An approach for estimation of night vision devices performance in respect of temperature variation

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Abstract: The majority of night vision devices are based on low light level amplifying technology. Designing of such systems with optical and electronic components can be done using the energy calculations method. As a result of this method the device working range can be estimated as a function of external and internal parameters. To determine the dependence between working range and ambient temperature, a new reference parameter of image intensifier tubes called equivalent temperature signal to noise is introduced. The experimental results show that variation in ambient temperature affects the working range. This dependency is illustrated for different image intensifier technology using under different ambient temperature. The proposed approach can be used to estimate device working range under given surveillance temperature.

Keywords: *night vision device, ambient temperature, working range, dark current, equivalent background input, new reference parameter.*

I. INTRODUCTION

The majority of night vision devices (NVD) are based on low light level amplifying technology. All of them are built around optoelectronic channel (or channels), consisting of objective, image intensifier tube (IIT) and eyepiece (ocular) [Borissova et al., 2001]. Designing of such systems with optical and electronic components have to be done taking into account both of components parameters and external surveillance conditions. This stage of designing relies on energy calculations method [Elizarenko et al., 1981]. The goal of energy calculations method is to determine the minimum energy threshold of NVD optoelectronic channel considering the used parameters of optical elements. This means to get some estimates for the useful input signal and values for the minimum input signal under which the device will operate normally. The minimum input signal or the threshold of device sensitivity depends on the noise amount that is always present in an optical device. The energy calculations method consists of 3 consequence stages that are inseparable part of the design as shown on Fig. 1.

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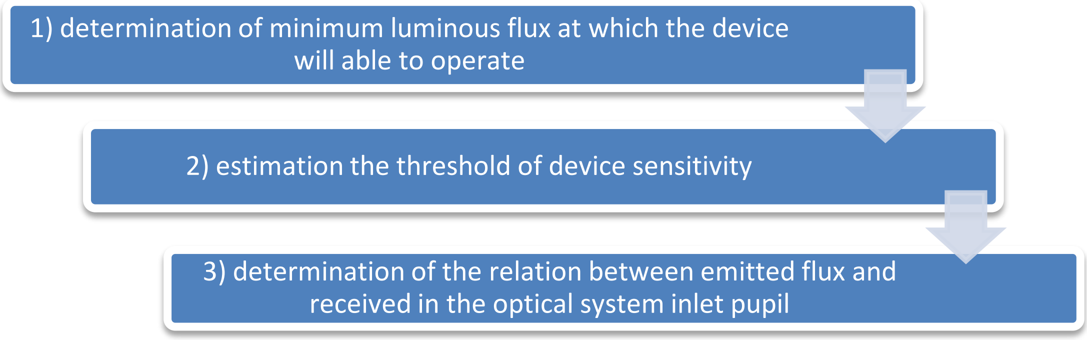

Fig. 1. Stages of energy calculations method

At first, the minimum luminous flux at which the device will able to operate are to be calculated. On the second stage, the estimation for threshold device sensitivity is needed and estimation about its dependence on external and internal factors is to be done. On the third stage, the relation between the emitted flux that is received in the optical system inlet pupil have to be expressed. The useful part of the light flux is expressed as a function of external conditions and the parameters of the optical system. Finding the appropriate optimal ratio between the luminous flux from the object and the minimum luminous flux (flux threshold) for optical system operation is essential. Selection of an optimal relation between these two flows – thresholds and minimum, represents the signal to noise parameter. This optimal relation for signal to noise parameter is the minimum signal to noise ratio at which the device will still operates. If the relation between the signal and the noise becomes less than the necessary minimum, the device will stop working. It should be noted that this relation refers to the whole optical device, and is different from the signal to noise parameter (μ) that is present in the specifications of the image intensifier tubes. The basic energy dependence is presented as follows:

$$\mu \leq \frac{\Phi_{in.\min}}{\Phi_{th}} \tag{1}$$

where: μ represents the required minimum ratio of signal to noise, $\Phi_{in.min}$ – the required minimum input flow, Φ_{th} – threshold of sensitivity.

The relation between arriving flux (Φ) at the surface (A) from any direction above the surface determines the illumination (E) as:

$$E = \frac{\Phi}{A} \tag{2}$$

For point source of light the illumination (E) of the object can be represented as:

$$E = \frac{I.\cos\omega}{R^2} \tag{3}$$

where: I is the intensity (or radiance), R is the distance between the point source of light and the receiver and ω is the solid angle.

In case of a point emitting object, the solid angle under which the object is observed is sufficiently narrow, i.e. $cos(\omega)$ = 1 and the relation for the light flux can be transformed as follows:

$$\Phi_{in} = \frac{I_{in}.A_{in}}{R^2} \tag{4}$$

where: Φ_{in} is the light flow that falls on the device, I_{in} is the intensity of point object, A_{in} is the inlet area and R is the distance between the light source and the device.

