The influence of spectral calibration error of the hyperspectral remote sensor on the TOA radiance

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Abstract. Based on the surface reflectance data of the calibration field and spectral calibration coefficients of typical hyperspectral remote sensor, the quantitative effects of the spectral calibration error of hyperspectral remote sensor on the top-of-the-atmosphere (TOA) radiance was analysed by simulating the TOA radiance with spectral calibration error. The results show that: (1) The TOA radiance errors caused by spectral calibration errors are mainly distributed in the solar and atmospheric absorption channels, and the water vapor absorption band errors near 1380 nm and 1870 nm are the largest. (2) With the increase of spectral calibration error, the maximum TOA radiance error in the whole spectrum range increases significantly. Taking a 10 nm resolution hyperspectral remote sensor as an example, 10\% and 30\% spectral calibration errors bring maximum errors of 34.28\% and 68.67\% to the TOA radiance, respectively. The spectral calibration error has a significant linear relationship with the maximum TOA radiance error ($R^2 > 0.98$). (3) The shape of spectral absorption region is sensitive to spectral calibration error, which provides a theoretical basis for the feasibility of spectral calibration based on absorption band. The above conclusions provide a reference for spectral calibration and calibration accuracy requirements of hyperspectral remote sensor.

1. Introduction

The hyperspectral remote sensor can obtain continuous spectral curve of the surface. It has unique technical advantages in the inversion of surface parameters, high-precision classification of surface types and target recognition. The spectral response of hyperspectral remote sensor might change after launch, because of the changes of optical path structure caused by environmental changes, aging of optical devices and mechanical vibration, resulting in the shift of the central wavelength of the spectral channel \cite{1} \cite{2}. Spectral calibration of hyperspectral remote sensor is the premise and basis of radiometric calibration \cite{3}. High-precision spectral calibration can ensure the accuracy of spectral characterization in the radiance spectrum of ground objects. Therefore, it is necessary to study the influence of spectral calibration error on the radiance data obtained by the hyperspectral remote sensor.

In this paper, based on the simulation of atmospheric radiation transmission process and channel spectral response function, the TOA radiance of hyperspectral remote sensor with different spectral calibration errors were obtained, and a quantitative analysis method of the influence of the spectral
calibration error of hyperspectral remote sensor on the TOA radiance was proposed. The quantitative analysis results can provide reference for on orbit spectral calibration accuracy requirements of hyperspectral remote sensor.

2. Method

The spectral calibration coefficients of typical hyperspectral remote sensor and the surface reflectance spectrum of the calibration field were selected. Based on the simulation of atmospheric radiation transmission process and channel spectral response function, the TOA radiance data with different spectral calibration errors were calculated, and then the distribution and transmission characteristics of TOA radiance errors caused by spectral calibration errors were analyzed.

2.1. Simulation of high-resolution TOA radiance spectrum

Based on the surface reflectance spectrum of Dunhuang Calibration Site in China, the MODTRAN4 radiative transfer code was used to simulate the high-resolution TOA radiance. The values of atmospheric and geometry parameters (in table 1) were used in simulation, and the sampling interval used for spectral output was 0.05 nm.

Table 1. Modtran4 input parameters.

| Modtran4 parameters       | Value       |
|---------------------------|-------------|
| Atmospheric mode          | Mid-Latitude Summer |
| CO₂ content               | 390ppm      |
| Aerosol type              | desert      |
| Wind speed                | 4.1m/s      |
| Altitude                  | 1.238km     |
| Sensor height             | 100km       |
| Observation zenith angle  | 180         |
| Relative solar azimuth angle | 90       |
| Zenith angle of the sun   | 45          |

Figure 1. Simulated high-resolution TOA radiance spectrum.

