Index decomposition analysis and optimization design of temperature inversion accuracy based on spaceborne high-resolution infrared camera

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Abstract. Spaceborne high-resolution infrared cameras can be widely used in environmental protection, disaster prevention and mitigation and other fields. Based on the demand for high-accuracy inversion of surface temperature in related fields, the detection accuracy of the camera is the focus of attention. Taking this as the starting point, this article systematically analyzes the composition of errors that affect the system's comprehensive indicators, sorts out the relationship and interaction principle of each error component, and establishes an error model. Through reasonable decomposition and allocation of the system's comprehensive indicators, the detection accuracy of the spaceborne high temperature infrared camera meets the mission requirements.

1. Introduction
The spaceborne high-resolution infrared camera can realize full-time, non-contact, high-precision temperature measurement and thermal state analysis of targets such as the atmosphere, water and ground objects. It is an important means of environmental monitoring and resource detection. The accuracy of land surface temperature inversion is the key to satisfying quantitative remote sensing business applications [1-3].

Index decomposition is a method to solve model-based multi-level system optimization design. For spaceborne high-resolution infrared cameras, the index decomposition of the system-level index of ground temperature inversion accuracy can provide beneficial help for its optimal design. By establishing the accuracy influencing factor model and calculating and analyzing the model error items one by one, the key items that affect accuracy can be identified, and then the functional performance can be improved through optimization schemes.

Liu Yinnian et al. summarized the design and development experience of the Gaofen-5 visible shortwave infrared hyperspectral camera, and gave the key indicators of the spaceborne infrared camera, but did not explain the indicator decomposition process[4]. Wang Haiyan (2009) [5], Cao Lihua (2012) [6], Cheng Lipeng (2016) [7] have studied the relative calibration algorithm of space-borne infrared cameras, and obtained the inversion error caused by the system calibration, but they did not analyze other error terms that affect the accuracy of the inversion.
2. Error mode establishment

According to Planck’s law, any object with an absolute temperature greater than 0K will radiate energy in the form of electromagnetic waves. For a blackbody, when its physical temperature is known, its radiant energy can be calculated using Planck’s formula:

\[
B(\lambda, T) = \frac{C_1}{\pi \lambda^3 \cdot [\exp(C_2 / \lambda T) - 1]}
\]

Among them, \(B(\lambda, T)\) represents the spectral radiance of an object at a temperature of \(T\) and a wavelength of \(\lambda\), and the unit is \(\text{W} \cdot \mu\text{m}^{-1} \cdot \mu\text{m}^{-1} \cdot \text{sr}^{-1}\). \(C_1\) and \(C_2\) are constant \((C_1=3.7418 \times 10^8 \text{W} \cdot \mu\text{m}^{-1} \cdot \mu\text{m}^{-1} \cdot \text{sr}^{-1}, C_2=1.439 \times 10^4 \mu\text{m} \cdot \text{K})\). But for most natural features, their thermal radiation needs to add the influence of emissivity \(\varepsilon(\lambda)\) to the Planck formula, and the radiance of their own emission is:

\[
L(\lambda, T) = \varepsilon(\lambda) \cdot B(\lambda, T) = \frac{C_1 \cdot \varepsilon(\lambda)}{\pi \lambda^3 \cdot [\exp(C_2 / \lambda T) - 1]}
\]

If the environmental radiation is considered, Assuming that the downward atmospheric radiant flux is \(L_{\text{atm}}(\lambda)\), Then the radiance of the target observed on the ground \(L_{\text{grd}}(\lambda)\) is the target’s own thermal radiation plus the atmospheric downward radiation reflected by the target, the formula is:

\[
L_{\text{grd}}(\lambda) = \varepsilon(\lambda)B(\lambda, T) + (1 - \varepsilon(\lambda))L_{\text{atm}}(\lambda)
\]

After atmospheric radiation transmission, the target radiance observed at the height of the sensor is:

\[
L_{\text{sen}}(\lambda) = \tau(\lambda)L_{\text{grd}}(\lambda) + L_{\text{atm}}(\lambda)
\]

