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Calibration of night vision goggles: an SI-units-based gain measurement technique

Vyacheslav B. Podobedov*, George P. Eppeldauer, and Thomas C. Larason

Sensor Science Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

Abstract

A gain measurement technique for the calibration of night vision goggles (NVG) is proposed and evaluated. This technique is based on the radiance measurements at the input and output of the NVG. In contrast to the old definition, which uses a non-International System of Units (SI) traceable luminance, the “equivalent luminance unit,” the suggested technique utilizes the radiance quantities that are traceable to the SI units through National Institute of Standards and Technology (NIST) standards. Due to the implementation of the scaling coefficients originating from the NVG spectral responsivities, the same NVG gain is expected within both techniques. The suggested method was evaluated at the NIST night vision calibration facility and the experimental data were compared to the results obtained with a commercial NVG test set. The comparison of the radiometric quantities obtained using the two different methods indicated differences up to 15% due to different calibration conditions. However, at proper calibration, equal NVG gains within both the suggested and old gain definitions were measured for the goggles equipped with a filmless image tube. The NVG gain uncertainty analysis, including the effect of no-moon night sky radiation, was performed for goggle types A, B, and C.

1. INTRODUCTION

The luminance gain of an image-intensifier-based device may be considered as a ratio of the output luminance to the input luminance [1–3]. This simplified approach, however, cannot serve as the universal night vision goggle (NVG) gain definition due to significant variations in the input and output photometric quantities. In particular, when NVGs become more sensitive to infrared (IR) radiation than to visible, the use of photopic units may lead to NVG testing artifacts [2]. Most of the night sky radiation detected by NVG is in the near-IR range above 800 nm [4, 5]. But for the luminance defined by the International Commission on Illumination (CIE), the $V(\lambda)$ photopic function characterizes only the visible range while it is indefinite in the longer-wavelength IR interval. The NVG manufacturing and testing procedures, however, need certain criteria to characterize the NVG gain. That includes the field NVG tests performed with limited access to complex laboratory equipment. By partially neglecting the preceding problems, the technical procedure for NVG gain calibration still follows the procedure described in [6, 7]. In this calibration, the fixed-level

*Corresponding author: vyacheslav.podobedov@nist.gov.

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IR input radiance of $2.4810^{-6} \text{ W sr}^{-1} \text{ m}^{-2}$ is treated as “equivalent luminance.” The value of this non-SI unit, “equivalent luminance,” was found from the equal NVG outputs when illuminated by radiation from blackbody (BB) source at 2856 K or from an IR light-emitting diode (LED) peaking at $\approx 820 \text{ nm}$. Accordingly, the NVG gain definition (old) which is still in use for NVG calibrations is

$$\text{Gain} = \text{output luminance} / \text{input luminance}, \quad (1)$$

where the input IR-LED radiance of $2.4810^{-6} \text{ W sr}^{-1} \text{ m}^{-2}$ is assumed to be equal to the “equivalent luminance” unit [6]. By characterization of the NVG output and input with a mix of different photometric and radiometric units, the definition [Eq. (1)] is the currently established value for NVG gain. The paradox of this approach is that a photometric unit cannot be used in the IR range where the $V(\lambda)$ function is not defined.

The uncertainty evaluation of the non-SI “equivalent luminance” is also problematic and has not been performed. In Ref. [6], an irradiance-ratio-based method was suggested to exclude the non-SI “equivalent luminance” from the NVG gain measurements. However, irradiance is distance dependent. This method could be used only if the NVG input and output geometries were fixed during the calibration, but the input and output geometries can be different between application and calibration. Additional problems and the increase of calibration uncertainties may be due to conversion of the output irradiance to luminance (as seen by the human eye).

The goal of this paper is to develop a new technique for NVG gain calibration using commercial test sets [6, 7] in field conditions. Candidate techniques utilize the radiance quantities that are traceable to the SI units through National Institute of Standards and Technology (NIST) standards. Taking into consideration the large amount of actively used NVG test sets and the existing calibration procedure, an important requirement for the new definition was to provide the same gain as in the old definition. This was performed by implementation of the two scaling coefficients $K1$ and $K2$ originating from the quantitative ratio between different radiometric units used in new and old definitions. Thus, with the LED radiation source calibrated in the SI radiance units, the new definition provides the same gain as a BB-based measurement using the “equivalent luminance” units.

