Radiometric Calibration Research for Infrared Spectral Imaging Remote Sensing Systems

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Abstract: Data accuracy is a fundamental characteristic of remote sensing detection systems. Radiometric calibration is a critical step in the quantitative analysis of remote sensing data, essentially aiming to precisely determine the quantitative relationship between system measurements and corresponding physical quantities. By analyzing the system's radiative transfer and conversion models, and employing algorithms such as the two-point method, piecewise linear method, and least squares method in conjunction with blackbody radiation experimental data, the calibration of infrared spectral image-associated remote sensing detection systems can be achieved. The research results indicate that the piecewise linear method yields smaller errors compared to the two-point method, while the least squares method based on a power function provides the optimal results. Furthermore, experimental results demonstrate that atmospheric absorption has a significant impact on the accuracy of full-band radiometric calibration for spectral image-associated systems.

Keywords: Spectral correlation; Radiometric calibration; Fourier Transform Infrared Spectroscopy (FTIR); Blackbody radiation; Remote sensing detection

1. Introduction

"As a worker must first sharpen his tools if he is to do his work well," research into the infrared radiation characteristics of typical targets urgently requires high-performance remote sensing detection systems for corresponding data measurement and model analysis, alongside the synchronous accumulation of target characteristic databases aligned with these systems [1-3]. Remote Sensing Fourier Transform Infrared Spectroscopy (OP/FT-IR, Open Path Fourier Transform Infrared Spectroscopy) is an emerging passive remote sensing detection technology that has developed rapidly in recent years [4,5]. Leveraging the interaction between light and gas molecules for gas analysis, remote sensing FT-IR possesses unparalleled advantages and application potential: (1) it enables convenient detection of multi-component gases with high measurement accuracy; (2) it allows for real-time remote sensing measurements in hazardous environments that are difficult to approach; (3) it requires no prior knowledge of the target object and no sampling; and (4) it facilitates the remote determination of physical parameters such as the absolute spectral energy distribution and temperature of thermal infrared radiation sources. Due to these significant advantages, remote sensing FT-IR technology has become a key development direction in gas analysis fields involving various toxic and harmful gases, as well as high-temperature exhaust plumes [6].

Spectral-image association denotes a target detection and measurement methodology that synergistically integrates infrared imaging with infrared spectral analysis. The integrated spectral-imaging sensor (Fig. 1) comprises a two-axis servo scanning mirror, dual-band optical lenses, an infrared imaging module, a Fourier Transform Infrared (FT-IR) spectrometer, and a data acquisition and control unit. Employing a co-aperture and co-axial optical architecture that unifies wide-field-of-view (WFOV) imaging with narrow-field-of-view (NFOV) spectral measurement, and coupled with a wide-area servo scanning mechanism, this system facilitates the spectral-imaging detection of moving targets.

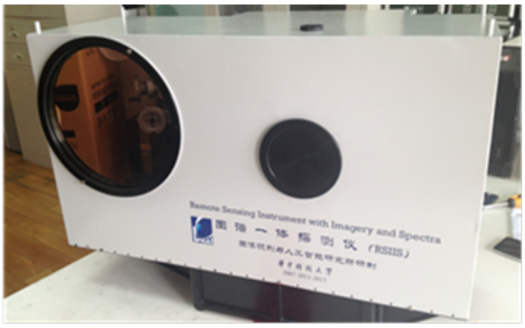

Figure 1: Remote Sensing Instrument with Imagery and Spectra.

2. Radiometric Calibration Methods

The primary objective of radiometric calibration algorithms is to fit measured calibration data with input conditions to derive calibration coefficients. These algorithms are generally categorized into statistical methods and computational methods. Statistical methods require large volumes of calibration data, involve complex computations, suffer from poor timeliness, and have their accuracy heavily influenced by various experimental factors, making them rarely used in engineering applications. Computational methods based on calibration data mainly include the two-point method, piecewise linear method, least squares method, and other data fitting algorithms. Specifically, the two-point method requires the radiometric response to be linear across the dynamic range; the piecewise linear method offers flexibility for systems with poor linearity; while the least squares method employs fitting approximation based on the principle of minimizing the sum of squared residuals, making it applicable to both linear and nonlinear system responses. Different radiometric calibration algorithms process calibration data differently, resulting in variations in the obtained calibration coefficients and imposing corresponding constraints on their scope of application.

