Infrared Physics & Technology 67 (2014) 131–137

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Monte Carlo uncertainty simulation of surface emissivity at ambient temperature obtained by dual spectral infrared radiometry

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HIGHLIGHTS

- Ambient temperature surface emissivity using dual spectral radiometry is evaluated.
- Emissivity uncertainty is evaluated using Monte Carlo simulations.
- Uncertainty is minimized for narrow, far apart, and low detector wavelength bands.
- Uncertainty is maximized as background temperature approaches surface temperature.

ARTICLE INFO

Article history:
Received 18 February 2014
Available online 25 July 2014

Keywords:
Emissivity
Dual spectral radiometry
Monte Carlo simulation

ABSTRACT

The Monte Carlo statistical method was used to estimate the uncertainty of the emissivity, obtained by dual spectral infrared radiometry, of gray surfaces at ambient temperature. A large number of simulations were carried out, by selecting a wide range of values from parameters that directly affect the resulting emissivity: the emissivity of the target surface, the background temperature of the surrounding surfaces, the maximum error of the detectors, and the width and spectral location of the bands of the detectors.

In summary, the level of uncertainty grows very quickly as the background temperature approximates the target surface. In terms of the spectral characteristics of the detectors, it was found that narrow bands, far apart from each other, and short wavelength bands provide the lowest uncertainty from all simulated emissivity values.

1. Introduction

Thermal radiation rises from the fact that every surface above a temperature of 0 K emits energy in the form of radiation in all possible directions. The intensity and spectral distribution of the emitting radiation is strongly dependent on the temperature and condition of the surface that originates it. This radiation may be detected by another surface, since, depending on the temperature difference between the emitting and receiving surface, it may change the temperature of the receiving surface, as it is absorbed by it. Other factors intervene in the detectability of the incoming radiation, such as the transparency of the transmission path, the distance and relative orientation between the two surfaces, and the condition of the receiving surface.

This phenomenon led to the development of radiation thermal detectors, in which the change in temperature of the detector due to absorbed radiation is used to generate an electrical output. Although thermal effects are in principle wavelength independent, radiation absorption is generally wavelength dependent. Thermal detectors typically operate at room temperature, are cheap and simple to operate; however they are usually characterized by modest sensitivity and slow response [1,2]. For most temperatures encountered in engineering applications, the radiation is emitted in the infrared (IR) range [3], so that most detectors operate in this range, being commonly termed as IR detectors. IR detectors can be used as IR thermometers, in which the output signal due to the detected radiation from a small target surface area is converted, though a calibration algorithm, into a measure of the surface temperature. In situations where it is desirable to know the temperature distribution across a surface, rather than just a small target area, IR cameras can be employed, in which the output signals from an array of IR detectors are used to generate a thermographic image of the surface.

Emissivity (ε) is the ability of a surface to emit radiation, which is generally a function of surface condition, temperature, wavelength,

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http://dx.doi.org/10.1016/j.infrared.2014.07.018
1350-4495/

and emitting direction. If emissivity is independent of wavelength, the surface is termed as gray; if emissivity is independent of direction, the surface is termed as diffuse. The radiation power emitted by a surface at a given temperature is proportional to its emissivity, up to the maximum limit of a perfectly black surface ($\varepsilon = 1$), in which radiation is emitted according to Planck's spectral distribution [3]. Consequently, for the correct measurement of surface temperatures with IR detectors, the emissivity of the target surface has to be known.

Dual spectral radiometry involves $n = 2$ radiation measurements performed in distinct wavelength regions. If the emitting target surface is gray, it is possible to infer its emissivity and temperature from the two radiation measurements, whose values are lower than those that would be obtained for a perfectly black surface [4]. The simplest published models are based on the ratio method, in which the reflected background radiation is ignored (the background is cold enough for its radiation to be neglected), Wiens's spectral distribution (approximation of Planck's distribution for short wavelengths) and infinitesimally thin spectral bands (to avoid the integration of the spectral distribution function) are assumed, resulting in a relatively simple analytical emissivity independent solution for temperature [4,5]. Similarly, a simple solution can also be obtained for ε. The ratio method suggests that increasing band separation reduces the effects of radiation measurement errors; however, the gray surface assumption becomes less likely as band separation increases [6].

