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Method of Measurement of Low Sky Temperature Using Infrared Camera

Abstract

During thermovision measurement in an open atmospheric space, the surroundings consists of two elements: the ground surface and apparent surface of the sky. To determine the equivalent ambient temperature it is necessary to know the temperature of the sky [3, 4]. It has been proposed to measure the temperature distribution of the sky using an infrared camera. However, such a measurement has a problem because often the temperature of the sky is too low to measure its value with an IR camera. The article presents a method for measuring the low temperature of the sky with a value outside the measuring range of the IR camera. The method consists in making a measurement with artificial values of measurement parameters that ensure obtaining the temperature value belonging to the measuring range of the camera. Then, using the developed algorithm, the obtained temperature value is converted to the actual conditions.

Keywords: thermovision measurements, open air space, radiation ambient temperature, radiation sky temperature.

Nomenclature

$\dot{e}_{\lambda}(\lambda,T)$ - spectral density of black body self-emission for temperature, resulting from Planck's law [1], W/(m^3)
$\dot{e}$ - emissive power of black body in spectral range $\Delta\lambda=\lambda''-\lambda'$ at a given temperature T, [1], W/m^2
$\dot{h}$ - irradiation of the considered surface, W/m^2
r - reflectivity of the considered surface ($r=1-\varepsilon$)
F - area of object under consideration, m^2
T_a - radiative ambient temperature, K
T_{at} - temperature of atmospheric air, K
T_o - temperature of considered object, K
T_w - temperature of window of IR camera, K
B, R, F - calibration coefficients of infrared camera PM595, K,-,-, respectively
ε - emissivity, generally
ε_o - emissivity of the examined object
$\varphi_{\mathrm{d},x-y}$ - local configuration factor between objects "x" and "y"
φ_{x-y} - average configuration factor between objects "x" and "y"
τ_{at} - transmissivity of atmosphere
τ_w - transmissivity of protection window
λ - wavelength of IR radiation, m or µm
λ', λ'' - operation spectral range of IR camera, (7.5 ÷13) µm

Indexes and abbreviations

1 - deals with parameters of initial measurement
a - deals with ambient conditions
at - deals with atmospheric air
o - deals with object under consideration
w - deals with external camera window
C - deals with calibration model of infrared camera
R - deals with radiation model of infrared camera
IR - infrared camera or deals with infrared camera detector
CM, RM - calibration or radiation model of IR camera, respectively

1. Introduction

Measurement with an infrared camera requires to define several measurement parameters in terms of quantity. These parameters include the emissivity of the tested surface, radiation ambient temperature and others. Very often we have a problem with the proper determination of the ambient temperature of the tested object, especially in open atmospheric space. Generally, the surrounding of the object which is placed in this space consists of two surfaces: hypothetical sky surface and ground surface [3, 4]. Normally, the temperature values of these elements are different. On the basis of this data, the value of the radiation equivalent ambient temperature of the surface to be tested should be determined [3, 4]. Sometimes the sky temperature is too low to measure it with the use of an IR camera. In the work a method for measuring the low temperature of the sky with a value outside the measuring range of the IR camera is developed. The method consists in making a measurement with artificial values of measurement parameters and then the obtained temperature value is converted to the actual measurement conditions.

2. Description of radiation model (RM)

In the work a model describing the influence of measurement parameters on temperature measurement result is proposed and presented. This model called "radiation model" (RM), is based on the description of radiation heat fluxes irradiating IR camera detector [1, 2].

The infrared thermography is based on the measurement of radiation heat flux emitted from the considered object. In the situation when the emissivity of the investigated object is less than 100%, the total radiative heat flux from the tested surface consists of several parts. The first part presents the self-emission heat flux whereas the other parts are the radiation fluxes which come from surrounding elements and are reflected by the considered surface. Thus, in a mathematical model during an infrared camera temperature measurement the following radiation heat fluxes arriving at an infrared detector should be taken into account:

a) radiation flux emitted by the examined object,
b) radiation flux emitted by the ambient elements and reflected from the examined object,
c) radiation flux emitted by the atmospheric air which is to be found between the object and the IR camera,
d) radiation flux emitted by the window or optics of IR camera.

The sum of self-emission heat flux and radiation heat fluxes coming from other surrounding elements and reflected by the surface under consideration is called the radiosity (denoted by $\dot{h}$) of the considered surface [1]. A general scheme of radiation heat transfer around the IR camera, which is used for determination of radiosity $\dot{h}_{IR}$, is shown in Fig. 1.