2. NEW NVG GAIN DEFINITION AND INPUT AND OUTPUT QUANTITIES USED AT CALIBRATION

The suggested new NVG gain definition is based on the input and output *radiance* quantities [4]:

$$\text{Gain}(\text{new}) = K1 \cdot K2 \cdot R2 / R1, \quad (2)$$

where $R1$ is an input radiance and $R2$ is an output radiance. Coefficients $K1$ and $K2$ characterize the radiance spectral features at the NVG input and output, respectively, as discussed later. Both coefficients are constants for the same type of NVG with standardized spectral characteristics.

New transfer-standard radiance/luminance meters (SMs) that can measure the radiance and luminance levels over a wider range than required for NVG characterization have been developed at NIST [8]. These meters also can be used to transfer the NIST luminance and radiance scales to various NVG test sets used in NVG calibration services.

Common conditions for the NVG application and calibration modes are presented in Fig. 1. In application mode 1, the human eye observes the enhanced image of the object illuminated by the night sky. The eye can evaluate the NVG gain as a luminance ratio from images observed with and without NVG. For the NVG gain calibration within our new gain definition as pictured in mode 2 of the figure, the object is replaced by an LED irradiated sphere source. Both the input and output NVG radiance values are measured and used with Eq. (2). The gain definition [Eq. (2)] has to satisfy the following conditions:

- a. The output and input quantities should be expressed in the same units (radiance) and the gain must be dimensionless.
- b. The definition utilizes SI traceable radiometric units for NVG calibration.
- c. NVG gain is independent of the amplitude of the input signal within the linear range of the output.
- d. The responsivity curve of the human eye evaluating the NVG output is taken into account.
- e. The reference to the old NVG gain definition has to be established to comply with data for previously calibrated NVGs.

The proposed NVG gain definition was tested with a NVG by evaluation of the input and output quantities with a transfer-standard radiance/luminance meter. This NVG has a filmless GaAs photocathode and a green phosphor screen. Related spectral characteristics shown in Fig. 2 will be discussed in the following sections.

A. Measurement of NVG Output

The output of NVC is produced by a luminophore screen optimized for the responsivity curve of the human eye. Phosphor screens such as P20, P43, P46, and others have an output primarily in the blue–green interval of the visible spectral range. The magnitude of the NVG output will be determined from different data sets:

1. Integrated spectral radiance corrected to the relative responsivity curve of the human eye. This option is a relatively complicated and time-consuming procedure.
2. NVG output luminance converted to the effective (photopic) radiance using the conversion factor of $1/683 \text{ W lm}^{-1}$

The second method automatically accounts for the possible variations in the spectral characteristics of the phosphor screen. Furthermore, a luminance meter is a part of the NVG calibration test sets. Therefore, the implementation of the new gain definition should not require significant changes in the hardware except for a minor test-set reprogramming.

For the available NVG, both options 1 and 2 were tested experimentally. The normalized spectral characteristics of the NVG output and input are presented together with the CIE standardized $V(\lambda)$ function in Fig. 2. The following analysis uses the normalized spectral radiance of the phosphor screen found from the spectral irradiance measurements. The same collection angle for relative comparison of radiance and luminance is anticipated. Applying the responsivity curve of the human eye, the following output quantities can be found from the integration of the NVG spectral output characteristic:

1. Radiance $R = \int_{\lambda} R(\lambda) d\lambda$ is $7.9710^{-1} \text{ W sr}^{-1} \text{ m}^{-2}$,
2. Effective (photopic) radiance $R_{\text{ph}} = \int_{\lambda} R(\lambda)V(\lambda)d\lambda = 5.7510^{-3} \text{ W sr}^{-1} \text{ m}^{-2}$,
3. Luminance $L = 683 \int_{\lambda} R(\lambda) V(\lambda)d\lambda = 3.93 \text{ lm sr}^{-1} \text{ m}^{-2}$.