The least squares method is a multi-point fitting technique that utilizes multiple radiometric calibration datasets to calculate calibration coefficients. Depending on the linearity of the actual remote sensing system's response curve, either linear (first-order) or higher-order polynomial fitting is selected to determine these coefficients. When performing function approximation using discrete calibration data, the fitting parameters are determined according to the criterion of minimizing the sum of squared residuals, as defined in Equation (4).

$$E = \sum_{k=1}^{N} (Gain(v) S_{input}(v) + offset(v) - DN(v))^2 \quad (1)$$

3. Experiments and Analysis

3.1 Experiment

The radiometric calibration campaign was conducted in two distinct phases. The first phase employed the near-field extended source method, utilizing a cavity blackbody (Model SR-200, CI-System, Israel) for proximal calibration. The second phase adopted the direct imaging method, leveraging an HFY-203D blackbody to perform calibration under near-range conditions.

The experiments were executed under controlled environmental conditions, with an ambient temperature of approximately 21°C and a relative humidity of 25% RH. Data acquisition spanned the infrared spectral region from 1,850 cm^{-1} to 5,000 cm^{-1}, with spectral resolutions set at 4 cm^{-1} and 8 cm^{-1}. The calibration protocol involved a blackbody temperature sequence ranging from 400°C to 1,300°C, maintained at a fixed measurement distance of 10 meters.

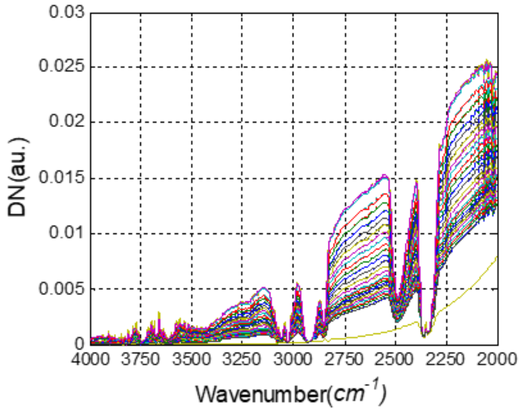

Figure 2: Digital number curve of the remote sensing system under different temperature blackbody.

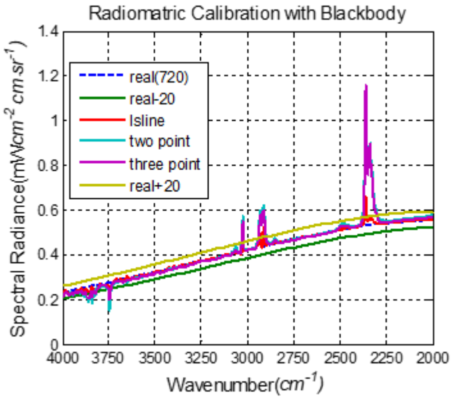

Figure 3: Comparison between radiometric calibration results and theoretical values under different algorithms.

3.2 Experimental Analysis

The spectral-image association remote sensing system was employed to measure the SR-200 blackbody across a temperature range of 600°C~900°C. Figure 4 illustrates the system's output Digital Number (DN) curves as a function of wavenumber. A comparative analysis against background outputs reveals that the DN response varies significantly across the spectral domain 2,000 cm^{-1} to 2,800 cm^{-1} as a function of temperature, exhibiting relatively weaker responses within the sub-interval 2,850 cm^{-1} to 5,000 cm^{-1}. Furthermore, diminished or negligible responses are observed at specific spectral points and regions. Although the near-field extended source method was utilized, complete isolation from ambient air was not achieved; consequently, atmospheric absorption effects persist. Notably, significant attenuation is evident at the absorption peaks corresponding to water vapor and carbon dioxide.

