Environmental Radiation Change-based Emissivity Measurement Method for Field Targets

Hui-Ming QU\textsuperscript{1,a,*}, Shi-Jing ZHAO, Jian DA, Zheng-Long CUI, Li-Feng LIU

\textsuperscript{1}Jiangsu Key Laboratory of Spectral Imaging & Intelligence Sense, Nanjing University of Science and Technology, Nanjing, Jiangsu, China

\textsuperscript{a}huimingqu@163.com

*Corresponding author

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Abstract. Emissivity measurement is the foundation of target infrared radiation characteristic analysis. The theoretical analysis, design, and implementation results of an indirect emissivity measurement approach for field targets are presented. With a blackbody as the active radiation source, an experimental facility is established to alter environmental radiation. Experiments are performed with different samples. Results show that this approach has a maximum error of 1.9% as opposed to that of direct measurement. The experiment verifies the feasibility and accuracy of the proposed method, which could meet the actual needs of in-situ emissivity measurement. The method provides the necessary means for non-contact infrared radiation field analysis.

Introduction

The true temperature measurement of target surface radiation is an important task in numerous scientific studies. In particular, the non-contact precision measurement of true surface temperature is difficult to accomplish. Infrared imaging temperature measurement has the advantages of being non-contact, highly sensitive, and fast; this approach has a wide temperature range, is capable of night vision, and has high security. Such measurement has been widely applied in the civil fields of high-voltage line inspection and industrial production, as well as in the military fields of reconnaissance and guidance, camouflage design, and detection [1-3]. The surface emissivity of a measured object mainly affects the thermal imager. Emissivity measurement is the foundation of target infrared radiation characteristic analysis. However, the thermal imager is also influenced by reflectivity, environment temperature, atmospheric temperature, atmospheric attenuation, and measurement distance. These factors result in inaccurate temperature measurements and affect the application field of the thermal imager. These conditions make the imager particularly erroneous in object surface emissivity estimation, which further influences temperature measurement precision [4-6]. Emissivity is a function of the radiation wavelength, temperature, direction, and surface state of targets. Thus, emissivity largely depends on the surface state of the object. Manual data are commonly unreliable in the field measurement of infrared radiation characteristics. Thus, actual emissivity measurements in the field are required. This study presents a field measurement approach for object emissivity at room temperature. Theoretical analysis and experimental measurements are conducted, and experimental results and analyses are presented.

Theoretical Models and Method

Emissivity refers to the ratio of radiation outwards through the surface of sample and radiation of a blackbody under the same conditions and with the same temperature. This concept is a measure of radiation capability and has a value that changes from 0 to 1. Emissivity represents the closeness of heat radiation of the actual object and blackbody radiation. According to the blackbody radiation law, the infrared radiation properties of any object can be known if emissivity is given. The ideal
blackbody emissivity is 1, whereas actual object emissivity is less than 1. In actual measurement, a thermal imager receives effective radiation in three parts: target radiation, reflected radiation in the surroundings, and atmospheric radiation [7]. Total received radiation is expressed as Eq.1.

\[ L = L_0 + \rho L_s + L_p \]  

Where \( L \) is the radiation brightness reaching the detector surface, \( L_0 \) is the target radiation, \( \rho \) is the target reflectance, \( L_s \) is the environmental radiation, and \( L_p \) is the atmospheric radiation. Atmospheric transmittance is set to 1.

The spurious radiation obtained when using a thermal imager has to be considered. Radiation thermometry with a thermal imager is a quantitative measurement based on blackbody radiation theory. Thus, such approach can be considered as a comparison measurement that uses the blackbody as reference radiation. Therefore, a system response function has to be established between the thermal imager and blackbody radiation. The system response function reflects the functional relationship of the measured output signal and input radiation. The optical system, electronic circuit, and detector response rate determine the system response function. The thermal imager calibration model is expressed as Eq.2.

\[ V = \alpha L + L_f \]  

Where \( V \) is thermal imager output value; \( L_f \) is the offset value caused by scattering background radiation, optical structure thermal radiation, and detector dark current; and \( \alpha \) is thermal imager responsivity. Substituting Eq.2 into Eq.1 yields Eq.3.

\[ V = \alpha(L_0 + \rho L_s + L_p) + L_f \]  

By adjusting Eq.3, we obtain Eq.4.