Due to mismatch of spectral characteristics of luminophore and $V(\lambda)$ function, the $K2$ in Eq. (2) found in direct measurements of spectral radiance (option 1) would be $5.7510 - 3/7.9710^{-3} = 0.72$. However, the correction of Radiance R with the $V(\lambda)$ function (photopic radiance $5.7510^{-3} \text{ W sr}^{-1} \text{ m}^{-2}$) will bring the coefficient $K2$ to unity.

The luminance of $3.93 \text{ lm sr}^{-1} \text{ m}^{-2}$ may be also measured directly (option 2). Then, applying the W/lm conversion factor of $1/683$, the same photopic radiance of $5.7510^{-3} \text{ W sr}^{-1} \text{ m}^{-2}$ will be obtained as by direct spectral radiance measurements accounting for the $V(\lambda)$ function. Thus, the coefficient $K2$ in both options will be equal to unity and may be omitted in Eq. (2).

B. Evaluation of the NVG Input Quantities

During NVG gain calibration, the radiation of the IR LED at the sphere output port is considered as an input to the NVG. To minimize possible error due to variation of the spectral position of the LED output, the latter must be chosen within the effective response interval of the NVG at about 820 nm. It should be noted that, in field applications, the spectral distribution of the illuminating source (night sky) has a near- continuous nature which is closer to a BB spectrum than to that of an LED. Nevertheless, for calibration purposes, the LED source is much more convenient than a BB. The new NVG gain definition results in the same gain value if measured with either an LED or a BB. The possible effect of the night sky spectrum is considered in Section 4. Thus, the LED was chosen in the near-IR range to be within the photocathode responsivity curves of GaAs photocathodes commonly used in NVGs. The GaAs photocathode is effective in the visible and near- IR ranges. Significant variations in responsivity, however, may be expected depending on the GaAs fabrication process [9,10]. The actual response of the photocathode (Fig. 2) of NVG described in Section 3.B was obtained experimentally. In this measurement, the tunable light source developed at NIST for absolute spectral responsivity calibration [11] of various sensors was utilized. The source radiation attenuated to the level preventing the saturation of the NVG output was applied to the photocathode while the radiation from the

luminophore was measured by a Si detector. Assuming that the spectral composition of the luminophore radiation is not affected by the spectrum of the input radiation, the signal from the Si detector weighted with a known output of the tunable source will directly mimic the spectral responsivity of the NVG photocathode presented in Fig. 2.

Several types of NVGs with different spectral characteristics at the present are standardized: types A, B, and C [12]. The spectral responses for these NVGs are presented in Fig. 3 with blue diamonds, red squares, pink diamonds, and green diamonds for NVG types A, B, C**, and C*, respectively. The difference in spectral response between the Class C* and Class C** curves is mostly due to a response flatness [13].

Due to the same type of photocathode used, all NVGs have similar spectral characteristics in the upper-wavelength range. At the low-wavelength end, the difference is due to the long-path filters installed into the NVGs to satisfy the different cockpit lighting compatibility issues [14]. In the spectral range of the test-set LED radiation, the input quantity and the measured ratio of output luminance to LED radiance (old gain definition) will be a constant for different types of NVG since the spectral responses of the type A, B, and C goggles are similar. When a NVG is used in a field application, where the object illumination (from the night sky) has a continuous nature, the gain will be higher for the NVG with a wider spectral range (type A in this case). To comply with this gain estimate, currently the IR LED radiance of $2.4810^{-8} \text{ W sr}^{-1} \text{ m}^{-2}$ is used for calibration of an NVG type B only. To adjust the measured gain, the different set points of LED radiance for measurement of type A and type C goggles were suggested [6]. The adjustment of LED output would change the measured NVG output and gain. The actual adjustment has to correlate with the NVG spectral efficiency within the broadband radiation of a 2856 K BB. Thus, in the old gain definition, the set equivalent luminance is not only a non-SI unit but its value changes with the type of the NVG.

