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TEST PROCEDURES FOR THE MEASUREMENT OF THERMAL SIGNATURE OF SMALL ARMS

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NATO LETTER OF PROMULGATION

30 August 2021

1. The enclosed Allied ENGINEERING Publication AEP-4785, Volume IV, Edition A, Version 1, TEST PROCEDURES FOR THE MEASUREMENT OF THERMAL SIGNATURE OF 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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Major General, GRC (A)
Director, NATO Standardization Office

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RECORD OF RESERVATIONS

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 measurement of the change in infrared radiation emitted by a weapon after it has been fired. This is commonly referred to as a weapon's "thermal signature." These procedures have been developed with an emphasis on suppressed weapons, but they are equally applicable for characterization of unsuppressed weapons. This test method describes procedures for determining the change in radiant intensity of a weapon after it has been fired via analysis of infrared imagery. Instrumentation, data collection procedures, calibration, and data reporting requirements are described herein.

1.2. BACKGROUND

1. The increase in temperature of a weapon after it is fired results in increased emission of blackbody radiation, most predominantly in the infrared regions of the electromagnetic spectrum.

2. This infrared emission is commonly referred to as a weapon's "thermal signature," and this emission scales with the weapon's temperature according to Plank's Law.

3. Though not directly visible to the human eye, infrared radiation can be detected using a variety of readily available imagers.

4. The two images shown in Figure 1 were collected using a microbolometer, a sensor that detects long-wavelength infrared (LWIR, ~8-12 µm) radiation. The image of a room-temperature suppressor (Figure 1a) shows less emission than from a suppressor on a weapon that has been fired (Figure 1b).

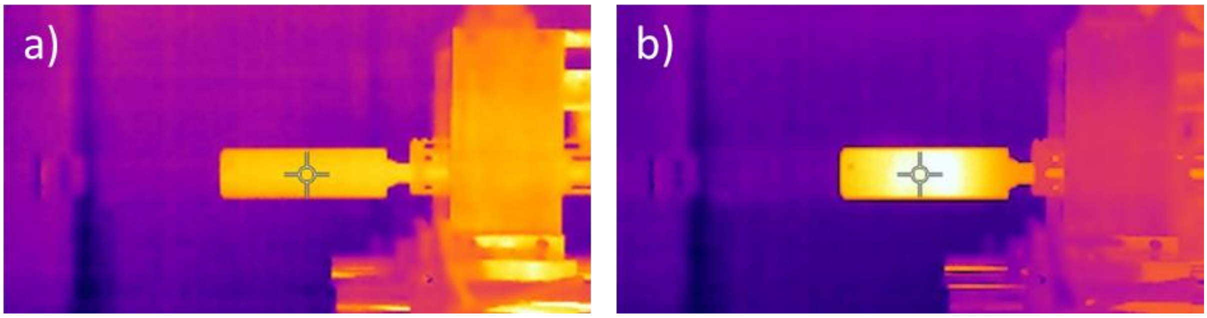

Figure 1 LWIR images of a suppressor before (a) and after (b) firing. (Automatic scaling was applied by software after collection.)

5. This method describes procedures for determining the change in radiant intensity (ΔI_e) of a weapon when it is fired. Change in radiant intensity was chosen as a metric for infrared weapon signature for the following reasons:

a. I_e closely correlates with detectability of weapon by an infrared sensor.

b. ΔI_e may be defined for a single round or multiple rounds within a burst according to operational requirements.

c. Use of a single quantity to describe their respective infrared signatures allows rapid comparison of multiple weapon systems.

6. Several metrics in addition to change in radiant intensity contribute to classification, recognition, and identification of a weapon, after it is detected. Images collected in accordance with this procedure will allow subsequent analysis beyond the immediate scope of this AEP. Specifically, the baseline radiant intensity of the weapon before it is fired will be measured.

7. The rate at which a weapon cools can significantly contribute to its infrared signature: a weapon that cools slowly will emit a larger infrared signature for a longer period of time than an otherwise identical weapon that cools more quickly. Unfortunately, variable environmental factors, especially changes in the rate of air flow around a weapon, can cause significant differences in cooling rates that will frustrate measurement repeatability in many weapon testing facilities. As such, protocols for measuring weapon cooling rates have not been included in this document, though these methods may be adapted to that purpose with careful control of environmental factors.[1]

8. This method is equally applicable for short-wavelength infrared (SWIR, ~1-3 µm), mid-wavelength infrared (MWIR, ~3-5 µm), and long-wavelength infrared (LWIR, ~8-12 µm) measurements.