\[ V = (\alpha L_0 + L_f) + \rho(\alpha L_s + L_f) - \rho L_f + \alpha L_p \]  

By observing Eq.4, we suppose

\[ V_0 = \alpha L_0 + L_f \]  

\[ V_s = \alpha L_s + L_f \]  

Where \( V_0 \) is thermal imager output value when the detector receives the target radiation, and \( V_s \) is thermal imager output value when the environmental radiation alone reaches the detector. Therefore, Eq.4 is transformed into Eq.7.

\[ V = V_0 + \rho V_s - \rho L_f + \alpha L_p \]  

We assume that atmospheric radiation is a uniform distribution that does not change over time. The value of atmospheric transmittance is 1 at a short distance. The emissivity of opaque objects is examined in the case of environmental radiation change within a short period. According to Kirchhoff’s law, emissivity is observed through absorption, reflection, and transmission processes, whereas incident radiation is observed on an object surface. Only the absorption and reflection processes are required to measure emissivity for opaque objects. Emissivity is equal to absorptivity. Therefore, we obtain Eq.8.
Where $\varepsilon$ is emissivity. A novel emissivity measurement method naming indirect measurements is derived from Eq.8. The indirect measurement method is performed by measuring target reflectivity to obtain emissivity indirectly. It is different from the direct measurement in several aspects. The direct measurement method requires that the target temperature be known in the absence of atmospheric and environmental effects. This method is suitable for laboratory measurements. This indirect measurement method does not require the target temperature to be known and it is suitable for field applications.

When atmospheric radiation $L_p$ and spurious radiation $L_f$ are constant as environmental radiation changes, the detector output Eq.7 is expressed as Eq.9.

$$V' = V_0 + \rho V_s' - \rho L_f + \alpha L_p$$  

Combining Eqs.7 and 9, we obtain Eq.10.

$$V' - V = \rho (V_s' - V_s)$$  

Then, $\rho = \frac{V' - V}{V_s' - V_s}$  

Combining Eqs.8 and 11, we obtain the emissivity of the measured target.

$$\varepsilon = 1 - \frac{V' - V}{V_s' - V_s}$$  

Where $V_s$ is the output of environmental radiation acting on the detector alone, $V$ is the output of all radiation acting on the detector, $V'_s$ is the output of environmental radiation acting on the detector alone after changing the environmental radiation, and $V'$ is the output of all radiation acting on the detector after changing the environmental radiation. According to Eq.12, target emissivity can be obtained by theoretically measuring object reflectance. Reflectance can be measured by changing environmental radiation. In the following section, experiments are conducted to verify the feasibility and accuracy of the proposed method.

**Experiments and Results Discussion**

The experimental facility mainly comprises an uncooled long-wave (8-12um) thermal imager, an extended area blackbody, a spectroscope, and a lens. A schematic diagram of the experimental apparatus is shown in Fig.1.

![Figure 1. Schematic diagram of the experimental apparatus.](image-url)
Blackbody radiation converges on the beam splitter through the converging lens, is reflected by the beam splitter to reach the target, and is then reflected to the detector.

Radiation thermometry is a quantitative measurement based on blackbody radiation theory. This measurement uses a blackbody as reference radiation. Therefore, the thermal imager facilitates radiometric calibration to determine the detector response according to the calibration model Eq.2. Radiation luminance from band $\lambda_1$ to band $\lambda_2$ is obtained by using Planck’s formula.

$$L = \frac{E}{\pi} \int_{\lambda_1}^{\lambda_2} C_1 \lambda^{-5} (e^{C_2/\lambda T} - 1)^{-1} d\lambda$$  \hspace{1cm} (13)

A radiation calibration experiment was conducted by setting the blackbody at different temperatures while the corresponding output value of the detector was recorded. The relationship between target radiation and detector output is then determined, as shown in Fig.2.

Figure 2. Relationship between blackbody radiation luminance and detector output.

The radiation calibration curve is linearly fitted to the output value with the use of the least squares method.

$$y = 20.9672x - 981.3774$$  \hspace{1cm} (14)

Therefore, the calibrated response relationship can be used to verify experimental results.