In the new NVG gain definition, the account of the NVG spectral response is provided by the coefficient $K1$, which is a constant for each type of NVG. The actual input radiance is therefore not critical since the measured output will change proportionally to the input. This approach comprises a linear output/input NVG gain characteristic discussed in Section 3.B.

3. MEASUREMENT OF NVG GAIN

A. Measurements of Simulated NVG Output with Commercial Test Set

To validate the gain measured by commercial test set (CTS), a NLST-calibrated, new-generation night-vision radiometer SM was used to verify the luminance levels at the NVG input and output. The spectral radiance responsivity of this transfer standard radiometer is close to constant between 620 and 900 nm due to the application of a special filter at the front. Flat radiometric response is convenient for calibration of LEDs with different peak wavelengths and spectral bandwidths. For luminance measurements, the radiometric filter combination can be replaced with a photometric filter combination. Thus, the SM can be used as a universal meter.

The LED-irradiated sphere source in the CTS serves as an NVG input. The peak wavelength of the LED is approximately 820 nm. The SM-measured radiance at both output ports of the CTS (left and right NVG sections) is $2.5310^{-6} \text{ W sr}^{-1} \text{ m}^{-2}$, close to the pre-set value of $2.4810^{-6} \text{ W sr}^{-1} \text{ m}^{-2}$ used by the CTS for calculation of the NVG gain. The output of the NVG is measured by the internal pre-calibrated luminance meter of the CTS. For verification of the luminance meter readings provided by the CTS, additional sphere-based sources were utilized together with the SM. The developed sphere-based source served to simulate the output of a NVG. It was alternately irradiated with a few LEDs operated in the different wavelength ranges (Fig. 4). The external sources were needed for two reasons. First, the CTS does not display an actual NVG output luminance during the gain measurements. Instead, the NVG gain calculated according to Eq. (1) is directly displayed. Thus, the verification of the internal luminance meter was performed by comparing the gain reading from the CTS (using the internal meter) and the gain obtained with a calibrated SM. The second reason was due to various spectral luminophore efficiencies that different NVGs may have. It was therefore reasonable to check the CTS internal meter in different wavelength bands.

A summary of the NVG gain measurements (within the old gain definition) is presented in Table 1. For all four sources used, the NVG gain from the CTS was higher than determined by the NIST night-vision radiometer SM. Actual gain ratios are shown in the last column of Table 1. The observed ratio variation with the source spectrum may indicate an error in the calibration of the internal luminance meter of the CTS. According to the manufacturer's specification, the calibration of this meter is performed using a narrow-band radiation from a green LED.

The next set of the data presented in Table 2 provides the comparison of the NVG gain measured using the old luminance ratio definition [Eq. (1)] and the output/input radiance ratio required for the new gain definition. At this point, the coefficient $K1$ has not been applied yet. As seen, the output/input radiance ratio used for gain measurements in the suggested new definition is about five times lower than the gain obtained from the output/input luminance ratio using the old definition. The reason for the discrepancy is the artificially defined "equivalent luminance" unit [6] used for the NVG input characterization. Notice that the equivalent luminance unit and the luminance unit used for the NVG output quantity do not match. The luminance from the 2856 K BB resulting in the same NVG output as an LED radiation of $2.48210^{-6} \text{ W sr}^{-1} \text{ m}^{-2}$ is $3.42610^{-4} \text{ lm sr}^{-1} \text{ m}^{-2}$. The conversion of $3.42610^{-4} \text{ lm sr}^{-1} \text{ m}^{-2}$ to photopic radiance results in a value of $3.42610^{-4}/683 = 5.01610^{-7} \text{ W sr}^{-1} \text{ m}^{-2}$ radiance from LED. To create the reference to the old NVG gain definition and match with the data of previously calibrated NVGs, it is reasonable to use the ratio of 4.95 as the coefficient $K1$ in the new NVG gain definition. Taking into account that $K2$ coefficient is unity for the photopic output measurements, Eq. (2) (new NVG gain definition) becomes

$$\text{Gain} = K \cdot \text{output radiance} / \text{input radiance}, \quad (3)$$

where the coefficient $K = K_1$ equalizes the numerical gain values in the new and old NVG gain definitions. It should be noted that the ratio of 4.95 was affected by several different parameters: spectral characteristics of both the BB and IR LED, spectral response of NVG type B, and the input radiance of $2.48210^{-6} \text{ W sr}^{-1} \text{ m}^{-2}$ set for the NVG type B. Table 3 summarizes the preceding numerical relations within the old and new NVG definitions. This table displays the example of radiometric quantities corresponding to NVG gain of 1000 within both the old and new gain definitions.

