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Influence of the Detector Characteristic on the Result of Sky Temperature Measurement with the Use of Long-Wave Infrared Camera

Abstract

During the temperature measurements by means of infrared camera the temperature of surrounding elements must be known. In the case of thermovision inspections of the objects exposed to open air space, the surroundings consists of two elements, it is the ground and hypothetical sky surface. The sky temperature measured by long-wave IR camera is of apparent character because it expresses the thermal radiation of the sky within the spectral operational range of this camera i.e. 7.5÷13 μm. The abovementioned spectral range is coincident with so called atmospheric window within which the thermal radiation of the sky is relatively low. The emissivity of atmosphere within this window is low in the central part and high near the limits of the aforementioned range. In relation with the detector characteristic of the IR camera it causes underestimation of the measured sky temperature. This work deals with the analysis of influence of the IR camera detector characteristic on the results of determination of sky temperature and its thermal radiation intensity.

Keywords: thermovision infrared measurements, sky thermal radiation, sky temperature, characteristic of infrared camera detector.

Nomenclature, subscripts and abbreviations

C	- constant coefficient
$\dot{e}_{\lambda}(\lambda,T)$	- spectral density of black body self-emission for temperature T, resulting from Planck's law, W/(μm·m^2)
$\dot{e}_{b\,\Delta\lambda}, \dot{e}_{bm\,\Delta\lambda}$	- emissive power of black body or model of black body in operational spectral range of infrared camera at a given temperature T, W/m^2
$\dot{e}_{g\,\Delta\lambda}$	- emissive power emitted by atmosphere in operational spectral range of infrared camera, W/m^2
$\dot{e}_{g\,d\,\Delta\lambda}$	- emissive power emitted by atmosphere in operational spectral range of infrared camera converted by detector into measurement signal, W/m^2
$\dot{e}_{g\,c\,\Delta\lambda}$	- emissive power for operational spectral range of infrared camera calculated on the basis of sky temperature measured by means of IR camera, W/m^2
$S_d(\lambda)$	- relative spectral response of infrared detector
T	- temperature, K
T_{at}	- temperature of atmospheric air, K
T_b	- temperature of black body, K
$\varepsilon(\lambda,T)$	- spectral emissivity of air at temperature T
λ	- wave length of thermal radiation, μm
λ', λ''	- spectral limits of infrared camera operation, μm
at	- deals with atmospheric air
b	- deals with black body
bm	- deals with model of black body (real black body)
c	- deals with IR camera measurement
d	- deals with infrared detector
g	- deals with grey body/gas
p	- deals with spectral range of pyrgeometer i.e. (4.5÷42) μm
$\Delta\lambda$	- deals with spectral range of infrared camera i.e. (7.5÷13) μm
G	- deals with ground
S	- deals with sky
IR	- infrared
LW	- long-wave

1. Introduction

The infrared camera measurement results allow to determine the temperature distributions on outer surfaces of the examined objects and to calculate the heat losses. The method which is based on the concept of one-off thermovision measurement of the considered object can be applied to determine the annual heat losses [5]. Knowledge of heat losses from the analysed objects has an important meaning in the elaboration of methods for improving technical conditions and the ways of operation of these objects (overhead pipelines, buildings and others) in terms of energy efficiency [3, 5].

During the infrared camera diagnostics several parameters influence the results of measurement of the temperature [3, 5, 6, 7]. Among these parameters the emissivity of surface under consideration as well as the temperature of the surrounding elements may be specified. The non-contact methods are based on the measurement of radiation heat flux coming from the surface taken into consideration. Usually the total radiative heat flux from the tested surface consists of two parts. The first part presents the self-emission heat flux, whereas the second part is the radiation flux which comes from surroundings and is reflected by the tested surface [3]. The problem arises when the ambient temperature of objects placed in the open air space needs to be determined. Generally, the ambient of objects exposed to the open air space consists of two surfaces: hypothetical sky surface and ground surface [3]. The aforementioned elements usually have different values of temperature [1, 2, 3] and because of it the ambient temperature value which should be entered into the measuring system of the infrared (IR) camera is not known. The method of determination of temperature representing the radiation of non-isothermal surroundings has been developed and shown in [3]. The aforementioned temperature is called an equivalent ambient temperature. To calculate its value in the case of objects exposed to the open air space, the temperature of sky must be known. It has been proposed to measure this temperature by means of IR camera, the same as that one used in potential further thermovision inspections [3, 4]. It should be remembered that this temperature is of apparent character and represents the sky thermal radiation within the operational spectral range of IR camera. The aforementioned method consists in the conversion of non-isothermal surroundings into one-element isothermal surroundings where a method of radiosity and configuration factors has been applied [3].

