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Investigation of the Minimum Possible Temperature of Objects to Compile the Infrared Signature

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Actuality. When compiling a signature in a given area of the infrared (IR) range of real terrestrial objects falling on the declining branch of the Planck curve, it is necessary to take into account the strong attenuation of infrared radiation with increasing wavelength. At the same time, such attenuation leads to a significant decrease in the reliability of measurement results with increasing wavelength. Therefore, in order to maintain the same reliability of the results obtained, the width of the spectral IR subband used to calculate the signature should increase with increasing wavelength. Thus, the question on choosing a function of dependence width of the wavelength range used to calculate the signature on the wavelength of the measurement, which could be implemented at a minimum temperature of the object, should be solved.
The purpose is to determine the function of dependence of the width of the wavelength range used to calculate the signature on the wavelength of the measurement, which could be implemented at a minimum temperature of the object. Such an optimum function would ensure maximum reliability of the result of calculating the signature of real objects.
Method. The problem is solved using the variational optimization method based on the temperature determination formula obtained on the basis of the Planck formula. The study of the denominator of this formula, taking into account the integral constraint set on the desired function, make it possible to determine the optimal type of this function, in which the signature can be calculated at the minimum temperature of the object.
Result. The minimum temperature threshold of the object has been determined, which ensures the implementation of the proposed measurement method, in which reliable determination of the infrared signature of the object is possible.

Keywords: signature; infrared range; measurements; optimization; sensitivity

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Introduction

The formulation of infrared (IR) images makes it possible to expand the functions of receiving and processing information about the surrounding world by the human eye [1, 2]. To detect various objects in the IR range, these objects and the background must be characterized by their own narrowband IR signatures, for which various theoretical provisions of the theory of atmospheric transmission and the theory of heat transfer are used [3–7].

Synthesized infrared signatures of objects can be compiled based on the results of one or more narrow-spectral measurements using narrowband filters. For example, as reported in [4], IR sensors containing spectrally narrowband filters tuned to the vibrational resonance frequency of the studied gas are used to detect many harmful gases. However, such filters are expensive and are tuned to only one frequency. For this reason, it is proposed to use new narrowband IR emitters in multispectral IR systems, which eliminates the need for expensive band-pass optical filters. The use of such emitters opens up new possibilities in the calibration of narrowband and narrow-spectral temperature meters of objects.

According to the work [5], infrared sensors installed on unmanned aerial vehicle (UAV) are successfully used to control the fire situation in forests. The effectiveness of such control can be improved by using both static (color, texture) and dynamic (size, location, shape) indicators of ignition. In this case, unlike signature analysis, the identification of the fire situation is carried out by creating a model for identifying forest fires using a probabilistic neural network.

As reported in [7], in infrared industrial thermography, the main factors leading to uncertainty in the results of IR measurements are: the emissivity of materials, the influence of the environment, the influence of optical band-pass filters, the effect of heat on optics, as well as the low temperature of the measured object.

According to [8], the scope of application of multispectral IR cameras is wide enough and they are an important tool used to measure heart rate and other indicators (blood oxygen saturation, respiratory parameters), leading to a slight change in skin color.

Modern equipment designed for the formation of IR signatures of various objects simulate the infrared signatures of objects by synthesizing narrow band signatures using object measurement data obtained in the short IR (SWIR), medium IR (MWIR) and long IR (LWIR) subbands. However, conducting IR surveys of objects in these subbands with an equivalent result represents a certain technical difficulty and a methodology should be developed to compare and translate the data of IR surveys of objects obtained in one subband in to the data area obtained in another subband of the IR spectral zone. For example, projectiles controlled by infrared radiation of objects using an encoding disk (reticle) use the SWIR subband, while image-forming projectiles use the LWIR subband [13–16]. The basis of such a technique can be further investigated in this paper by the minimum possible temperature of the object, at which it is possible to compile an IR signature under some additional restrictive condition.

1 Materials and methods

The essence of existed technique to calculate the temperature of the object upon which the required IR signature can be formed briefly as follows [17]:

1. By approximating the Planck formula, the surface temperature of an object, assumed as blackbody is estimated.

2. Compensation for the error of this approximation.

It is known that the intensity of radiation emanating from a blackbody is estimated as

$$L(T) = \int_{\lambda_1}^{\lambda_2} \frac{\varepsilon(\lambda) C_1}{\lambda^5 \exp\left(\frac{C_2}{\lambda T}\right) - 1} \, d\lambda \ [\mathrm{W/cm^2 cч}], \tag{1}$$

where $\varepsilon(\lambda)$ is emissivity; λ is wavelength;

$C_1 = 1,191 \cdot 10^4 \ \mathrm{W \cdot mm^4/cm^2 \cdot mf}$;

$C_2 = 1,428 \cdot 10^4 \ \mu\mathrm{m} \cdot \mathrm{K}$.

