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Updating a model of noise equivalent temperature difference of infrared systems for finite distance between sensor and object

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Classical noise equivalent temperature difference (NETD) models have been derived based on the assumption that the distance between the object and the IR sensor is infinite. A few years ago a NETD model for finite object-system distance was published that showed significant dependence of the NETD values on the object-system distance. However, the model has two significant limitations. First, there has not been derived a clear relationship between the NETD and the parameters of the optical system. Second, the same can be said about the relationship between the new model and the classical ones. In this paper, these limitations are removed. A modified NETD model is presented that can be treated as a more general version of the classical models. A clear relationship between the NETD for finite distances and the parameters of the optical systems has also been found.

1. Introduction

Temperature resolution is one of the most important parameters of infrared systems. It is usually taken as the noise equivalent temperature difference (NETD) and defined as the blackbody temperature difference between a target and its background required to produce a peak signal-to-rms noise ratio of unity at a suitable point in an electrical channel of the device [1].

Independent of some insignificant differences there is a common feature of most popular models of the NETD parameter [2]–[6]. For reasons of convenience an assumption has been made in measuring and deriving relation for the NETD that states: the distance between the tested object and the sensor is infinite. It means that the distance between object and optics s is many times longer than the distance between image of the object and optics s'. For such a situation the distance between image of the object and optics s' is approximately equal to the focal length f' of the imaging optics and the optical lateral magnification β is near null. The assumption is almost always fulfilled for military observation IR systems. However, for a variety of practical applications of civil measurement systems the distance has to be short and the assumption is not fulfilled. Therefore, the classical NETD models [2]–[6] cannot be applied to infrared systems under short-distance conditions.

A NETD model for finite distance between object and system was published a few years ago [7]. The model enables calculation of the NETD for any object-system distance according to the formula

$$\mathrm{NETD} = \frac{\beta^2 \sqrt{\Delta f}}{\pi\tau_0\sqrt{A_d}\sin^2 u_m \int\limits_{\lambda_2}^{\lambda_1} D^*(\lambda)\dfrac{\partial L_\lambda}{\partial T_{ob}}d\lambda}, \tag{1}$$

β – the lateral magnification of the optical system, $\sin u_m$ – the numerical aperture of the optical system in the object space, τ_0 – an effective optical transmittance, A_d – the detector area, Δf – electronics bandpass, $D^*(\lambda)$ – the detector detectivity for a wavelength λ, $\partial L/\partial T_{ob}$ – the derivative of the spectral luminance with respect to temperature at the radiation wavelength λ and temperature T_{ob}.

There are two serious limitations of this NETD model. First, formula (1) presents no clear relationship between the NETD and the parameters of the optical system. Second, the same can be said about the relationship between the model in the form of formula (1) and the classical ones presented in works [3]–[6].

In this paper, the NETD model presented in [7] has been modified. The relationship between typical parameters of the optical system and the NETD for finite object-system distance has been derived. A clear relationship between this modified NETD model and the classical models has been found. In this way the limitations of the model presented in work [7] have been removed.

2. Derivation of NETD model

For the purpose of clarifying the problem of NETD dependence on parameters of optical system several assumptions have been made. First, the IR detector is put exactly into the image plane of the tested object, and it sees, due to the cold shield, only the optics. Second, the well-corrected imaging aplanatic optics that fulfils the

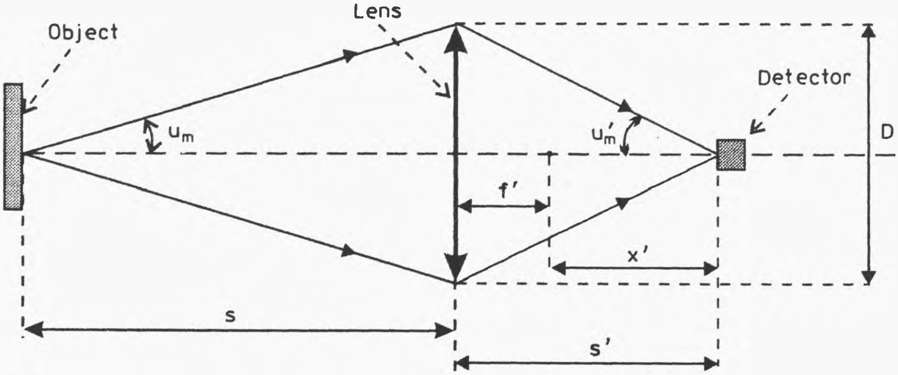

Fig. 1. Assumed optical systems of the infrared device

sine condition is used. Third, no optical filters and scanning systems are present. When the assumptions are fulfilled, we can consider the situations as presented in Fig. 1.