The next problem is the determination of sky total radiation temperature responsible for thermal emission of sky. In order to determine this temperature, the measurement with the use of a long-wave (LW) infrared camera with a special configuration of its measurement parameters has been also proposed [3, 4]. In this measurement technology the sky is treated as a hemispherical shell. In the case of cloudless weather the sky temperature is relatively low and diversified whereas, during cloudy nights this temperature is relatively high and quite uniform [3, 4]. Such method of determination of sky thermal radiation with the use of infrared camera measurement has been successfully verified [3, 4]. To verify the developed method, the results obtained with the use of a LW IR camera and measurement results obtained by means of the pyrgeometer have been compared. The results of this comparison are quite satisfactory, however there are differences amounting to 5-7%, relatively, [4]. The reasons of measurement discrepancies have been already mentioned, [3, 4]. The aim of this analysis was to recognize the influence of the infrared detector sensitivity characteristic on the sky temperature measurement results and to estimate quantitatively the scale of this effect.

2. Presentation of the problem

Long-wave IR cameras operate within spectral range so-called "atmospheric window" where the thermal radiation of atmosphere is relatively low. In Fig. 1 there is a part of total spectral range of atmospheric air thermal radiation shown which presents the spectral absorptivity (emissivity) of atmosphere layer. The diagram was generated with the use of spectral line model [8] and includes the aforementioned atmospheric window. During these calculations only the main active gases responsible for emission and absorption of thermal radiation in the atmosphere, i.e. steam and CO_2, were taken into consideration. The calculations were carried out for typical contents of these components in the atmospheric air. They are specified in Tab. 1, case 1. The main task of this diagram was to show a character and estimate a scale of spectral emissivity changes of the atmosphere layer. Because of it, for the calculations a minimum thickness of atmospheric layer which usually does not contain any clouds was assumed [2]. It is obvious that the active thickness of the atmosphere in reality is greater than the assumed value amounting to 1000 m, Fig. 1. However, the scale of the analysed phenomenon will be similar.

The operation range of LW IR camera covers the spectral band 7.5÷13 µm. In Fig. 1 there can be seen that the spectral emissivity value of atmosphere near the window limits is much more than in the central part of this range. This phenomenon brings about some deformation of the final measurement result during the thermovision examination of sky because close to the limits of operation spectral range of the IR camera the radiation intensity is the highest, Fig. 1, but the detector efficiency of its conversion into output signal is the lowest, Fig. 3. This phenomenon will occur in the situations when the spectral emissivity of the tested surface is not uniform and depends on wavelength of thermal radiation. In consequence, the temperature indicated by the IR camera in this case is somewhat lower than the temperature value representing the thermal emission flux of atmosphere within the abovementioned window.

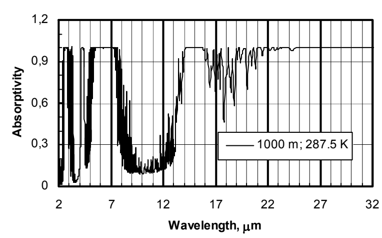

Fig. 1. Dependence of the spectral absorptivity (spectral emissivity) of the atmosphere layer on the temperature and wavelength of thermal radiation

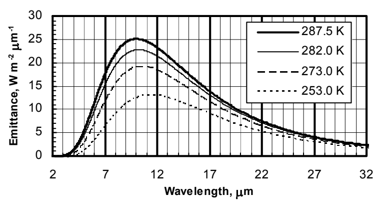

Fig. 2. Spectral emission density of a black body as a function of the thermal radiation wavelength for different values of its temperature

During the calibration process of IR camera, the model of black body is used to set up the relationship between the radiative energy flux emitted by the aforementioned body which has a known temperature and a temperature value indicated by the IR camera. The heat exchanging inside the camera measurement chamber is relatively sophisticated but its construction and software ensure that the output detector signal is dependent unambiguously on a radiation energy flux entering through lens and irradiating the detector. In a microbolometric detector the absorbed radiation energy is consumed for heating up the detector and thus changing its electrical resistance [9, 10]. This resistance change is measured and processed into temperature which can be used to create an image. This type of sensor belongs to the group of thermal detectors. Theoretically, the sensitivity characteristic as a function of wavelength for this detector type should be flat [10]. In fact, the real characteristics, due to different reasons, are not exactly flat [6, 10].