The coefficient K must be adjusted according to the change in the NVG spectral response for the arbitrary-type NVGs, including A and C. Within the new NVG gain definition, we suggest setting the coefficient K equal to 5.42 and 4.71 for NVGs type A and C, respectively. There is no more need to adjust the output LED radiance [6] as mentioned in Section 2.B. Notice that the NVG input radiance is not critical for the gain measurements assuming a linear response characteristic of the NVG. The suggested values for coefficient K are based on the known spectral responses of the type A and C NVGs, prorated to that of type B. The K_i coefficients are obtained from the integrated NVG input quantities as follows:

$$K_i = K_B \int_{\lambda} S_i(\lambda) N(\lambda) d\lambda / \int_{\lambda} S_B(\lambda) N(\lambda) d\lambda, \quad (4)$$

where $S_i(\lambda)$ is a normalized (standard) NVG responsivity, index i denotes the i -type NVG, $S_B(\lambda)$ is the normalized (standard) responsivity of NVG type B, and $N(\lambda)$ is the spectral radiance of the 2856 K blackbody. The spectral radiance of the blackbody still serves as a reference to obtain the same NVG gain when measured with either BB or LED. A similar procedure was suggested in Ref. [7] to address the difference between the individual NVG spectral responsivities.

During the NVG gain calibration with the GTS, the NVG input is preset to $2.4810^{-6} \text{ Wsr}^{-1} \text{ m}^{-2}$. The output quantity (luminance) is measured and then converted into the NVG gain. Thus, an alternative option to prorate the measured gain for different type of NVGs may be the adjustment of the input, as suggested in Ref. [3], while using the same coefficient $K = 4.95$. The input radiance then should be set to $2.6810^{-6} \text{ Wsr}^{-1} \text{ m}^{-2}$ and $2.3310^{-6} \text{ Wsr}^{-1} \text{ m}^{-2}$ for NVG types A and C, respectively. Accordingly, the same NVG gain as with the utilization of different K coefficients and a fixed radiance of $2.4810^{-6} \text{ Wsr}^{-1} \text{ m}^{-2}$ will be measured.

B. Gain Measurements of the NVG

To evaluate the new NVG gain definition and compare it to direct gain reading from the CTS, the input and output quantities of the NVG were measured with both an SM and GTS meter. The radiance from the near-IR LED in the CTS was used as an input for the NVG. For the spectral response of the NVG presented in Fig. 2, an effective spectral match of the NVG response and the LED spectral distribution was observed. The GaAs photocathode used in the tested NVG is known to cover a wider spectral range than the wavelength coverage of the type A, B, and C NVGs. The NVG input radiance was measured directly with the SM and compared to the expected output of the CTS. The output NVG (photopic)

radiance was found from luminance measurements with the SM, as described in Section 2.A. For better statistics, the data for both left and right sections of the NVG were included in gain evaluation. A summary of the results is shown in Table 4. As expected, due to the specific spectral responsivity of the NVG photocathode shown in Fig. 2, the NVG gain for the new definition is higher. Indeed, the preset parameters for gain measurement by the CTS assume the responsivity of NVG type B. The new gain definition accounts for the particular spectral responsivity of the tested NVG, and the gain in Table 4 is shown as a product of the measured output/input radiance ratio multiplied by the coefficient K according to Eq. (3). The co-efficient K of 6.7 for the tested NVG was found by comparison of the tested NVG to the type B NVG, as indicated in Eq. (4). Thus, in the new NVG gain definition, the coefficient K_i serves as a reference to the input characteristic of the NVG for evaluation of the gain.