Assuming $\lambda_c = (\lambda_1 + \lambda_2)/2$; $\Delta\lambda = \lambda_2 - \lambda_1$: the radiation intensity $L(T)$ can be estimated as

$$L(T) = \frac{\varepsilon C_1 \Delta\lambda}{\lambda_c^5 \left[\exp\left(\frac{C_2}{\lambda_c T}\right) - 1\right]}. \tag{2}$$

From expression (2) we find

$$T = \frac{C_2}{\lambda_C \ln\left(\frac{\varepsilon C_1 \Delta\lambda}{L \lambda_c^5} + 1\right)}. \tag{3}$$

Figure 1 shows a grapho analytical procedure for determining radiation intensity and a gray level of object, as an additional informative parameter, taking into account temperature and values of ε.

Thus, the level of a gray object can be defined as

$$G(L) = a[L - L(T_{min})] + G_{min}, \tag{4}$$

where a is the steepness of the characteristic $G(L)$.

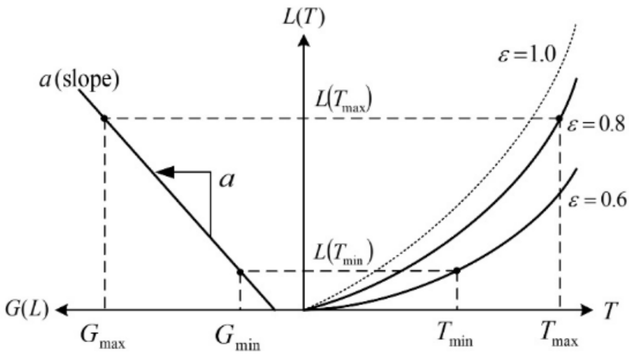

Fig. 1. Grapho analytical procedure for determining the level of a gray object at known values of ε and T

At the same time, the above-described existing method for determining radiation intensity and gray levels using formulas (1)-(4) separately for each IR subband does not take into account the fact that the width of the spectral IR subband used must increase with increasing wavelength over the entire IR subband to maintain the same reliability of the results obtained. Therefore, it is necessary to determine the relationship between the parameters λ_c and $\Delta\lambda$ at which the calculated average integral value of the object temperature would reach a minimum, i.e. the required intensity $L(T)$ or the narrow band IR signature would be realized. Let us consider the question of the influence of the wavelength dependent decreasing branch of the Planck curve on the proposed method for determining minimum temperature on based of formula (3).

Consider the descending branch of the Planck curve (Fig. 2).

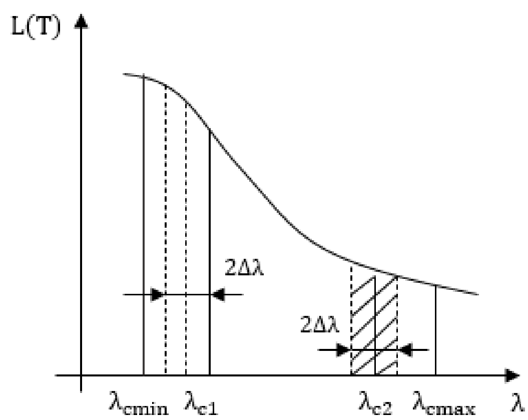

Fig. 2. The choice of λ_c and $\Delta\lambda$ depending on the wavelength

Obviously, with increasing wavelength, the useful signal decreases in magnitude. In this case, the function

$$\Delta\lambda = \varphi(\lambda_C) \tag{5}$$

would ensure that the minimum possible value of the object's temperature is recorded. It should be noted that Planck's law describes the case of considering an ideal blackbody. In the real case, natural objects have Planck curves that are very different from the ideal curve of electromagnetic radiation intensity $L(T)$. Taking into account the above, to find the optimal function $\varphi(\lambda_C)$, we assume the following restrictive condition

$$\int_{\lambda_{cmin}}^{\lambda_{cmax}} \varphi(\lambda_C) d\lambda_C = C_0; \quad C_0 = const. \tag{6}$$

Let's consider the question of the formation of the optimization functional of the procedure for choosing the best function $\varphi(\lambda)$. Taking into account expression (3) for $C_2 = \text{const}$, it is obvious that searching for the minimum of T is equivalent to searching for the maximum of the denominator of this expression. Therefore, the target functional F_1 can be formed as

$$F_1 = \frac{1}{\Delta\lambda_C} \int_{\lambda_{cmin}}^{\lambda_{cmax}} \lambda_C \ln\left(\frac{\varepsilon C_1 \varphi(\lambda_C)}{L\lambda_c^5} + 1\right) d\lambda_C. \tag{7}$$

Taking into account expressions (6) and (7), the target functional F_0 of unconditional variational optimization is defined as

$$F_0 = \int_{\lambda_{cmin}}^{\lambda_{cmax}} \frac{\lambda_C}{\Delta\lambda_C} \ln\left(\frac{\varepsilon C_1 \varphi(\lambda_C)}{L\lambda_c^5} + 1\right) d\lambda_C + \\ + \gamma \left[\int_{\lambda_{cmin}}^{\lambda_{cmax}} \varphi(\lambda_C) d\lambda_C - C_0\right], \tag{8}$$

where γ is the Lagrange multiplier.