As the assumed optics fulfils the sine condition

$$\beta = \frac{\sin u}{\sin u'}, \tag{2}$$

we can modify formula (1) to the form

$$\mathrm{NETD} = \frac{\sqrt{\Delta f}}{\pi \tau_0 \sin^2 u'_m \sqrt{A_d} \int\limits_{\lambda_2}^{\lambda_1} D^*(\lambda) \frac{\partial L_\lambda}{\partial T_{ob}} d\lambda}. \tag{3}$$

Next, using classical geometrical relationships, for situations presented in Fig. 1, and the well-known Newton formulae, we obtain

$$\sin u'_m = \frac{D/2}{\sqrt{\left(f' + \frac{f'^2}{s-f'}\right)^2 + \left(\frac{D}{2}\right)^2}} \tag{4}$$

where f' is the focal length of the imaging optics, D is the diameter of the optics aperture and s is the distance between the optics and the tested object.

Now, we can transform the formula (3) to a new form

$$\mathrm{NETD} = \frac{4\left[\left(f' + \frac{f'^2}{s-f'}\right)^2 + \left(\frac{D}{2}\right)^2\right]\sqrt{\Delta f}}{\pi D^2 \tau_0 \sqrt{A_d} \int\limits_{\lambda_1}^{\lambda_2} D^*(\lambda) \frac{\partial L(T_{ob}, \lambda)}{\partial T_{ob}} d\lambda}. \tag{5}$$

The relationship between the NETD and the parameters such as the object-system distance s, focal length f', and aperture D, is useful for most infrared systems. However, for infrared microscopes the lateral magnification β is more convenient.

Based on geometry rules and the Newton formulae, as done before, we can derive relationship between numerical aperture in imaging space $\sin u'_m$ and the lateral magnification β

$$\sin^2 u'_m = \frac{1}{4F^2(1+\beta)^2+1} \tag{6}$$

where F is the optics number (ratio of focal length f' to diameter D).

Putting the formula (6) into (5), we obtain

$$\mathrm{NETD} = \frac{[4F^2(1+\beta)^2+1]\sqrt{\Delta f}}{\pi^2 \tau_0 \sqrt{A_d} \int\limits_{\lambda_1}^{\lambda_2} D^*(\lambda) \frac{\partial L(T_{ob}, \lambda)}{\partial T_{ob}} d\lambda}. \tag{7}$$

If the object-optics distance s is many times longer than the focal length of the optical system $f'(f'^2 \ll s-f')$, then $\beta \to 0$ and we obtain

$$\mathrm{NETD} = \frac{(4F^2+1)\sqrt{\Delta f}}{\pi\tau_0\sqrt{A_d}\int\limits_{\lambda_1}^{\lambda_2} D^*(\lambda)\frac{\partial L(T_{ob},\lambda)}{\partial T_{ob}}d\lambda}. \tag{8}$$

In the case when $F \gg 1$, the formula simplifies further to the form of the well-known Ratches model [2], [4], [5]

$$\mathrm{NETD} = \frac{4F^2\sqrt{\Delta f}}{\pi\tau_0\sqrt{A_d}\int\limits_{\lambda_1}^{\lambda_2} D^*(\lambda)\frac{\partial L(T_{ob},\lambda)}{\partial T_{ob}}d\lambda}. \tag{9}$$