An additional factor affecting the measured gain may be due to possible nonlinearity of the NVG characteristics. The NVG nonlinearity may be due to a charge saturation effect in the NVG image intensifier. Another source may be the automatic gain control which prevents the NVG from damage by reduction of the NVG gain at a higher input radiation level. The linearity of the NVG gain characteristic presented in Fig. 5 was verified experimentally. It was found that, within the uncertainty of the experiment, the NVG output may be considered as a linear function of its input signal in the range of the input radiance between $10^{-7} \text{ Wsr}^{-1} \text{ m}^{-2}$ and $10^{-5} \text{ Wsr}^{-1} \text{ m}^{-2}$ where the gain measurements were performed.

4. NIGHT SKY RADIATION AND NVG APPLICATIONS

In the calibration procedure, the NVG gain is measured using IR radiation and is referenced to blackbody radiation. In field applications, only broadband radiation from the no-moon night sky affects the NVG input. Unlike the radiation of a 2856 K BB standard source with a well-known spectral distribution, the spectrum of the no-moon night sky radiation may vary in both the radiance level and spectral distribution depending on different factors, including observation place, time, fog, rain, and others [4,5,15]. In particular, the actual radiation at the NVG input depends also on the optical properties of the monitored object, i.e., absorption, reflection, and scattering. Therefore, certain errors for the NVG gain may be expected due to the difference in the spectral distribution of the BB and night sky radiation. As will be shown shortly, this difference is unlikely to be observed by the human eye. However, the related uncertainty estimation may be provided by comparing the contribution of a particular spectrum to the NVG input. Taking all environmental conditions and optical properties of the object into consideration would be impractical. However, in a simplified approach based on the radiation spectral distribution only, Eq. (4) may be applied for estimation of the gain correction factors [16]. The spectral shapes of no-moon night sky radiance and irradiance used for analysis are presented in Fig. 6. The spectral radiance presented is an average of about 200 experimentally recorded spectra [4]. The estimate of the gain correction for the NVG output, which is caused by a difference in the spectral distribution of BB and no-moon night sky radiance, was performed accounting for the experimental distributions presented in Fig. 6. The related K_i coefficients presented in Table 5 and prorated to those of BB were obtained in the same integrating procedure as in case of BB radiation (Section 2.B) utilizing the night sky spectral distributions. Because no standard

for NVG gain under the night sky illumination exists, the gain of the NVG type B and a spectrum of the 2856 K blackbody were chosen as a reference. Accordingly, Table 5 was compiled assuming no errors for NVG type B for both BB and night sky spectral radiance, i.e., the coefficient K does not change. As shown in Table 5, the expected error due to the specific shape of the night sky radiation spectrum is under several percent. This value may be small compared to the effect of the simplified approach just shown, ignoring the actual spectrum emitted by the monitored object. The present estimate just provides an idea on how the illumination spectrum may affect the NVG gain defined in the calibration procedure using the standard sources. Notice that the expected several percent difference in the NVG gain is relatively small for absolute evaluation by human vision.

5. UNCERTAINTY ANALYSIS

The uncertainty components of the NVG gain calibration discussed here include the errors of input and output NVG quantities in the new definition. The basic components are due to the difference in the LED spectral characteristics, the variation in the spectral responses of the same type of NVGs, and the measurement errors of both the input and output radiometric quantities. Actual calculation of the uncertainty components was performed by a specially designed program. The latter treated the tabulated data for standardized NVG spectral responses, $S(\lambda)$ and the source output characteristics, including $L(\lambda)$ (LED) and $W(\lambda)$ (BB at 2856 K), presented in Fig. 3. Except when using the standardized spectral characteristics, the program allowed the modeling of possible variation of the $S(\lambda)$ LED peak position and an LED FWHM. The main goal was to calculate the value of integral $\int_{\lambda} S(\lambda)L(\lambda)d\lambda$ characterizing the NVG gain and to evaluate its relative changes due to possible variation of LED parameters as described in the following. Notice that for modeling purposes the actual variations were chosen based on the known performance of real LEDs.