Among them, \(\tau(\lambda)\) is the atmospheric transmittance from the target to the sensor, and \(L_{\text{atm}}(\lambda)\) is the upward thermal radiation from the atmosphere. After merging, the radiation transmission model is as follows:

\[
L_{\text{det}}(\lambda) = \tau(\lambda)[\varepsilon(\lambda)B(\lambda, T) + (1 - \varepsilon(\lambda))L_{\text{atm}}(\lambda)] + L_{\text{atm}}(\lambda)
\]

It can be seen from the above formula that the inversion accuracy of the surface temperature is affected by the measurement error of the satellite sensor’s entrance pupil radiance \(L_{\text{det}}(\lambda)\), the specific emissivity error \(\varepsilon(\lambda)\), and the atmospheric correction error such as \(\tau(\lambda), L_{\text{atm}}(\lambda), L_{\text{atm}}(\lambda)\), and the inversion algorithm error. Meanwhile, the satellite sensor entrance pupil radiance \(L_{\text{det}}(\lambda)\) can be decomposed into thermal infrared sensor measurement error, thermal infrared camera calibration error, and channel response error. Therefore, the surface temperature measurement error model is shown in Figure 1.

3. Analysis of influencing factors

3.1. Impact on temperature inversion by NETD of sensor

A) Theoretical model of NETD

The noise of thermal infrared sensors can generally be calculated by Noise Equivalent Temperature Difference (NETD). This index is very important to the accuracy of temperature inversion. HyspIRI has proposed a 0.2K index, MTI, MODIS, Sentinel-3 all proposed indicators better than 0.05K, so that MTI, MODIS, etc. can achieve temperature inversion accuracy better than 1K. NETD is related to sensor design, similar to the signal-to-noise ratio of visible light cameras, and related to optical system parameters, sensor response, sensor noise, and circuit noise. The calculation formula is as follows:

\[
\text{NETD} = \left(\frac{dM}{dT}\right)_{T=300K} \sqrt{\frac{\text{IFOV}^2 \cdot D_0 \cdot \tau \cdot D^* \cdot \delta}{2}}
\]

\(\text{IFOV}\): Instantaneous Field Of View

\(A_d\): Pixel size,
$\Delta f$: Equivalent Noise Bandwidth (ENB),

$D_0$: Optical system aperture,

$\tau$: Optical system transmittance,

$D^*$: Detector detection rate,

$\delta$: Process factor;

$\left(\frac{dM}{dT}\right)_T$: For a blackbody with a temperature of $T$, the radiance change caused by the unit temperature change.

### Figure 1. Surface temperature measurement error model.

**B) Influence on temperature inversion**

Analyze the radiance error which is caused by NETD.

Let $k_1 = c_1 / \lambda^5$, $k_2 = c_2 / \lambda$,

$$B(\lambda, T) = \frac{k_1}{\exp(k_2 / \lambda) - 1}$$  \hspace{1cm} (7)

$$\sigma(L(NETD)) = \frac{\partial B(\lambda, T)}{\partial T} \cdot NETD = \frac{k_2 B(\lambda, T)}{T^2} \cdot \left(\frac{B(\lambda, T)}{k_1} + 1\right) NETD$$  \hspace{1cm} (8)

Land surface temperature inversion error caused by NETD:

$$\sigma_L[T] = \frac{\partial T}{\partial L(T_{iso})} \cdot \sigma(L(T_{iso})) = \frac{\partial T}{\partial B(\lambda, T)} \cdot \frac{\partial B(\lambda, T)}{\partial L(T_{iso})} \cdot \sigma(L)$$  \hspace{1cm} (9)

$$\frac{\partial T}{\partial B(\lambda, T)} = \left[1 + k_1 / B(\lambda, T)\right] \cdot B(\lambda, T)^2 \cdot \ln^3[1 + k_1 / B(\lambda, T)]$$  \hspace{1cm} (10)

$$\frac{\partial B(\lambda, T)}{\partial L(T_{iso})} = \frac{1}{\tau \cdot \varepsilon}$$  \hspace{1cm} (11)

Atmospheric transmittance $\tau$ is mainly affected by atmospheric water vapor content. According to the mid-latitude summer average atmosphere, there is the following fitting formula:

$$\tau = 0.978 - 0.13\omega - 0.001\omega^2$$  \hspace{1cm} (12)

NETD of sensor is the main error term that can be implemented for optimal design. When performing specific analysis and calculation and optimization design work, it is necessary to set boundary conditions.
in combination with actual task scenarios, and analyze based on different design states. This article will make a detailed analysis of this error term in Chapter 4.