In further considerations IR camera detector is treated as a pointwise element. Thermal irradiation of IR camera detector through camera lens by surrounding elements, see Fig. 1, is described by the following form:

$$\dot{h}_{IR}\,\mathbf{d}F_{IR}=\varepsilon_o\,\dot{e}_o\,\tau_{at}\tau_w\,F_o\,\varphi_{\mathrm{d},o-IR}+ \\ \varepsilon_a\,\dot{e}_a\,r_o\,\tau_{at}\tau_w\,F_o\,\varphi_{\mathrm{d},o-IR}+\varepsilon_w\,\dot{e}_w\,F_w\,\varphi_{\mathrm{d},w-IR}+\varepsilon_{at}\,\dot{e}_{at}\,\tau_w\,\mathbf{d}F_{IR} \tag{1}$$

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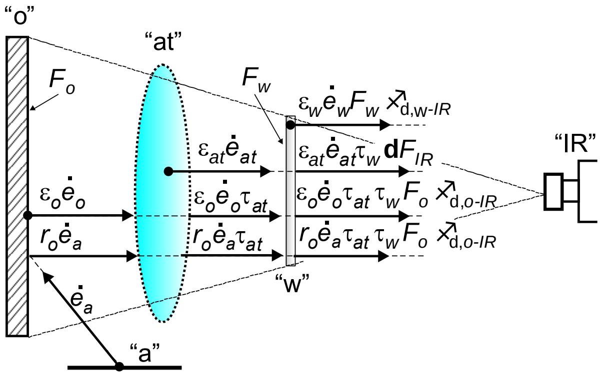

Fig. 1. Scheme of radiation heat fluxes irradiating detector of IR camera

After making obvious assumption that ε_a=1 and after applying the reciprocity principle:

$$F_o\,\varphi_{d,o-IR} = \varphi_{IR-o}\,\mathbf{d}F_{IR}; \quad F_w\,\varphi_{d,w-IR} = \varphi_{IR-w}\,\mathbf{d}F_{IR} \tag{2}$$

and assuming that $\varphi_{IR\text{-}o}$=1, $\varphi_{IR\text{-}w}$=1, as well as after omitting elementary surface dF_{IR} which appears in all terms of equation (1), an accurate relation expressing the unit flux of radiation energy coming from all considered elements and arriving at an IR camera is obtained [2, 3, 4]:

$$\dot{h}_{IR} = \varepsilon_o\,\dot{e}_o\tau_{at}\tau_w + \dot{e}_a r_o\,\tau_{at}\tau_w + \varepsilon_w\,\dot{e}_w + \varepsilon_{at}\,\dot{e}_{at}\,\tau_w\,. \tag{3}$$

The output signal s from the camera detector is closely coupled with the aforementioned energy flux and can be described by the formula [2, 5]:

$$s \approx \psi\,\dot{h}_{IR} = \psi\big(\varepsilon_o\,\dot{e}_o\tau_{at}\tau_w + \dot{e}_a r_o\,\tau_{at}\tau_w + \varepsilon_w\,\dot{e}_w + \varepsilon_{at}\,\dot{e}_{at}\,\tau_w\big)\,. \tag{4}$$

The relation (4) should be written twice. First time it should be applied for initial measurement conditions "1" to calculate value of $\dot{h}_{IR,1}$ and the second time for other measurement conditions to express real value $\dot{h}_{IR}$. Obviously, for new conditions the value of measurement signal is the same and therefore we can write:

$$s = s_1 \quad \text{as well as} \quad \dot{h}_{IR} = \dot{h}_{IR,1}\,. \tag{5}$$

Finally, on the basis of relations (4, 5), a relation expressing radiation flux of self-emission of the considered object in new measurement conditions can be obtained:

$$\dot{e}_o = \frac{\dot{h}_{IR,1} - \big(\dot{e}_a r_o\,\tau_{at}\tau_w + \varepsilon_w\,\dot{e}_w + \varepsilon_{at}\,\dot{e}_{at}\,\tau_w\big)}{\varepsilon_o\,\tau_{at}\tau_w}\,. \tag{6}$$

The knowledge of $\dot{e}_o$ value allows to determine the object temperature T_o for new measurement conditions. This temperature can be calculated from the relation given below:

$$\dot{e}_o = \dot{e}_o(T_o) = \int_{\lambda'}^{\lambda''} \dot{e}_\lambda(\lambda, T_o)\,\mathbf{d}\lambda\,. \tag{7}$$

The temperature T_o occurs in the formula (7) in an implicit form. To prove the presented algorithms several calculation examples have been performed. The obtained results are presented in next section.