Using the relations (1) and (4) the relation between emitted power from the point object and threshold of sensitivity device can be expressed as:

$$\mu \le \frac{I_{in}.A_{in}}{\Phi_{th}.R^2} \tag{5}$$

Considering the Beer-Lambert law, the empirical relationship between absorption of light by a material through which the light is passing can be expressed [Beer-Lambert Law and Visible Light Spectrometers]. When a beam of light passes through a substance, some of the light may be absorbed and the remainder transmitted through the sample. The ratio of the intensity of the entering light (I_{in}) to that exiting (I) at a particular wavelength is defined as transmittance τ:

$$\tau = \frac{I_{in}}{I} \text{ or } I_{in} = I.\tau \tag{6}$$

Reflected light from the surveillance target object passes through the atmosphere environment, through the lens and finally falls within image intensifier screen. Taking into account these considerations, the NVD working range R can be calculated as:

$$R \ge \sqrt{\frac{I.\tau_a.\tau_o.A_{in}}{\mu.\Phi_{th}}} \tag{7}$$

where: R – working range (m), I – intensity (lx), τ_a, τ_o – atmosphere and optical transmittance (dimensionless), A_{in} – inlet pupil (m^2), μ – signal to noise ratio providing the normal device operation (dimensionless), Φ_{th} – threshold of IIT sensitivity (lm).

As final result of energy calculation method, the device working range can be estimated as proportional to the square root of the area of the inlet aperture, light emitted power, and atmosphere transmittance, and is inversely proportional to the minimum signal to noise ratio, and threshold of optical device sensitivity. Using such approach, an analytical model for night vision goggles working range (detection, recognition and identification range) is described [Borissova, 2005].

It is interesting to estimate how ambient temperature affects the device working range. The ambient temperature varies during the night, seasons and geographic location. Unlike the objective and ocular, image intensifier tube as the most important module of NVD is affected by the temperature. Intensifier tube dark current, called "Equivalent Background Illumination" or "EBI", is not a significant factor at room temperature, but can seriously degrade image contrast and intra-scene dynamic range at such high temperatures [Bender et al., 2004]. The EBI is affected by temperature with higher temperatures producing higher EBI. The EBI level determines the zero contrast level between low-brightness objects being observed and inherits background illumination level [Cooke, 2005]. Excessive EBI tends to reduce contrast at low light levels and high temperatures because EBI doubles for every 3-4 degree Celsius rise in temperature [Travis, 1996]. This paper seeks to define mathematical relation for estimation the dependence of NVD working range under different ambient temperatures.

II. PROBLEM DESCRIPTION

The most temperature sensitive element of NVD is image intensifier tube due the used photoelectric effect. The kinetic energy of ejected electron from photocathode is related with the ambient temperature. In the absence of any input illumination on the photocathode, the phosphor screen will still show a definite background illumination. The phosphor screen of image intensifiers converts the electron avalanche from the micro channel plate back into photons. Equivalent background illumination (EBI) can be interpreted as a measure of the dark current, the flux electrons generated by the components and forces within an image intensifier in the absence of photoelectrons. The given values of EBI in datasheets are measured at ambient temperature of 21 ^{o} Celsius [MIL-STD-1858]. EBI is affected by temperature – the warmer the night vision device, the brighter the background illumination [Homeland Security, 2007]. With temperature increasing, the EBI values became noticeable increased. Higher EBI means lower image contrast at low luminance, as well as, a significant reduction in range performance. The effect of this is most notable when viewing deep sky objects which have very weak luminosity and in environments where the ambient light levels are at a minimum [Night Vision, 2011]. The EBI level determines the lowest light level at which an image can be detected [Homeland Security, 2007]. It is believed that the thermal electron emission of photocathode leads to the excessive EBI [Zhu, et al., 2013]. The problem can be formalized as: to define a mathematical expression for relation between the EBI parameter, device working range and ambient temperature.

III. ESTIMATION OF NVD WORKING RANGE IN RELATION OF TEMPERATURE VARIATION

The signal to noise ration given in the factory specifications are measured in the laboratory using a reference source and the light level of 10^{-4} lx. On the IIT screen a light spot is focusing with diameter of 0.2 mm. The signal-to-noise ratio can be measured under light levels that differ from the reference level of illumination. In such cases it is possible to use the relation between noise and the electrons quantity that reach the IIT screen using the following expression [Bosch, 2000; Bosch & Boskma, 1994]:

$$\frac{S}{N} = \sqrt{\frac{A_{ob}.E.S.t_i}{Q.F}} \tag{8}$$

where: A_{ob} – target area (m^2), E – input illumination (lx), S – photocathode sensitivity (A/lm), t_i – integration time (s), Q elementary charge $1.6.10^{-19}$ C, F – noise factor.

Accordingly to the U.S. military standard (MIL-STD-105), the EBI is measured at ambient temperature of 21 degrees Celsius. This is why a new reference parameter of IIT called equivalent temperature signal to noise $(S/N)_{et}$ is introduced:

$$T_e\left(\frac{S}{N}\right)_{et} = \frac{S}{N} \text{ or } \left(\frac{S}{N}\right)_{et} = \frac{1}{T_e}\left(\frac{S}{N}\right) \tag{9}$$

where: T_e is the reference temperature under which are measured the IIT ($T_e = 21^o$ C) and $(S/N)_{et}$ is the equivalent temperature signal to noise.