Both the LED peak position and its FWHM spectral width will affect the measured NVG gain even if the spectral peaks of the LEDs are located within the NVG response function close to its maximum and the output radiance is measured correctly. The CTS is equipped with an LED that peaks at ≈ 820 nm. The LED-related uncertainty components for the B-type NVGs were calculated from the variation of the integral quantity $\int_{\lambda} S_B(\lambda)L(\lambda)d\lambda$. The $S_B(\lambda)$ (normalized NVG type B spectral response) is expected to be constant while the $L(\lambda)$ (LED parameter) may vary. A maximum 10 nm shift in the LED peak position and a 10% variation in the FWHM of the 820 nm LED was assumed in the calculation of the uncertainty components. The imposed limits cover the practically possible variations of the LED parameters. The uncertainty components related to variation of the LED parameters are shown in the first two rows of Table 6. Along with LED radiation, the spectral response $S(\lambda)$ of NVG contributes to the NVG input quantity. The actual variation of $S(\lambda)$ for the same type of NVG is defined in the factory-issued list of technical performance. The unknown variation in the NVG spectral response may not be detected during calibration due to a limited spectral range of the LED radiation. This component of uncertainty presented in the third row of Table 6 was therefore calculated using the 30 nm spread of the spectral NVG characteristic [12] and spectral radiance of a BB at 2856 K. The remaining uncertainty components are due to measurements of input and output NVG quantities. The related numbers are known from the performance of the radiometers and photometers used in the

calibration. The uncertainty components presented in the fourth and fifth rows of Table 6 are based on the performance of the NIST transfer standard SM [8].

The field effects related to spectral distribution of the night sky radiation do not directly contribute to the uncertainty of the NVG gain calibration. However, certain inconsistencies of the gain measured for different types of NVGs may be expected. As shown in Section 3, the estimated errors are unlikely to be detected by the human eye in field applications.

6. CONCLUSION

A new definition for NVG gain calibration using SI traceable radiometric units has been developed and evaluated. The definition is based on the ratio of the output radiance to input radiance utilized for the NVG gain calibration. The NVG gain calibrated with an LED is traceable to the 2856 K BB standard radiation source. The responsivity of the human eye is accounted for in the evaluation of NVG output. The NVG-type scaling coefficient implemented in the new definition makes the gain values in both the new and old definitions the same. This coefficient is a constant for the same type of NVG and its value originates from the artificial unit, called “equivalent luminance,” that was included in the old definition. Unlike with the old definition, the gain is now dimensionless and does not depend on the amplitude of the input signal within the linear model. The new definition specifies that the source radiation (820 nm LED) be located within the spectral responsivity of the NVG input as in the case of NVG types A, B, and C. If the NVG is more sensitive to visible light, the LED should be selected properly and the coefficient K should be redefined as described in Section 3.A.

The measurements of the input and output radiometric quantities for the NVG with a filmless image tube were provided for evaluation of the new definition. Experimental simulation of the NVG output for the gain measurement with different sphere-based LED sources allowed spectral characterization of various luminophores that may be used in the NVG designs. In this simulation, the spectral characteristics of the goggle output were studied to characterize the photopic radiance utilized in the new definition. The data obtained indicate the equivalence of photopic radiance measured with either the spectral radiance meter or the luminance meter. These measurements account for the spectral mismatch of the NVG output radiation and the CIE $V(\lambda)$ photopic function. The comparison of the gain data from the commercial test set and the NIST night vision facility indicates equal NVG gain in both the new and old NVG gain definitions within the experimental uncertainty.

The spectra of the field night sky (no-moon) radiance were evaluated to estimate the NVG input quantities. It was shown that the spectral shape of the input radiance may affect the NVG gain defined in the calibration procedure. In particular, for NVG types A, B and C, the night sky radiance, if used for the gain measurement, would introduce the several-percent error. It is anticipated, however, that actual effect would be small for the human vision.

Research is being continued to minimize the spectral mismatch between calibration and field applications by using more than one LED at calibration to mimic the lowest (without the moon) night sky distribution.