Figure 5 presents the radiometric calibration results derived from the aforementioned algorithms, sequentially displaying the outcomes of the Least Squares Method (LSM), the Two-Point Method, and the Piecewise Linear Method alongside theoretical calculations. For the LSM, a power function was employed as the fitting model. The input temperature sequence for the calibration algorithms spanned T=600℃/700℃/800℃/900℃, with specific calibration temperatures set at 720℃.

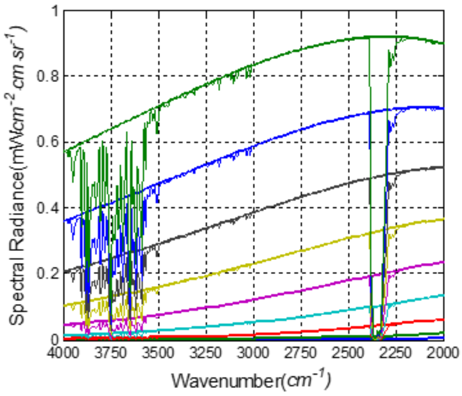

Figure 4: Theoretical calculation value and the curve after atmospheric absorption of blackbody radiation at different temperatures.

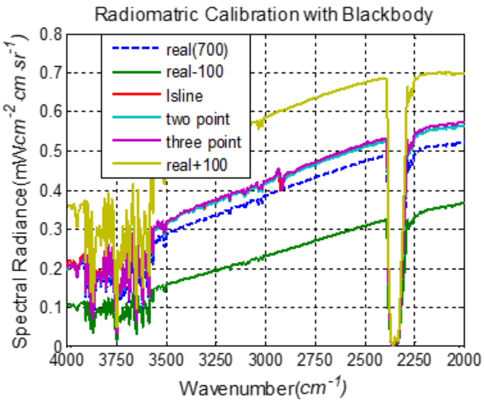

Figure 5: Comparison between radiometric calibration results and theoretical values under different algorithms.

The results indicate that within the majority of the spectral response region, the calibration error remains within ±20℃. However, larger calibration errors are observed at select atmospheric absorption peaks, particularly within the interval 2,3000 cm^{-1} to 2,400 cm^{-1}. Regarding the Piecewise Linear Method, while the results presented utilize three input temperatures, increasing the input to five or seven temperatures yielded no significant improvement in performance. In terms of comparative algorithmic efficacy, the Piecewise Linear Method offers only marginal improvements over the Two-Point Method, whereas the Least Squares Method demonstrates superior overall performance.

Subsequent calibration experiments employed the direct imaging method, with the HFY-203D blackbody positioned at a distance of 10 meters from the remote sensing system. Given the blackbody's aperture diameter of $D = 40mm > \sqrt{4r^2\omega/\pi} = 25.6mm$, it is assumed that the blackbody radiation fully fills the spectral measurement field of view (FOV).

Figure 6 illustrates the spectral radiance of the blackbody at various temperatures, as well as the corresponding radiance observed at a distance of 10 meters. In this analysis, atmospheric transmittance (or absorption) was computed using the MODTRAN software.

Applying the aforementioned radiometric calibration algorithms with an input temperature sequence of T=300℃/400℃/800℃/900℃ and specific calibration temperatures of 700℃, the calibration results depicted in Figure 7 were obtained. The figure reveals that within the atmospheric absorption peak region of 2,300 cm^{-1} to 2,400 cm^{-1}, the significant calibration errors are primarily attributed to the atmospheric transmittance approaching zero. This extreme attenuation results in a negligible system response within this spectral interval.

5. Conclusion

Remote sensing measurements utilizing Fourier Transform Infrared (FTIR) spectroscopy are susceptible to various interfering factors. By analyzing the system's radiative transfer and radiation conversion models, this study successfully accomplished the calibration of the spectral-image association remote sensing detection system. This was achieved by integrating calibration algorithms—specifically the Two-Point Method, the Piecewise Linear Method, and the Least Squares Method—with experimental blackbody radiation data.

The results demonstrate that the Piecewise Linear Method yields lower errors compared to the

Two-Point Method, while the Least Squares Method, employing a power function fitting model, delivers the optimal performance. Furthermore, the experimental findings underscore that atmospheric absorption exerts a significant influence on the accuracy of full-band radiometric calibration.

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