9. This document does not attempt to present complete background information related to infrared imaging. Much of the pertinent background information related to this methodology can be found in “The Infrared & Electro-Optical Systems Handbook: Volume 5, Passive Electro-Optical Systems,” which is publicly available for download via the Defense Technical Information Center (https://apps.dtic.mil/dtic/tr/fulltext/u2/a364023.pdf).

1.3. SCOPE

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

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[1] For repeatable measurements of cooling rates, it is suggested that testing be performed in an environmentally controlled range, that the ambient temperature be maintained as close to constant as possible for the duration of the test, and that the airflow around the weapon be restricted to minimize changes in convective cooling rates. Air flow restrictions may be accomplished by erecting a temporary enclosure around the weapon using plastic film (such as disposable paint drop-cloths, plastic plumbing fixtures, and adhesive tape. Plastic film is usually opaque to infrared radiation, so imagers should be placed inside or the temporary enclosure.

2. The scope of this test procedure is to specify:

   a. Procedures for collection of infrared imagery of a weapon in the spectral band(s) of interest before and after it is fired.

   b. A method to calculate the change in radiant intensity (ΔI_e) of a weapon using this infrared imagery.

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

4. Determining detection thresholds and/or 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. **Infrared Imager:** An infrared imager with a known spectral response band shall be used to record images of the weapon. The spectral response band shall be defined by the 50% response threshold wavelengths of the imager as configured for measurement.

   a. **Edge or bandpass filters (optional):** Filters may be used to define or limit the spectral response band of the infrared imager. Recommended band limits are 8-12 μm for long wavelength infrared (LWIR), 3-5 μm for mid-wavelength infrared (MIWR), and 0.9-1.7 μm for short-wavelength infrared (SWIR).

2. **Thermometer or thermocouple:** a thermometer or thermocouple shall be used to measure environmental temperatures.

3. **Humidity gauge:** a gauge capable of measuring and reporting the relative humidity in the test environment.

4. **Wind speed gauge:** a gauge capable of measuring and reporting the wind speed at the weapon.

5. **Image manipulation software:** Software must be minimally capable of the following operations:

   a. Defining regions of interest within an image.

   b. Summing pixel intensities/counts within those regions.

6. **Calibration:** Infrared imagers shall be calibrated with respect to irradiance of the sensor (E_e) or radiance of the object (L_e) in accordance with their manufacturers' recommended procedures. Calibration shall be valid for 12 months.

2.2. INSTRUMENTATION ORIENTATION

1. **Weapon Mounting:** The test weapon shall be placed in a fixed mount capable of returning the weapon to a repeatable position after it is fired. The mount shall not obscure visibility by the imager of parts of the weapon that may become hot after firing.

2. **Imager Orientations:** Imagers shall be mounted at fixed positions relative to the test weapon to ensure that perspective is maintained for "hot" and "cold" images. Two standard weapon signature orientations are specified: "silhouette" and "line of fire" as illustrated in Figure 2.

   a. **Silhouette:** This position was selected to approximate the view of the weapon as will be presented to an adversary's sensors when the weapon is being carried. This orientation is typically a “worst case scenario” in which the largest possible cross-section of the weapon is presented for detection.

(1) The infrared imager(s) shall be placed approximately 3 m from the center point of the weapon, perpendicular to the line of fire. The imager shall be at the height of the line of fire.

(2) The center point of the weapon shall be determined with all muzzle devices and accessories fitted.

(3) Varying the distance between the weapon and the imagers is acceptable as long as the entire weapon is within the field of view of the imager. Once a distance for measurement has been selected, it should be maintained for the entirety of the test.

(4) The center point of the weapon shall be placed in the horizontal center of the field of view of the imager. The firing line shall be placed in the vertical center of the field of view of the imager.

b. **Line of Fire:** This position was selected to approximate the view of the weapon as will be seen by an adversary immediately after firing:

(1) The infrared imager(s) shall be placed 5±1.5° from the line of fire and approximately 3 m from the muzzle.

(2) This distance shall be measured from the front surface of the weapon to the front lens element of the imager.

(3) Varying the distance between the weapon and the imagers is acceptable as long as the entire weapon is within the field of view of the imager. Once a distance for measurement has been selected, it should be maintained for the entirety of the test.

(4) The center point of the weapon shall be placed in the horizontal center of the field of view of the imager. The firing line shall be placed in the vertical center of the field of view of the imager.