Three samples (fiberboard, porcelain, and plastic) are selected as test targets in the experiment. The samples and the blackbody are placed under the same conditions at a distance of 0.5 m from the detector. Each sample was measured five times. Emissivity was taken as the average value. The test results are shown in Tab.1.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Average</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberboard</td>
<td>0.9618</td>
<td>0.9563</td>
<td>0.9479</td>
<td>0.9635</td>
<td>0.9457</td>
<td>0.9550</td>
<td>0.80%</td>
</tr>
<tr>
<td>Porcelain</td>
<td>0.9175</td>
<td>0.9338</td>
<td>0.9218</td>
<td>0.9358</td>
<td>0.9191</td>
<td>0.9256</td>
<td>0.86%</td>
</tr>
<tr>
<td>Plastic</td>
<td>0.9129</td>
<td>0.9210</td>
<td>0.8834</td>
<td>0.8932</td>
<td>0.9185</td>
<td>0.9058</td>
<td>1.66%</td>
</tr>
</tbody>
</table>

Table 1. Target emissivity measurement data with indirect method.

We calculate the standard uncertainty of the measurement results by using Eq.15. This measurement reflects the discrete degree of the value relative to the average. Measurement uncertainty is less than 2%, which verifies the stability of this approach.

$$S = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N - 1}}$$  \hspace{1cm} (15)
Figure 3. (a) Image of the blackbody radiation to the porcelain plate and (b) differential image after radiation changing.

Fig.3(a) and (b) show the thermal imager measurement images of a porcelain plate under different environmental radiations. The lighter portion is attributed to the blackbody radiation focus. The indirect target emissivity test is conducted using the method presented in the previous section. Measurement results are compared with those of the direct measurement method in Tab.2 to evaluate the effects of the proposed method.

Table 2. Results comparison with direct measurement method.

<table>
<thead>
<tr>
<th>Material</th>
<th>Direct method</th>
<th>Indirect method</th>
<th>Max. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberboard</td>
<td>0.9412</td>
<td>0.9550</td>
<td>0.0138</td>
</tr>
<tr>
<td>Porcelain</td>
<td>0.9101</td>
<td>0.9256</td>
<td>0.0155</td>
</tr>
<tr>
<td>Plastic</td>
<td>0.8886</td>
<td>0.9058</td>
<td>0.0172</td>
</tr>
</tbody>
</table>

Tab.2 shows a 0.017 (1.9%) maximum error for object emissivity between the indirect and direct measurement methods. The result is less than 5% of the maximum error of multi-wavelength emissivity measurement in reference [8]. We observe that higher emissivity results in lower measurement error. The measured value of the proposed method is larger than that of the direct measurement method, which can be attributed to the short measuring distance. Consequently, the surface temperature of the detector increases. Measurement error mainly occurs because of the uneven distribution of target surface roughness and the non-uniformity of the blackbody.

According to reference the most important aspect of target radiation characteristic measurement is atmospheric transmittance [9]. An atmospheric transmittance measurement method is provided in the literature. The uncertainty of atmospheric transmittance measurement ranges from 6% to 10.5%. The accuracy of target radiation inversion ranges from 0.1% to 3.4%. The problem with target temperature inversion is that target emissivity has to be known. Emissivity measurement is important in camouflage target characteristic measurement. Therefore, target emissivity measurement is significant in the analysis and inversion of target radiation characteristics. The proposal method enables the precise non-contact measurement of emissivity without preconditions of knowing the field temperature of the target.

Conclusions

The paper describes a method to estimate emissivity from emitted radiance of a given target. The method does not need the temperature of the target, which is normally one of the major issues with this kind of estimation procedures. Temperature is eliminated with the use of a differential method which is based on changing the radiation reflected by the environment around the target. The model of indirect measurement was established through theoretical derivation, and an experimental facility was built. Controllable blackbody radiation was used to simulate environmental radiation change. The differential value of thermal radiation was measured to avoid the influence of absolute error from uncontrollable environmental factors in a direct radiation measurement. The proposed approach is
more convenient than other methods in that it does not require contact with the measured object and the determination of target temperature. Experiments are performed with different samples. Results show that this approach has a maximum error of 1.9% as opposed to that of direct measurement. The results confirm that the proposed method provides good stability and higher test result accuracy than that of conventional methods. Thus, the technique has extensive application prospects in such areas as the detection of camouflage targets, in-situ characteristic analysis of target radiation in the field, non-contact temperature measurement of unknown materials, and fault detection of equipment in dangerous environments.

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References