3.2. The influence of calibration error on temperature inversion
The error formula for the inversion of land surface temperature caused by the error of radiometric calibration is as follows:

\[
\sigma_{[T]} = \frac{\partial T}{\partial L(T_{\text{ino}})} \cdot \sigma[L(T_{\text{ino}})] = \frac{\partial T}{\partial B(\lambda,T)} \cdot \frac{\partial B(\lambda,T)}{\partial L(T_{\text{ino}})} \cdot \sigma[L]
\]  

(13)

\[
\frac{\partial T}{\partial B(\lambda,T)} = \frac{k_1 \cdot k_2}{[1+k_1/B(\lambda,T)] \cdot B(\lambda,T) \cdot \ln[1+k_1/B(\lambda,T)]}
\]  

(14)

\[
\frac{\partial B(\lambda,T)}{\partial L(T_{\text{ino}})} = \frac{1}{\tau \cdot \varepsilon}
\]  

(15)

Based on the actual calibration capability of the laboratory, it is generally taken as 0.0851, and the corresponding temperature inversion error is 0.57K.

3.3. The influence of channel response error on temperature inversion
The radiance measured by the sensor is the weighted integral average of the spectral radiance and the band response function:

\[
B_{\text{ef}}(T) = \frac{\int_{\lambda_1}^{\lambda_2} f_i(\lambda) B_i(\lambda,T) d\lambda}{\int_{\lambda_1}^{\lambda_2} f_i(\lambda) d\lambda}
\]  

(16)

After analysis, the channel response error index is better than 0.1K.

3.4. The influence of surface emissivity estimation error on temperature inversion
Land surface temperature inversion error \( \varepsilon(\lambda) \) caused by estimation error of surface emissivity

\[
\sigma_{[T]} = \frac{\partial T}{\partial \varepsilon(\lambda)} \cdot \sigma[\varepsilon(\lambda)] = \frac{\partial T}{\partial B(\lambda,T)} \cdot \frac{\partial B(\lambda,T)}{\partial \varepsilon(\lambda)} \cdot \sigma[\varepsilon(\lambda)]
\]  

(17)

\[
\frac{\partial B(\lambda,T)}{\partial \varepsilon(\lambda)} = \frac{1}{\varepsilon^2 \cdot \tau(\lambda)} \left[ \frac{L_{\text{atm}}(\lambda) - L_{\text{ino}}(\lambda)}{\tau(\lambda)} + L_{\text{atm}}(\lambda) \right]
\]  

(18)

For a temperature of 300K, if the estimation error is 0.005, the land surface temperature inversion error can be calculated to be 0.024K.

3.5. The influence of atmospheric correction error on temperature inversion
With reference to the ground retrieval algorithms for similar loads on foreign satellites and the existing atmospheric correction models, in an ideal situation, the atmospheric parameters and atmospheric correction model errors can be better than 0.7K.

3.6. The influence of inversion algorithm error on temperature inversion
In view of the current state of technology, the algorithm will amplify the random noise in the observation data by approximately 5 times. For the current infrared cameras whose NETD is generally less than 0.05K, the algorithm's own error is 0.25K.

4. Optimization analysis based on index decomposition
Through the above analysis, in order to meet the needs of quantitative remote sensing applications, the focus should be on improving the NETD of the sensor. By trying different spectrum settings and optical system parameters, combined with the feasibility of project implementation, to achieve the optimal state of the system. The common spectral range of infrared remote sensing applications is 8.475–12.5 μm,
which can be divided into different bandwidths and combined with different optical system designs to analyze its NETD. This article uses the combinations for analysis in Table 1.