In order to extend the ratio method to non-gray surfaces, multiwavelength radiometry methods have been investigated, in which radiation measurements are performed at $n > 2$ wavelengths, and ε is modeled as a smooth function of wavelength with a maximum of n - 1 unknown coefficients. Earlier studies considered emissivity functions with exactly n - 1 coefficients, which, together with target temperature, were calculated from a system of n simultaneous equations with n unknowns (target temperature is the remaining unknown) [4,6–9]. This approach was investigated by Coates [8] through the simulation of systems with $1 \leqslant n \leqslant 10$ wavelengths, concluding that multiwavelength radiometry, even in the absence of radiation measurement errors, results in very large errors when $n > 3$, which was attributed to overfitting. Khan et al. [6] also concluded that there is no significant advantage in using more than two wavelength bands.

Coates [8] also suggested that overfitting problems can be eliminated by increasing the number of wavebands, so that the number of unknown coefficients in the emissivity function would be lower than n - 1, resulting in overdetermined systems of equations to be solved by some conventional least square method. Hunter et al. [10,11] and Khan et al. [12] applied this method to develop a multiwavelength radiometer, reporting accurate temperature measurements. Mazikowski and Chrzanowski [13] simulated a overdetermined multiwavelength system, concluding that it is possible to achieve reasonable accuracy of emissivity measurements if the difference between target and background temperatures is high.

Small et al. [14] followed another approach: the outputs of two detectors working on different wavelength bands were modeled through exponential functions, containing three empirical scaling factors, obtained by calibration with a blackbody at different temperatures; the two calibrated exponential functions were subsequently equated for gray surfaces with a known background temperature, so that surface temperature and emissivity could be evaluated.

More sophisticated published models incorporate the effects of other sources, such as background and internal radiation, and also the integration of Planck's distribution function along the wavelength range of the bands [13,15–17]. Chrzanowski [15] observed that temperature errors are minimized for narrow spectral bands, far from each other, located in the short wavelength IR range, and when the target temperature is high.

Most models mentioned so far deal with high target temperatures, combined with low temperature background surfaces; in other cases, the effects of background radiation are simply ignored. It is the purpose of the present paper to investigate the use of a dual spectral radiometry system to estimate the emissivity of building surfaces (assumed to be gray), typically at ambient temperature. The suggested system is composed by two IR detectors with distinct wavelength bands, located inside an enclosure with controlled surface temperature, so that both detectors point at the target surface through a small opening in the enclosure, with their fields of views unobstructed by the enclosure walls. Moreover, the enclosure opening area matches the target surface, so that the latter only receives radiation from the enclosure interior. Consequently, both IR detectors receive radiation from two sources: radiation emitted by the target surface, whose temperature and emissivity are unknown; background radiation emitted by the enclosure inner walls, assumed as perfectly black (the opening area is much smaller than the enclosure area, so that the opening behaves like a blackbody [3]) and with known temperature, which is reflected by the target surface. Finally, in terms of the spectral characteristics of the detectors, it is assumed for simplicity that each detector equally absorb all incoming radiation within a given wavelength band and that all radiation outside this band is rejected.

More specifically, the objective of the present work is to simulate the proposed dual spectral system, focusing on which of the following variables minimizes uncertainty: the output temperature uncertainty of the IR detectors, the spectral characteristics of the detectors (width of the spectral bands, distance between bands, and spectral location of the bands), and the background temperature. While no real surface is truly gray, it can be assumed for certain materials that the emissivity of the target surface is constant over that part of the spectrum corresponding to the bandwidth of the detectors [3]. Besides, it is also assumed that there is no error associated with the temperature of the enclosure inner walls. The omission of these two sources of uncertainty is due to the fact that, for a first approach, it is necessary to identify the optimal spectral characteristics of the detectors and also to quantify the level of uncertainty as a function of background temperature.

2. Detector model

As shown in Fig. 1, three important regions must be considered in a radiation measuring system: the target surface at a given temperature T_s and emissivity ε_s, the detector, whose output signal (S) depends on the incoming radiation, and the background surfaces surrounding the target surface and detector, whose temperature is T_a. As stated in the previous section, the following simplifications were assumed: the background surfaces behave as perfectly black, i.e. their emissivity $\varepsilon_a = 1$; the target surface is gray, i.e. ε_s is constant through the wavelengths considered in this study; the detector absorbs all incoming radiation from the target surface within a band between lower and upper cutoff wavelengths λ' and λ'', respectively, and all radiation outside this band is rejected.

When the target surface is presented to the detector, its temperature starts to adjust due to the newly incoming radiation, tending to an equilibrium value once steady state is reached, in which the heat flux absorbed by the detector balances with the outgoing heat flux. The radiation received from the target surface is formed by two contributions: the radiation power emitted by the surrounding background surfaces ($L_\lambda(T_a)$) and reflected by the target surface, whose reflectivity, according to Kirchhoff's law [3], is equal to 1 - ε_s; the radiation power emitted by the target surface