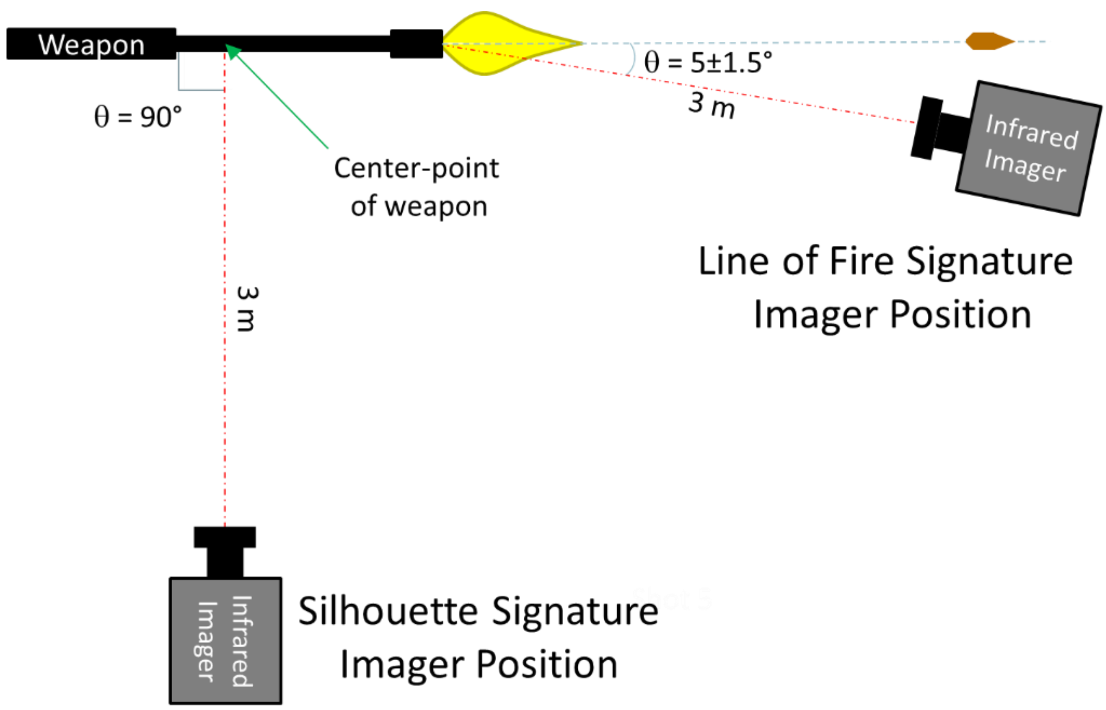

Figure 2 Overhead view of imager and weapon orientation for measurement of silhouette and line of fire infrared signatures.

3. **Image Background (optional):** A uniform background in the collected images will greatly simplify image processing. A screen made of a material that is non-reflective in the band(s) of interest may be placed behind the weapon to provide a uniform background. Textured materials (such as plywood) should be avoided. Some fabrics that are non-reflective and opaque in the visible region of the electromagnetic spectrum may not have the same optical qualities in infrared bands. Suitability of specific fabric backdrops should be confirmed in the laboratory prior to use in a test.

4. **Ranges:** The procedures described herein may be used at both indoor and outdoor range. Use of indoor ranges is highly recommended to improve environmental control and avoid heating from direct exposure to sunlight and potential rapid changes in ambient temperature. If measurements are performed at outdoor ranges, use of a canopy or other sun shade over the weapon and test instrumentation is highly recommended to minimize temperature changes due to radiative heating or spurious reflections off of the weapon that are not immediately apparent.

2.3. FIRING SCHEDULES

1. Firing schedules are considered a matter of national interest and may be changed as appropriate for specific weapon systems.

2. Firing schedules for each weapon shall be consistent between each weapon within a test to enable comparison between different weapon configurations.

2.4. DATA ACQUISITION AND PROCESSING

1. The weapon shall be placed in the fixed mount and allowed to reach ambient temperature. Physical contact with the weapon shall be minimized during this time to avoid warming due to heat transfer from the operator to the weapon.

2. The temperature, humidity, wind speed, and wind direction shall be recorded prior to recording images. For tests performed in an indoor range, wind speed measurements may be omitted if the test area has minimal air flow during testing (if, for example, the range ventilation system has been temporarily shut off for the duration of a test). For indoor ranges with active ventilation during testing, wind speed measurements near the weapon shall be recorded.

   a. The ambient temperature shall be 10 - 30°C.

   b. Wind speed shall be <8 km/h.