### Table 1. Spectral setting scheme.

|          | 3 Bands (μm) | 4 Bands (μm) | 5 Bands (μm) |
|----------|--------------|--------------|--------------|
| Band 1   | 8.475–9.135  | 8.475–8.825  | 8.475–8.655  |
| Band 2   | 9.735–10.875 | 8.925–9.275  | 8.825–9.125  |
| Band 3   | 11.1–12.5    | 10.3–11.3    | 10.165–10.575|
| Band 4   | /            | 11.5–12.5    | 11.3–11.7    |
| Band 5   | /            | /            | 12.185–12.5  |

For each spectrum division scheme, consider the resolution requirements and the average surface temperature of typical observation areas such as cities, forests, glaciers, and deserts. Use F number 1–2, surface temperature 280K–330K as boundary conditions for simulation, Other simulation parameters are shown in Table 2.

### Table 2. Simulation parameter.

| Parameter | NEB (Hz) | Pixel size (μm) | Transmittance | Detection rate (m·Hz^{0.5}/W) | Process factor |
|-----------|----------|-----------------|---------------|-------------------------------|----------------|
| value     | 714.3    | 20              | 0.68          | 2.8×10^9                      | 0.9            |

The simulation results are as follows:

![Figure 2. NETD based on 3 bands.](image)

Based on 3 spectrum bands, the NETD range is 6.2mK–43.7mK for band 1, 4.4mK–27.6mK for band 2, 4.6mK–26.6mK for band 3.
Based on 4 spectrum bands, the NETD range is 11.5mK~82.3mK for band 1, 12.1mK~83.0mK for band 2, 5.5mK~33.0mK for band 3, 6.7mK~38.2mK for band 4.

From the comparison of the above schemes, it can be seen that although the 3-spectrum scheme can obtain better NETD, it has fewer spectra and limited remote sensing information. While the 5-spectrum scheme NETD is too high, which will affect the imaging quality. In summary, considering application requirements and actual engineering capabilities at the same time, a 4-band configuration combined with an F number of 1.55 is selected as the optimal solution.
5. Evaluation of temperature inversion accuracy

Based on the optimized design scheme, calculate the inversion accuracy of the actual surface temperature. Assuming that the average surface temperature is 300K, the calculation result of the sensor NETD is shown in Table 3.

| Project          | Value | Unit  |
|------------------|-------|-------|
| Band             | 8.475–8.825 | 8.925–9.275 | 10.3–11.3 | 11.5–12.5 | μm |
| Pixel size       | 20    | 20 | 20 | 20 | μm |
| NEB              | 714.3 | 714.3 | 714.3 | 714.3 | Hz |
| Fnumber          | 1.55  | 1.55 | 1.55 | 1.55 | / |
| Transmittance    | 0.68  | 0.68 | 0.68 | 0.68 | / |
| Detection rate   | 2.8×10⁹ | 2.8×10⁹ | 2.8×10⁹ | 2.8×10⁹ | m·Hz⁰.⁵/W |
| Process factor   | 0.9   | 0.9 | 0.9 | 0.9 | / |
| NETD (@300K)     | 37.8  | 38.9 | 16.4 | 19.5 | mK |

Assuming that the average surface emissivity is 0.8 and the surface emissivity error is set to 0.005, from the calculation results in Table 3 combined with the analysis content in Section 3, the surface temperature inversion accuracy table can be further calculated, as shown in Table 4:

| Project               | Parameter error | Inversion accuracy (K) |
|-----------------------|-----------------|------------------------|
| NETD of sensor        | 38.9mK          | 0.054                  |
| Calibration error     | 0.4K            | 0.57                   |
| Channel response error| /               | 0.1                    |
| Emissivity estimation error | 0.005       | 0.024                  |
| Atmospheric correction error | /            | 0.7                    |
| Inversion algorithm error | /                | 0.25                   |
| Surface temperature inversion accuracy | 0.944 | |

The land surface temperature inversion accuracy is better than 1K, which can meet the requirements of the land surface temperature inversion task based on satellite infrared remote sensing.

6. Conclusion

In this paper, an error model of the inversion index of a spaceborne high-resolution infrared camera is established, the action forms and treatment methods of various errors are analyzed, and the simulation boundary conditions are set in combination with actual application requirements and engineering feasibility, and completed optimization design work. Aiming at the optimization results of this article, calculations based on typical application scenarios have verified the effectiveness of the method described in this article. This method has universal reference value for the development and technical verification of spaceborne infrared cameras.

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