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Fig. 1.
NVG evaluation (1) in a field application and (2) in the calibration setup.

Fig. 2. Normalized NVC spectral characteristics: GaAs photocathode responsivity (solid dots, red), radiance of the phosphor screen (diamonds, black), and the $V(\lambda)$ function (hollow dots, green).

Fig. 3.
Normalized spectral characteristics of the type A, B, C*, and C** NVGs blackbody at 2856 K and IR LED.

Fig. 4.
Normalized spectral output of the LED sphere-based source.

Fig. 5. NVG output radiance versus the input radiance. The data are presented for both left and right sections of NVG.

Fig. 6.
Normalized spectra of the no-moon night sky spectral radiance.

Table 1

Comparison of NVG Gain from CTS and NIST Luminance Data Using the Old NVG Gain Definition

Source	Peak WL, nm	Gain CTS	Gain NIST Data	Gain Ratio
1	462	2430	2177	1.1
2	527	2660	2384	1.1
3	565	2660	2430	1.09
4	626	2360	2063	1.14

Table 2

NVG Output/Input NIST Data Comparison When Using the Old and New Gain Definitions

Source	Peak WL, nm	Out/In Luminance Ratio (for gain_old)	Out/In Radiance Ratio (for gain_new)	Out/In Data Ratio
1	462	2177	430	0.2
2	527	2384	471	0.2
3	565	2430	480	0.2
4	626	2063	408	0.2

Table 3

Example of the NVG Output/Input Quantities Related to NVG-B Gain of 1000

NVG Parameter	Old Definition	New Definition
INPUT (Near-IR LED)	Radiance ($2.48 \cdot 10^{-6} \text{ Wsr}^{-1} \text{ m}^{-2}$) treated as EQUIVALENT Luminance of 10^{-1} non-SI unit	Radiance ($2.48 \cdot 10^{-6} \text{ Wsr}^{-1} \text{ m}^{-2}$)
OUTPUT	Luminance (10^{-1} noil -SI unit)	Radiance ($5.02 \cdot 10^{-4} \text{ Wsr}^{-1} \text{ m}^{-2}$)
K	N/A	4.95
GAIN	$\frac{\text{OUTPUT}}{\text{INPUT}} = 10^3$	$K \frac{\text{OUTPUT}}{\text{INPUT}} = 10^3$

Table 4

NVG Gain Measurements with Input from the CTS

Sample #	NVG Input Radiance, $\text{Wsr}^{-1} \text{m}^{-2}$	Gain (CTS)	NVG Output Radiance, $\text{Wsr}^{-1} \text{m}^{-2}$	Gain (New Definition)
1_L	2.68E-06	3538	1.86E-03	4649
2_R	2.71E-06	3608	1.92E-03	4744
3_L	2.68E-06	2964	1.68E-03	4216
4_R	2.69E-06	3365	1.86E-03	4628
5_L	2.69E-06	3451	1.82E-03	4530
6_R	2.71E-06	3470	1.80E-03	4452
7_L	2.69E-06	3451	1.81E-03	4509
8_R	2.71E-06	3415	1.79E-03	4424
9_L	2.64E-06	3441	1.79E-03	4547
10_R	2.69E-06	3384	1.77E-03	4421
STD_L, %		6.1		3.2
STD_R, %		2.5		2.9

Table 5
 Ki Coefficients and Estimated Errors for NVG Gain Definition in Field Applications

Input	Ki Coefficients			Error, %		
	A	B	C*	A	B	C*
NVG Type						
Night sky spectral radiance	5.2	4.95	4.8	-4.1	0	2.3
BB and LED radiance	5.42	4.95	4.71	0	0	0

Table 6

Uncertainty Budget for Type B NVG Gain Measurements, %

#	Component	Standard Uncertainty	Expanded Uncertainty ($k = 2$)
1	LED peak position	1.2	
2	LED FWHM	0.1	
3	NVG spectral response	2.5	
4	Input radiance	1.5	
5	Output radiance	0.7	
	Combined uncertainty	3.0	6.0