3. A still "cold" image of the weapon shall be recorded using an infrared imager prior to firing after the weapon has reached ambient temperature.

4. One or more rounds shall be fired through the weapon according to an established firing schedule. Use of a remote trigger actuator is recommended to avoid temperature changes to the weapon due to heat from the operator.

5. A still "hot" image of the weapon shall be recorded using an infrared imager after allowing the weapon to thermally equilibrate for at least 5 seconds, but not more than 10 seconds after completion of the firing schedule[2].

2.5. CALCULATIONS OF INFRARED SIGNATURES

1. The following calculation methods are provided as a matter of convenience. Alternate methods may be used to achieve a mathematically equivalent result. (Note: atmospheric transmission losses have been assumed to be negligible for the distances over which these measurements will typically be performed within a laboratory or test range.)

2. **Calculation for imagers calibrated with respect to the radiance (L_e) of an object:** This method assumes that the imaging software is able to calculate the area of an object that is represented by each pixel when the distance between the imager and an object is provided, and that the software is subsequently capable of calculating

[2] These times assume that no insulating materials or shielding devices have been placed around the weapon. If these devices are used, the external temperature of the weapon may continue to increase for a much longer period of time than the 5 seconds recommended herein. Analysis of the effectiveness of such insulating and shielding materials is beyond the scope of this document.

the radiance[3] of an object. If the software being used contains this feature, this method is typically the most direct method for calculating radiant intensity.

a. The "cold" image of a weapon should be imported into image analysis software.

b. The distance between the weapon and imager should be input into software. (Refer to the manual for the specific software being used for how to input this value.)

c. The image should be displayed as Le in units of $\frac{\mathrm{W}}{\mathrm{sr}\times\mathrm{cm}^2}$.

d. The radiance value for each pixel ($L_{e,px}$) should be converted to radiant intensity ($I_{e,px}$) by multiplying $L_{e,px}$ by the area of the weapon represented by each pixel ($A_{o,px}$) (Equation 1).

$$I_{e,px} = L_{e,px} \times A_{o,px} \qquad \text{Eq 1.}$$

(1) The area represented by each pixel ($A_{o,px}$) can be calculated using the distance between the imager and weapon (d_o), the focal length of the lens (f), and the dimension, or "pitch", of each pixel on the imager (h_{px}) according to Equation 2.

$$A_{o,px} = \left(d_o\left(\frac{1}{f} - \frac{1}{d_o}\right) \times h_{px}\right)^2 \qquad \text{Eq 2.}$$

e. A region of interest (ROI) containing the entire weapon and minimal background should be selected in software.

f. The sum of $I_{e.px}$ values within the ROI should be calculated (Equation 3).

$$I_{e,cold} = \sum_{ROI} I_{e,px} \qquad \text{Eq 3.}$$

g. Steps 2.5.2.a through 2.5.2.f should be repeated for the associated "hot" image of a weapon.

h. The change in the radiant intensity for the weapon (ΔI_e) should be calculated by subtracting $I_{e,cold}$ from $I_{e,hot}$ (Equation 4).

$$\Delta I_e = I_{e,hot} - I_{e,cold} \qquad \text{Eq 4.}$$

3. **Calculation for imagers calibrated with respect to the irradiance (E_e) of the sensor:** This method describes calculations to be used if the imager is calibrated with respect to the irradiance of the sensor (E_e).

[3] Radiance is defined as the radiation emitted within a solid angle per unit area of a surface, and is typically reported in units of $\frac{\mathrm{W}}{\mathrm{sr}\times\mathrm{cm}^2}$.

a. A “cold” image of a weapon should be imported into image analysis software.

b. The image should be displayed in terms of irradiance (E_e) at the sensor (typically units of W/cm^2).

c. The irradiance value for each pixel ($E_{e,px}$) should be converted to radiant intensity ($I_{e,px}$) of the object per pixel according to Equation 5[4] where do is the distance from the lens to the weapon.

$$I_{e,px} = E_{e,px} \times (d_o)^2 \qquad \text{Eq 5}$$

d. Calculation of ΔI_e shall proceed according to steps 2.5.2.e through 2.5.2.h.