Extremum (minimum or maximum) of F_0 is reached if the condition

$$\frac{d\left\{\lambda_C \ln\left(\frac{\varepsilon C_1 \varphi(\lambda_C)}{L\lambda_c^5} + 1\right) + \gamma\varphi(\lambda_C)\right\}}{d\varphi(\lambda_C)} = 0 \tag{9}$$

is fulfilled.

From condition (9) we obtain

$$\frac{\lambda_C}{\Delta\lambda_C} \cdot \frac{1}{\varphi(\lambda_C)} + \gamma = 0. \tag{10}$$

From expression (10) we find

$$\varphi(\lambda_C) = -\frac{\lambda_C}{\Delta\lambda_C \gamma}. \tag{11}$$

Given expression (11) in condition (6), it follows:

$$-\int_{\lambda_{cmin}}^{\lambda_{cmax}} \frac{\lambda_C}{\Delta\lambda_C \gamma} d\lambda_C = C_0; \quad C_0 = const. \tag{12}$$

From expression (12) it could be found that

$$-\frac{\lambda_c^2}{2\Delta\lambda_C \gamma}\Bigg|_{\lambda_{cmin}}^{\lambda_{cmax}} = C_0. \tag{13}$$

From condition (13) it follows

$$\gamma = -\frac{\left(\lambda_{cmax}^2 - \lambda_{cmin}^2\right)}{2\Delta\lambda_C C_0}. \tag{14}$$

Taking into account expressions (11) and (14), it could be found

$$\varphi(\lambda_C)_1 = \frac{2\lambda_C C_0}{(\lambda_{cmax}^2 - \lambda_{cmin}^2)}. \tag{15}$$

When solving (15), the functional (8) reaches a maximum, since the derivative of expression (10) by $\varphi(\lambda_C)$ is always a negative value.

2 Discussion

Thus, as a result of the optimization, the denominator of the expression (2) in the mean integral sense reaches a maximum, and therefore, the temperature T in the same sense reaches a minimum. As can be seen from expression (15), $\Delta\lambda$ is directly proportional to the value of λ_C. This leads to an important conclusion that in order to register low-temperature objects, it is necessary that the width of the infrared subband increases with increasing wavelength during IR optical radiation studies. To carry out the procedures for comparing IR images obtained on SWIR, MWIR, LWIR subranges, the value of the minimum temperature calculated taking into account expressions (7) and (15) can be used as:

$$T_{min} = \int_{\lambda_{cmin}}^{\lambda_{cmax}} \frac{\lambda_C}{\Delta\lambda_C} \ln\left[\frac{2\varepsilon C_1 C_0}{L\lambda_c^4(\lambda_{cmax}^2 - \lambda_{cmin}^2)}\right] d\lambda_C. \tag{16}$$

Obviously, the registration of objects with a minimum temperature and further comparison of images obtained in the SWIR, MWIR and LWIR ranges of such an object means an increase in the sensitivity of the infrared object detector.

Conclusion

1. The decreasing type of the Planck curve of real objects in the IR range dictates the need to expand the studied IR subranges to calculate the IR signature of low-temperature objects.

2. There is a minimum temperature threshold for an object whose IR signature cannot be determined below this threshold.

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Дослідження мінімально можливої температури об'єктів для складання інфрачервоної сигнатури

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Актуальність. При складанні сигнатури в заданій області інфрачервоного діапазону реальних земних об'єктів, що потрапляють на спадаючу гілку кривої Планка, необхідно враховувати сильне загасання інфрачервоного випромінювання зі збільшенням довжини хвилі. У той же час таке загасання призводить до значного зниження достовірності результатів вимірювань зі збільшенням довжини хвилі. Отже, щоб зберегти таку ж надійність отриманих результатів, ширина спектральної ІЧ-підсмуги, яка використовується для обчислення сигнатури, повинна збільшуватися зі збільшенням довжини хвилі. Таким чином, необхідно вирішити питання щодо вибору функції ширини залежності діапазону довжин хвиль для розрахунку сигнатури від довжини хвилі вимірювання, яку можна було б здійснити при мінімальній температурі об'єкта.

Мета – визначити функцію залежності ширини діапазону довжин хвиль, що використовується для розрахунку сигнатури, від довжини хвилі вимірювання, яке можна було б здійснити при мінімальній температурі об'єкта. Така оптимальна функція забезпечить максимальну достовірність результату обчислення сигнатури реальних об'єктів.

Метод. Задача розв'язана методом варіаційної оптимізації на основі формули визначення температури, отриманої на основі формули Планка. Дослідження знаменника цієї формули з урахуванням інтегрального обмеження, встановленого на шукану функцію, дають змогу визначити оптимальний тип цієї функції, при якому можна розрахувати сигнатуру при мінімальній температурі об'єкта.

Результат. Визначено мінімальний температурний поріг об'єкта, що забезпечує реалізацію запропонованого методу вимірювання, при якому можливе достовірне визначення інфрачервоної сигнатури об'єкта.

Ключові слова: сигнатура; інфрачервоний діапазон; вимірювання; оптимізація; чутливість