Taking into account the device working range relation (7), signal to noise ratio relation (8) and introduced equivalent temperature signal to noise by (9), the NVD working range R can be expressed as:

$$R = \sqrt{\frac{\tau_a.\tau_o.A_{in}.I.A_{ob}^{et}.E^{et}.S.t_i}{\mu.\Phi_{th}.Q.F.T^2}} \tag{10}$$

where: R – working range (m), τ_a, τ_o – atmosphere and optical transmittance (dimensionless), A_{in} – inlet pupil (m^2), I – intensity (lx); A_{ob}^{et} – reference target area focused on photocathode (m^2), S – IIT luminous sensitivity (A/lm), E^{et} – reference input illumination on photocathode (lx), t_i – integration time (s), μ – signal to noise ratio providing the normal device operation (dimensionless), Φ_{th} – threshold of IIT sensitivity (lm), Q – elementary charge ($1.6.10^{-19}$ C), F – IIT noise factor (dimensionless), T – ambient temperature (^{o} C).

The relation (10) can be used to estimate device working range under given surveillance temperature taking into account both of device parameters and external conditions.

IV. NUMERICAL EXPERIMENTATION AND DISSCUSION

To verify the practical applicability of the proposed dependence of NVD working range and temperature variation some numerical calculations are done. The used input data to determine the NVD working range in relation to the ambient temperature takes into account the following environmental conditions and optical device parameters:

- inlet pupil area A_{in} = 0,01 m^2
- atmosphere transmittance τ_a = 0,7
- optical transmittance τ_o = 0,78
- point light source with intensity I = 100 Cd
- reference target area focused on photocathode A_{ob}^{et} =3,14.10^{-8} [m^2]
- reference input illumination on photocathode E^{et} = 10^{-4} lx
- integration time t_i = 0,1 s
- signal to noise ratio providing the normal device operation μ = 10
- limiting device sensitivity of Φ_{th} = 10^{-7} lm
- noise factor F = 1.9
- elementary charge Q = 1,6.10^{-19} C

The dependence between NVD working range and ambient temperature using the proposed relation (10), the following parameters of image intensifier tube type XX1940AM integrated into NVD are used: luminous sensitivity = 500 *µA/lm* with signal to noise ratio of 21.

In case of ambient temperature of 21^o C and IIT type *XX1940AM*, the working range reaches 753 meters. Increasing the temperature to the 30^o C leads to reducing the working range to 530 meters. Some temperature values and calculated by (10) working ranges of NVD (with IIT type *XX1940*) are shown in Table 2:

Table 1. Dependence of NVD working range from temperature (IIT XX1940)

T, [^{o} C]	21	24	27	30	33	36	39	42
R [meters]	799	699	621	559	508	466	430	399

When the image intensifier tube is replaced by IIT type *XX2040* with signal to noise ratio of 20 and luminous sensitivity of 600 *µA/lm*, the corresponding working range and temperature dependency are shown in Table 2.

Table 2. Dependence of NVD working range from temperature (IIT XX2040)

T, [^{o} C]	21	24	27	30	33	36	39	42
R [meters]	875	766	681	613	557	510	471	437

Using the IIT *XX2540D* with signal to noise ratio of 25 and luminous sensitivity of 700 *µA/lm*, the corresponding results for working range influenced by temperature are shown in Table 3.

Table 3. Dependence of NVD working range from temperature (IIT XX2540D)

T, [^{o} C]	21	24	27	30	33	36	39	42
R [meters]	946	827	735	662	602	551	509	473

For NVD with image intensifier tube type *XX1940* and temperature range between 21 and 42^o C, the working range vary within interval of 753 to 379 meters. The variation of NVD working range from 830 to 415 meters is obtained as result of image intensifier tube type *XX2040* using and the same temperature range. When image intensifier tube type *XX2540D* is used, the NVD working range is shifted from 897 to 448 meters under temperature range (21 ÷ 42)^o C. Increasing of the ambient temperature leads to decreasing the NVD working range. The increasing of IIT luminous sensitivity is proportional to the NVD working range.

VI. CONCLUSION

Variation of ambient temperature affects the NVD parameters, respectively its working range. Raising the temperature of the environment reflects in increasing the temperature of the whole device. The paper describes an approach for preliminary estimation of NVD working range under given surveillance temperature. To determine the dependence between working range and ambient temperature, a new reference parameter of image intensifier tubes called equivalent temperature signal to noise is introduced. The experimental results show that variation in ambient temperature affects the working range. When XD-4TM technology is using, the device working range is increased with about 10% greater than technology SHD-3TM using. The value of this increasing is kept constant in the whole investigated temperature range. For *XR5TM* technology the increasing the working rage is about 8-10 % compared to *XD-4TM*.

Due to their nature, the EBI become significant in very hot environments. The obtained results show that the EBI is an important parameter influencing the NVD working range. To compensate in some degree this dependency NVD should use IIT with higher luminous sensitivity. Using this approach some preliminary estimation for NVD device working range can be obtained to determine the performance of particular NVD under different surveillance conditions.

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