2.2. Simulation of TOA radiance with spectral calibration error

For each spectral channel of hyperspectral remote sensor, 1%, 5%, 10%, 20%, 30% and 50% of the spectral resolution value were used as spectral calibration errors. Based on the convolution of the high-resolution TOA radiance and spectral response functions (SRFs), which was simulated by Gaussian function [1] in equation (1), TOA radiance with spectral calibration errors were simulated.
the process of SRFs simulation, channel center wavelengths were shifted with spectral calibration errors ($\Delta \lambda$) from the nominal channel center wavelengths.

$$f(i, \Delta \lambda) = \exp \left[ \frac{-\left( \frac{\lambda - (\lambda_c(i) + \Delta \lambda)}{h_b(i)/2\sqrt{\ln(2)}} \right)^2}{2} \right]$$

(1)

Where $\lambda_c(i)$ and $h_b(i)$ is the nominal center wavelength and bandwidth of channel $i$.

2.3. Calculation of convolved TOA radiance error

By comparing the convolved TOA radiance before and after adding the spectral calibration error, the influence of the spectral calibration error on the TOA radiance was characterized by the percentage error in equation (2).

$$\varepsilon_c(\Delta \lambda) = \frac{L_{\text{ch}}(i, \Delta \lambda) - L_{\text{ch}}(i)}{L_{\text{ch}}(i)}$$

(2)

Where $L_{\text{ch}}(i)$ is the convolved TOA radiance with nominal spectral calibration coefficients of channel $i$, $L_{\text{ch}}(i, \Delta \lambda)$ is the convolved TOA radiance with spectral calibration error of channel $i$.

3. Results and Analysis

In this paper, EO-1 Hyperion was selected as the representative push broom hyperspectral remote sensor, whose spectral resolution is about 10nm. Based on the center wavelength and bandwidth coefficients of Hyperion spectral channels, TOA radiance with different spectral calibration errors were simulated.

![Figure 2. TOA radiance percent error caused by spectral calibration error.](image)

Simulation results in Figure 2 show that the radiance errors caused by the spectral calibration errors are mainly concentrated in the typical absorption bands, including the solar Fraunhofer channel near 430nm, the O\textsubscript{2} absorption channel near 760nm, the water vapor absorption channels near 940nm, 1140nm, 1380nm and 1870nm, and the CO\textsubscript{2} absorption channel near 2010nm. Among them, the errors of water vapor absorption channels near 1380nm and 1870nm are largest, and Fraunhofer absorption
In the same absorption channel, the radiance error increases with the increase of spectral calibration error. There is a significant linear relationship between the spectral calibration error and the maximum value of radiance error in the whole spectrum, and $R^2$ is greater than 0.98.

### 4. Conclusion

In this paper, a quantitative analysis method for the influence of spectral calibration error of hyperspectral remote sensor on the TOA radiance has been proposed, which is based on the simulation of the TOA radiance of hyperspectral remote sensor with different spectral calibration errors. The main conclusions are as follows:

1. In the whole spectral range, the radiance error caused by the spectral calibration error is basically distributed near the solar and atmospheric absorption channels, including the solar Fraunhofer absorption channel, O$_2$ absorption channel, water vapor absorption channels, and the CO$_2$ absorption channel. Among them, the errors of water vapor absorption channels near 1380nm and 1870nm are largest.

2. In the same absorption channel, with the increase of spectral calibration error, the maximum value of radiance error increases significantly. Taking the 10 nm resolution hyperspectral remote sensor as an example, the maximum errors of 34.28%, 68.67% and 129.57% are caused by the 10%, 30% and 50% spectral calibration errors, respectively. There is a significant linear relationship between the spectral calibration error and the maximum value of radiance error in the whole spectrum range, and $R^2$ is greater than 0.98. High precision spectral calibration of hyperspectral remote sensor is an important factor to ensure the accuracy of TOA radiance.

3. The shape of solar and atmospheric absorption band is highly sensitive to the spectral calibration error, especially for the O$_2$ absorption band near 760nm. The spectral calibration error has a significant effect on the absorption depth of absorption bands, which provides a theoretical basis for the feasibility of spectral calibration based on absorption bands.

### 5. Acknowledgments

This work was financially supported by National Key Research and Development Program of China (2017YFB0503903).

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