3. Verification of RM model

The developed model has been verified by comparing the obtained results by means of radiation model (denotation RM) with the results of the thermal camera (denotation IR) and additionally with the results obtained using the model applied in the camera calibration process (CM-calibration model).

The measurement signal value in this model which is generated by the object "x" at temperature T_x is expressed by the approximate relation (8) presented in [5]:

$$s_x = \frac{Rc}{\mathbf{exp}(B/T_x) - F} \tag{8}$$

where Rc, B, F are individual constants determined during the calibration procedure of IR camera, [7, 8]. For the considered camera ThermaCAM PM595 manufactured by FLIR company they amounted to Rc =101920, B =1463.4 K and F =1 [5].

Next, the equation expressing the total signal resulting from thermal radiation of examined object, radiation its surroundings and atmosphere can be formulated, [5]. Now this equation should be written twice, first time for initial measurement conditions denoted by "1". Owing to this, the initial value of measurement signal s_1 is calculated. Next it is obvious that for the new values of measurement parameters value of measurement signal "s" is the same as previously, therefore it can be written s=s_1. Finally, after some transformations the relation (9) can be obtained [5]:

$$s_o = \left[\frac{s_1}{\tau_{at}} - (1-\varepsilon_o)s_a - \frac{1-\tau_{at}}{\tau_{at}}s_a\right]\frac{1}{\varepsilon_o}\,. \tag{9}$$

On the basis of value s_0 calculated from relationship (9) for new measurement parameters and relation (8), the new object temperature $T_{o,C}$ for these conditions can be calculated [5]:

$$T_{o,C} = \frac{B}{\mathbf{ln}\left(\dfrac{R}{s_o} + F\right)}\,. \tag{10}$$

To verify the radiation model (RM) the discrepancies defined by (11) between temperature values obtained on the basis of model (RM) and (CM) denoted by $\Delta T_{o,R\text{-}C}$ as well as temperature indicated by the infrared camera (IR) denoted by $\Delta T_{o,R\text{-}IR}$ were calculated:

$$\Delta T_{o,R-C} = T_{o,\,RM} - T_{o,\,CM} \quad \text{and} \quad \Delta T_{o,R-IR} = T_{o,\,RM} - T_{o,\,IR} \tag{11}$$

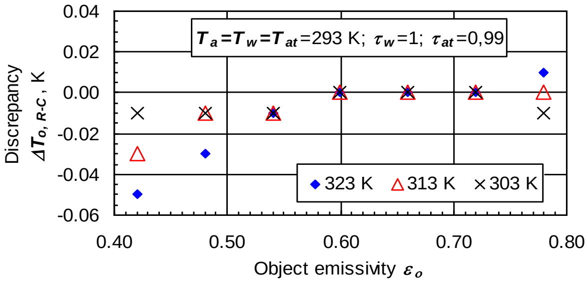

Fig. 2. Object temperature discrepancies in the object temperature between radiation (RM) and calibration (CM) models for the specified in the legend initial object temperature values, $\varepsilon_{o,1}$=0.60

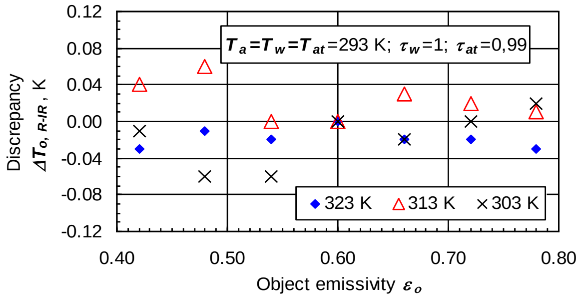

Fig. 3. Object temperature discrepancies in the object temperature between radiation model (RM) and infrared camera indication (IR) for the specified in the legend initial object temperature values, ε_{o1}=0.60

The results presented in Figs 3, 5 do not show the accuracy of the thermovision measurement, but the discrepancies between the IR camera measurement results and the results of the calculation obtained by means of RM model. Small values of these differences indicate that the RM model is in good agreement with the camera's measurement algorithm.