In Fig. 3 one can see a sample of such characteristic which will be used in further considerations. The temperature increase of thermal sensor is proportional to the amount of the absorbed infrared radiation flux which strikes the detector surface. This flux is generated by the examined object. Summing up, it can be said that the temperature value indicated by the IR camera results from the amount of the heat absorbed by its detector. Next, this quantity is converted into the object temperature on the basis of the relations established during the calibration process of the IR camera.

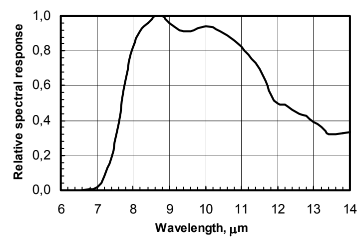

Fig. 3. Relative spectral response $s_d(\lambda)$ of the FPA microbolometric detector as a function of wavelength of thermal radiation

During the calibration of the IR camera usually a model of a black body is used. This model has the emissivity ε_{bm} almost amounting to 1.00 ($\varepsilon_{bm}\approx 1.00$) but, in fact, always occurs the relation $\varepsilon_{bm}<1.00$. The energy flux emitted by the black body model during the calibration procedure within the camera spectral range is expressed by the relation:

$$\dot{e}_{bm\,\Delta\lambda} = \varepsilon_{bm} \int_{\lambda'}^{\lambda''} \dot{e}_{\lambda}(\lambda, T_{bm})\,\mathrm{d}\lambda\,, \tag{1}$$

and this radiative energy flux converted into output measurement signal generated by the detector is described by the expression:

$$\dot{e}_{bm\,d\,\Delta\lambda} = \varepsilon_{bm} \int_{\lambda'}^{\lambda''} \dot{e}_{\lambda}(\lambda, T_{bm})\, s_d(\lambda)\,\mathrm{d}\lambda\,, \tag{2}$$

whereas the relationship $s_d(\lambda)$is shown in Fig. 3.

On the basis of the aforementioned quantities a calibration coefficient C_b can be introduced:

$$C_b = \frac{\dot{e}_{bm\,d\,\Delta\lambda}}{\dot{e}_{bm\,\Delta\lambda}} = \frac{\dot{e}_{b\,d\,\Delta\lambda}}{\dot{e}_{b\,\Delta\lambda}} = \frac{\int_{\lambda'}^{\lambda''} \dot{e}_{\lambda}(\lambda, T_{bm})\, s_d(\lambda)\,\mathrm{d}\lambda}{\int_{\lambda'}^{\lambda''} \dot{e}_{\lambda}(\lambda, T_{bm})\,\mathrm{d}\lambda}\,. \tag{3}$$

The radiation energy flux emitted by the atmosphere within the atmospheric window (and simultaneously the operation spectral range of the infrared camera) is described by the relation:

$$\dot{e}_{g\,\Delta\lambda} = \int_{\lambda'}^{\lambda''} \varepsilon(\lambda, T_{at})\, \dot{e}_{\lambda}(\lambda, T_{at})\,\mathrm{d}\lambda\,, \tag{4}$$

where $\varepsilon\ (\lambda,, T_{at})$ expresses the changes of spectral emissivity of atmosphere within the atmospheric window. In further analysis, for all considered calculation cases the individual relations $\varepsilon(\lambda, T_{at})$ were calculated on the basis of spectral line model [8] taking into account the parameters specified in Tab. 1. The calculation results for sample parameters are shown in Fig. 1.

Not all amount of energy delivered to the detector via the IR camera lenses is turned into the output signal by the detector. The radiation flux emitted by the sky and converted into the measurement signal generated by the detector during the measurement process can be expressed as follow:

$$\dot{e}_{g\,d\,\Delta\lambda} = \int_{\lambda'}^{\lambda''} \varepsilon(\lambda, T_{at})\ \dot{e}_{\lambda}(\lambda, T_{at})\ s_d(\lambda)\,\mathrm{d}\lambda\,. \tag{5}$$

For the abovementioned fluxes can be also calculated the ratio $C_g = \dot{e}_{g\,d\,\Delta\lambda} / \dot{e}_{g\,\Delta\lambda}$. It can be proved that between the calculated quantities the following relation occurs: $C_g < C_b$.