3. Calculations

The ratio of NETD value for finite distance s to NETD value for distance s equal to infinity can be called the magnification factor MF. The factor can be calculated using two equivalent formulae:

$$\mathrm{MF} = \frac{4\left[\left(f'+\frac{f'^2}{s-f'}\right)^2+\left(\frac{D}{2}\right)^2\right]}{D^2(4F^2+1)} \tag{10}$$

or

$$\mathrm{MF} = \frac{4F^2(1+\beta)^2+1}{4F^2+1}. \tag{11}$$

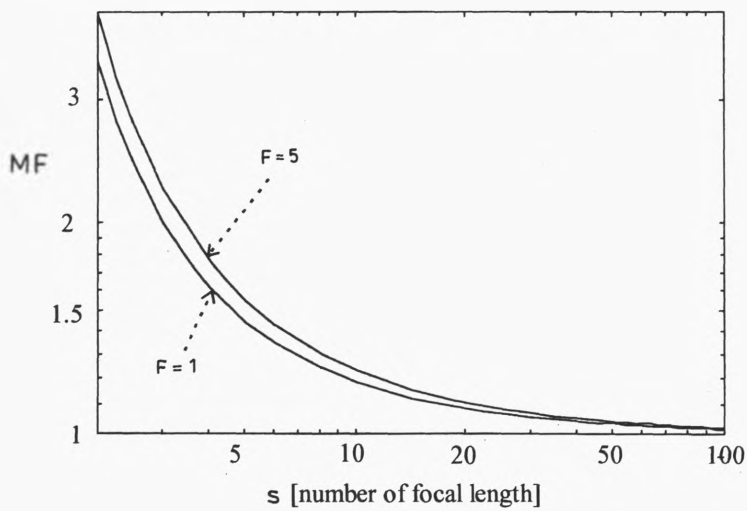

Fig. 2. Dependence of magnification factor MF on the object-optics distance s

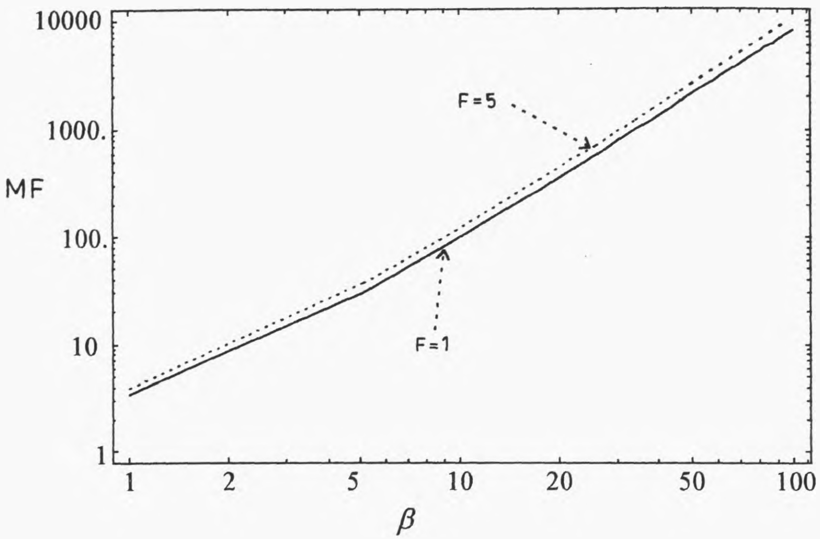

Fig. 3. Dependence of magnification factor MF on optical lateral magnification β

The magnification factor MF carries information of how many times the temperature resolution NETD in this measurement situation is higher than that for the ideal situation when the distance s equals infinity. From formulae (10) and (11) we can conclude that the factor can vary from 1 to infinity and that it decreases with distance s and increases with lateral magnification β. As shown in Fig. 2, the dependence of MF on distance s significant for distances s below $20f'$. Such distances occur quite often in practice. It means that even in typical measurement conditions the real values of the NETD can be significantly higher than the value determined using classical NETD models. In the case of infrared microscopy (Fig. 3), when lateral magnification $\beta > 1$, the differences are even greater.

4. Conclusions

The results of the analysis and calculations lead us to two conclusions. First, the classical models of the NETD parameters can be considered as a particular case of a more general developed model. The classical models should be used only when the object-optics distance s is at least a hundred times longer than the focal length f' and for optical systems of large F-number. When this condition is not fulfilled, employment of the classical models can lead to significant errors in NETD determination. Second, temperature resolution NETD of infrared systems quickly rises with the optical lateral magnification β that causes a serious difficulty in construction of infrared microscopes.

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