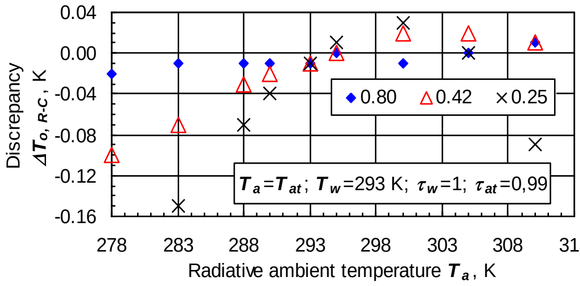

Fig. 4. Object temperature discrepancies in the object temperature between radiation (RM) and calibration (CM) models for the specified in the legend object emissivity values, $T_{a,1}$=293 K

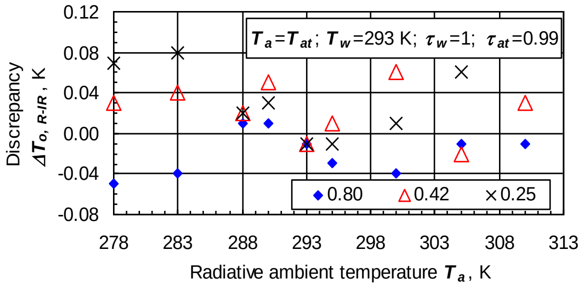

Fig. 5. Object temperature discrepancies in the object temperature between radiation model (RM) and infrared camera indication (IR) for the specified in the legend object emissivity values, $T_{a,1}$=293 K

4. The use of RM method

The presented method can be applied for the extrapolation of measurement results outside the measurement range of IR cameras, especially while measuring extremely low temperature. This possibility is very useful while measuring the temperature of sky [3, 4]. Owing to setting up of artificial values of measurement parameters a result of measured temperature "$T_{o,1}$" can be read thanks to moving it into the operation range of infrared camera, Tab. 1. Next, after the use of developed algorithm the true values of measured temperature can be retrieved, Fig. 6.

Tab. 1. Initial values of object temperature and IR camera measurement parameters

Parameter	$T_{o,1}$	$\varepsilon_{o,1}$	$T_{a,1}$	$\tau_{at,1}$	$T_{at,1}$	$\tau_{w,1}$	$T_{w,1}$
Dimension	K	-	K	-	K	-	K
Meas. 1	246.0	0.50	200.0	1.00	200.0	0.30	200.0
Meas. 2	273.2	0.50	200.0	1.00	200.0	0.30	200.0
Meas. 3	298.9	0.50	200.0	1.00	200.0	0.30	200.0

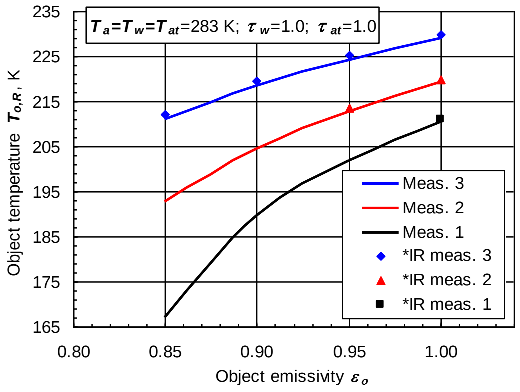

Fig. 6. Object temperature extrapolated outside of measurement range of the considered camera with the use of RM model of IR camera (lines-Meas.1, 2, 3) and results obtained from IR camera represented by points *IR (points denoted by "*" are to be found outside of the certified measurement range of IR camera but still within its operation range)

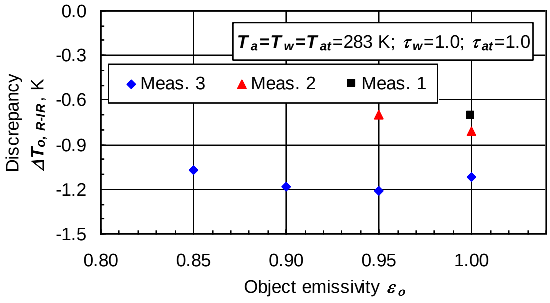

Fig. 7. Temperature discrepancies in the object temperature between radiation model (RM) and infrared camera indication (IR) for the considered series and values of specified in the legend measurement parameters

5. Final remarks

In the presented work the method for of measurement of extremely low temperature of the sky is developed.

To verify this method many calculation examples were performed with the use of aforementioned method for various configurations of measurement parameters and a high conformity of obtained results with results obtained by means of calibration camera model [5] and results from the infrared camera was achieved. In the work the results of measurements performed by means of IR cameras ThermaCAM SC2000 and SC620 FLIR as well as software ThermaCAM Researcher Pro FLIR were used. The developed method can be also applied for the analysis of influence of potential errors in the determination of thermovision measurement parameters on the measurement results [5, 6]. In comparison with individual calibration models [5, 7, 8] the proposed method is of universal character and can be applied for different kinds of long-wave infrared cameras.

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