In order to eliminate the influence of surroundings on the measurement result during the thermovision examination of sky, in the IR camera measuring system should be set the object emissivity amounting to 1.00. To cancel the thermal absorption and radiation of the air layer which is to be found between the object and IR camera lens, the distance between the object and the camera has to be set as 0.00 or almost zero. In this case the camera measuring system will convert the signal obtained from the detector into the sky temperature T_{Sbc} according to the relation (6), treating the sky as the black body:

$$\dot{e}_{g\,c\,\Delta\lambda} = \frac{\dot{e}_{g\,d\,\Delta\lambda}}{C_b} = \int_{\lambda'}^{\lambda''} \dot{e}_\lambda \left(\lambda, T_{S\,b\,c}\right) \mathrm{d}\lambda \,. \tag{6}$$

The energy flux $\dot{e}_{g\,c\,\Delta\lambda}$ calculated in this manner is smaller than $\dot{e}_{g\,\Delta\lambda}$ due to the aforementioned relation, i.e. $C_b > C_g$. From this relation arises the conclusion that the sky temperature T_{Scb} indicated by the IR camera will be underestimated. The radiation flux emitted by the sky within the "atmospheric window" and described by the relation (4) can be also expressed as the radiation of sky treated as a black body at temperature T_{Sb}:

$$\dot{e}_{g\,\Delta\lambda} = \int_{\lambda'}^{\lambda''} \dot{e}_\lambda \left(\lambda, T_{S\,b}\right) \mathrm{d}\lambda \,. \tag{7}$$

3. Calculation sample results

To recognize the problem quantitatively, the numerical calculations in accordance with the presented method have been carried out. The results are collected in Tab. 1. It should be emphasized that these results deal only with the sky thermal radiation within the operation spectral range of IR camera i.e. 7.5-13 µm. The most interesting is the difference calculated as follows:

$$\Delta \dot{e}_{\Delta\lambda} = \dot{e}_{g\,\Delta\lambda} - \dot{e}_{g\,c\,\Delta\lambda} \,, \tag{8}$$

and the difference related to the radiation flux emitted within the spectral range of IR camera operation:

$$\delta' \dot{e}_{\Delta\lambda} = \Delta \dot{e}_{\Delta\lambda} / \dot{e}_{g\,\Delta\lambda} \,, \tag{9}$$

as well as this difference in relation to the thermal flux emitted within the operational spectral range of pyrgeometer:

$$\delta'' \dot{e}_{\Delta\lambda} = \Delta \dot{e}_{\Delta\lambda} / \dot{e}_{g\,p} \,. \tag{10}$$

It should be noticed that the result of measurement realized by means of the pyrgeometer contains almost entire total thermal emission of sky. On the basis of Eqs (6, 7, 8), the difference between the real sky radiation temperature T_{Sb} and the sky temperature measured by IR camera T_{Scb} can be calculated:

$$\Delta T_S = T_{S\,b} - T_{S\,b\,c} \,. \tag{11}$$

Tab. 1. Input data and calculation results of the sky emission determined on the basis of the sky temperature measured by means of LW infrared camera, molar fraction of carbon dioxide 385 ppm

No	Atmo-spheric temp.	Atmo-spheric pressure	Relative humidity	Vapour molar fraction	$\Delta\dot{e}_{\Delta\lambda}$	$\delta'\dot{e}_{\Delta\lambda}$	$\delta''\dot{e}_{\Delta\lambda}$	ΔT_S
-	K	hPa	%	% H_2O	W/m^2	%	%	K
1	287.5	1033	70.0	1.15	1.9	*	*	*
2	276.5	993	81.8	0.63	1.1	3.8	0.5	1.3
3	282.2	1005	80.3	0.91	1.5	3.2	0.6	1.3
*) – not determined								

The example values of the aforementioned quantities are presented in the last columns of Tab. 1. As we can see, the obtained values of $\Delta\dot{e}_{\Delta\lambda}$ are of the order of 1÷2 W/m^2. Therefore, we can state that it is not the crucial importance reason of discrepancy between the pyrgeometer measurement result and the calculated one which was determined on the basis of sky temperature measurement [4] by means of the IR camera.

4. Conclusions and remarks

In this paper a method for evaluation of influence of the bolometric detector characteristic on the results of celestial vault temperature measurement has been proposed. The paper contains the qualitative and quantitative analysis of this phenomenon. The analysed effect could be also observed in laboratory experiment while using a solid body with emissivity depending on wavelength. Generally, due to the selective character of atmosphere thermal radiation within the main atmospheric window, the sky temperature measured by the IR LW camera is underestimated. However, the scale of underestimation is not significant because it is of the order of 1÷2 W/m^2 in the case of IR typical bolometric FPA detector characteristic taken into consideration.

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