radiometer configuration summary.

Spectral Band	Sensor	Filter(s)	Collection Optics	Amp Gain
Photopic (Vis)	Silicon photodiode (Brand, model, SN)	Photopic* Response (Brand, model)	∅ 50.4 mm, f = 60 mm (Brand, model)	70 & 30 dB
Near Infrared (NIR, 600-900 nm)	Silicon photodiode (Brand, model, SN)	600 nm long-pass, 900 nm short-pass (Brand, model)	∅ 50.4 mm, f = 60 mm (Brand, model)	70 & 30 dB
Shortwave Infrared (SWIR, 900-1600 nm)	Indium Gallium Arsenide (Brand, model, SN)	900 nm long-pass, 1600 nm short-pass (Brand, model)	None	70 & 30 dB
Midwave Infrared (MWIR, 3.6-4.8 μm)	Lead Selenide (Brand, model, SN)	3.6 μm long-pass (Brand, model)	None	Fixed

*CIE 1931 2° standard observer model

Luminous intensity (CIE 1931 2° standard observer model) was measured using a Brand X MODEL NUMBER amplified silicon photodiode fitted with a 2-inch diameter, 60 mm focal length collection lens and a photopic response filter (Brand and model of filter). Near-infrared (NIR, 600-900 nm) emission was measured using a Brand X

MODEL NUMBER2 amplified silicon photodiode fitted with a 2-inch diameter, 60 mm focal length collection lens, a 600 nm long-wavelength pass filter, and a 900 nm short-wavelength pass filter (Brand and model of filters). Short-wavelength infrared (SWIR, 900-1600 nm) emission was measured using a Brand X MODEL NUMBER3 amplified indium, gallium, arsenide (InGaAs) detector fitted with a 900 nm long-wavelength pass filter and a 1600 nm short wavelength pass filter (Brand and model of filters). The mid-wavelength infrared (MWIR, 3.6-4.8 μm) response was measured using a Brand X MODEL NUMBER4 lead selenide (PbSe) fixed amplification photodetector fitted with a 3.6 μm long wavelength pass filter (Brand and model of filters) which defined the high-energy edge of the band. The low-energy edge of the band was defined by the inherent roll-off of the detector at 4.8 μm, and no collection optics were used with this detector.

Data Acquisition: Voltage outputs from the radiometers were sampled and digitized at 100,000 samples per second using a DAQBrand USB-DAQWIDGET multi-function data acquisition module and custom software written in PROGRAMMING LANGUAGE. The start of data collection was triggered by a TTL pulse sent from a BRAND & MODEL high-speed photography controller fitted with a contact microphone (Brand and model) attached to the frame of the weapon. The trigger gain was adjusted to provide a pulse upon ignition of the round so that the camera shutter would open and data collection would begin before gasses or the bullet exited the barrel. For the visible, NIR, and SWIR bands, two radiometers with different gains were used to simultaneously record the flash intensity to provide a larger effective dynamic range. For shots where the output of the higher-gain radiometer was greater than 9.8 V, the signal was assumed to have been clipped by the limit of the amplifier electronics, and the signal from the lower-gain radiometer was used. For shots where no clipping was observed, the output of the higher gain radiometer was preferentially used since it was less noisy. Higher gain settings for the amplifiers did result in a reduction of their effective bandwidth, but this did not result in a significant change to the integrated flash intensity—the increased noise in the low-gain signals was shown to be a larger source of error for low-intensity shots.

Calibration: Visible, NIR, and SWR detectors were calibrated vs. a 45 W quartz tungsten halogen (QTH) lamp (Brand Y Model 123456-78, Serial Number 0987654) with a known spectral radiant intensity (NIST traceable, calibration performed by the OEM on CALIBRATION DATE). The MWIR detectors were calibrated vs. a 1000 °C blackbody (brand, model, and SN) fitted with a variable exit aperture. (Blackbody calibration was performed by the OEM on CALIBRATION DATE). The spectral radiance of this source was calculated assuming that it behaved as an ideal blackbody as described by Planck’s law. Since PbSe detectors are inherently AC coupled, an optical chopper operating at approximately 200 Hz was placed between the detectors and the blackbody’s exit aperture to provide signal modulation. For detectors with variable amplification, calibration was performed independently for each gain setting used. The 50% response wavelengths supplied by the filter or sensor manufacturers were used to define spectral band limits for each sensor except for the visible radiometer, which assumes the CIE 1931 2° standard observer model photopic response function.

Photography: A CAMERA COMPANY Model number 3456 machine vision camera fitted with a LENSBRAND Model 56789 25mm lens (aperture set to f/2.8) was placed close to the radiometer array to provide a visible image which encompassed the field of view of the radiometers. A gain of 20 was used for all images. Images from this camera were recorded via the PROGRAMMING LANGUAGE interface and saved as *.tiff files without compression. A SLR-BRAND model XXX-XX digital SLR camera (ISO 1600 fitted with a MODEL DESIGNATION 17-85 mm zoom lens set to a focal length of 50 mm and an aperture of f/5.6) was placed approximately 5 feet to the left of the muzzle. Images from this camera were recorded as “large” *.jpg files. Images have been resized, but otherwise have not been modified unless specifically noted.

AEP-4785 VOLII (B)(1)