2.6. DATA REPORTING

1. At a minimum, the following data shall be included when reporting infrared weapon signatures:

a. The change in in-band radiant intensity (ΔI_e).

b. Firing schedule.

c. Any special weapon preparation considerations (such as whether the weapon was specially cleaned, if any non-standard lubricants were present, etc.) as available.

d. Range environmental conditions to include, at a minimum, temperature humidity, wind speed, and wind direction. Wind speed may be omitted if testing was performed at an indoor range with minimal airflow during testing.

e. Physical orientation of the instrumentation to include, at a minimum, location of imagers(s) relative to the weapon.

f. Description of the instrumentation used to include, at a minimum, model numbers and vendors/sources of imagers, focal lengths and apertures of lenses/optics, filters, and any other devices within the imaging system. The band boundary wavelengths shall be specifically highlighted (for example, 8.3-11.5 μm).

g. Imager calibration information to include, at a minimum, the name of the calibration laboratory or OEM who performed the calibration, date of calibration, and sufficient information to allow traceability to a primary reference. If

[4] For $d_o > 20 \times \sqrt{A_{o,px}}$, the error for this simplified formula will have an error <0.1%.

calibration was performed by the user, then similar information regarding the reference source used for calibration shall be documented.

h. 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.

2.7. ERROR CONSIDERATIONS

1. Though a full error calculation for infrared signature measurements is beyond the scope of this document, some sources of error include the calibration error of the imager, physical alignment errors, changes in reflections off of objects within the imagers' fields of view, and differences in rates of heat transfer to the environment (typically due to different ambient temperatures or air flow). Practically, these errors limit the fidelity with which data collected during different tests or at different facilities can be compared. Care should be taken to ensure that environmental conditions and instrumentation configurations are consistent when comparing different data sets.

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Annex - A CALCULATION OF PIXEL SIZE

1. If the height of each pixel (h_{px}), also called the "pixel pitch", of a sensor is unknown, it can be calculated from an image of an object as long as the following other parameters are known: the length of the object (L_o), the distance between the object and the lens (d_o), and the focal length (f) of the lens.

2. For the purposes of this example, a 1 m × 5 cm × 0.5 cm flat aluminum bar will be assumed.

   a. Place the aluminum bar a known distance from the imager. The two ends of the bar should be equidistant from the imager such that the plane containing the bar is parallel to the plane of the imager. The distance between the imager and plane containing the front surface of the bar the bar is defined as d_o.

   b. Record an image of the bar oriented diagonally within the field of view of the imager. The recorded image should look similar to that illustrated in Figure 3, but with higher resolution.

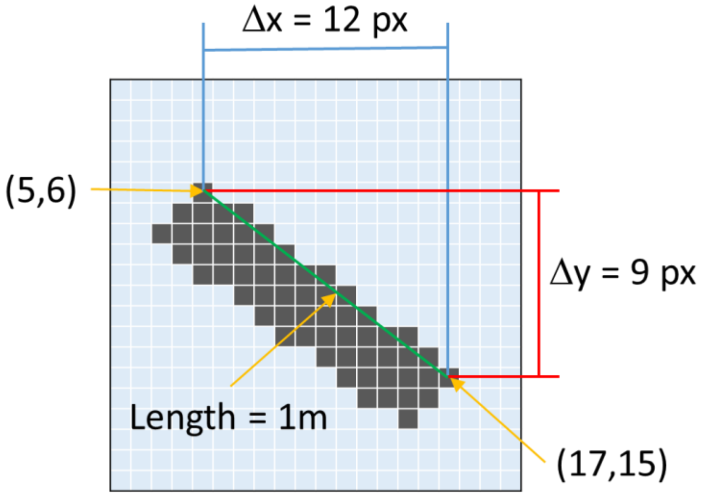

Figure 3 Example image used for determining the pixel pitch of a 20 pixel x 20 pixel imager.

   c. In software, identify the pixel coordinates containing the end-points of a long edge of the bar.

   d. Calculate the difference in position between these two points for the x and y dimensions (Δx and Δy respectively).

   e. Calculate the projected length of the bar in the x coordinate (L_x) according to Equation 6.

$$L_x = \frac{L_o}{\sqrt{1+\left(\frac{\Delta y}{\Delta x}\right)^2}} \quad \text{Eq 6.}$$

f. Calculate the edge dimension or a pixel (hpx), or the “pixel pitch”, according to Equation 7.

$$h_{px} = \frac{L_x}{\Delta x \times d_o\left(\frac{1}{f} - \frac{1}{d_o}\right)} \qquad \text{Eq 7.}$$

3. This example assumes a sensor with square pixels, which is the norm for imaging sensors. If, however, the height and width of the pixels in an imager are not the same, then the above method can be adapted to determine pixel dimensions using two different images in which the known-length object is oriented perfectly vertically in the first and perfectly horizontally in the second.

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