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Large-scale earth surface thermal radiative features in space observation

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ABSTRACT

It is necessary to complete the earth thermal radiative modeling, since it is the most important background in space infrared observation. A new method was proposed to calculate the earth thermal infrared radiation combined with remote sensing technology. The simplified model also was proposed when the solar radiative impact is neglected properly. The practical split-window algorithm was used to retrieve the global surface temperature from MODIS data products. Integrated with MODTRAN code to calculate the atmospheric radiation and transmittance, the earth thermal infrared features were calculated in typical months. Moreover the radiance dependence on viewing angle was discussed. Through the comparison with CERES measurement results, this model has been proved effective and practicable, and that it would have a further application in space thermal environment analysis or space infrared observation technology.

1. Introduction

Along with the continuous development of aerospace industry, the research demand of space observation and recognition is rapidly growing. Many of computational models [1–4] were presented about thermal infrared features analysis of space objects, such as satellites and other space vehicles. So far the published researches on thermal infrared features of earth background are quite inadequate, which have essential value either as environment flux in space thermal analysis, or as background in space infrared observation. In order to calculate the earth infrared features, the surface temperature should be obtained in advanced. Some analytical models [5–8] can be used to calculate the temperature of natural terrain, when the surface information is sufficient known. However, when it is applied into global scale, an enormous amount of statistical work are unable to be accomplished about the surface properties, therefore the accuracy of analytical calculation cannot be assured in limited known parameters.

More effective approach is to use remote sensing technology from the satellite data [9]. NASA's Earth Observing System (EOS) program provides a series of remote sensing satellite and scientific instruments designed for global observation of the land surface, oceans and atmosphere. MODIS (Moderate Resolution Imaging Spectroradiometer) is one of EOS instruments, and is widely used in temperature retrieval of earth surface. The accuracy of temperature retrieval from MODIS data is specified at 0.3 K for sea surface and 1 K for land surface [10].

Besides the surface temperature, the influence of earth's atmosphere is non-ignorable. The thermal radiation from the earth's surface would be affected by atmospheric absorption, scattering and radiation. MODTRAN (moderate resolution atmospheric transmission) code is effective and convenient software designed to calculate atmospheric radiation and transmission. The MODTRAN code uses the discrete-ordinates method [11], and the approximations are accurate within 0.5%–2%. The spectral resolution of calculation results is 2 cm^{-1} FWHM (Full Width at Half-Maximum) in averaged steps of 1 cm^{-1}, and the spectral range is from 0.2 μm to infinity [12].

2. Theoretical model

2.1. Infrared radiation calculation

The infrared radiance of the earth background detected from space includes the earth's surface thermal emission I_e, atmospheric radiation I_{atm}, which is resulting from self-emitting and scattering of solar radiation, the earth's surface reflection of the

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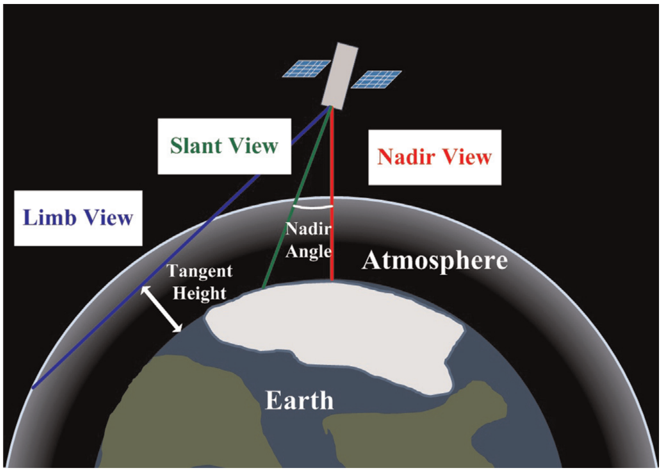

Fig. 1. Different types of viewing geometry in earth observation.

solar beam and the atmospheric downward radiation I_r:

$$I(\lambda, \mu, \theta_s, \phi_s) = t(\lambda, \mu)\left[I_e(\lambda, \mu) + I_r(\lambda, \mu, \theta_s, \phi_s)\right] + I_{atm}(\lambda, \mu, \theta_s, \phi_s) \quad (1)$$

where $t(\lambda, \mu)$ is the atmospheric transmittance depending on the wavelength and viewing zenith angle, θ_s is the solar elevating angle, ϕ_s is the relative solar azimuth angle to the viewing direction, and μ is cosine of viewing angle. For simplification, anisotropic factor of earth's surface is not considered in the calculation. Two atmospheric windows 3–5 μm and 8–14 μm, are taken into consideration in thermal infrared band. Beyond the windows, the atmospheric transmittance is almost zero, so only the atmospheric radiation is able to be detected.

There are different viewing geometries in earth observation of satellite detector, as shown in Fig. 1. Nadir view and slant view are the two geometries which are ended at earth's surface. Nadir view is the vertical downward viewing geometry, and slant view always has an angle with nadir direction. The other one is that the satellite's line-of-sight traverses the atmosphere without touching the surface, which called limb view

In limb view, the infrared radiance includes only the radiation of atmosphere. In one kind of atmospheric model, the limb infrared characteristics have a strong correlation with the tangent height of line-of-sight. In addition, the relative position between the sun and the observer also influences the limb infrared radiance.

The thermal radiation and reflected radiation constitute the effective radiation from the ground surface. The global surface temperature should be retrieved first, and the band effective emissivity could be estimated from the retrieved surface coverage type. Given the emissivity $\varepsilon(\lambda, \mu)$ and the surface temperature T, the thermal emissive radiation can be obtained:

$$I_e(\lambda, \mu) = \varepsilon(\lambda, \mu) I_B(\lambda, T) \quad (2)$$

where, $I_B(\lambda, T)$ is the spectral intensity of black body with the temperature of T, using the Plank function.

The surface reflected radiation can be calculated as the following expression [13]:

$$I_r(\lambda, \mu, \theta_s, \phi_s) = f_r(\lambda, \mu, \theta_s, \phi_s)\cos\theta_s E_s(\lambda) + \int_0^{2\pi}\int_0^1 f_r(\lambda, \mu, \mu', \phi')\mu' I_{atm}(\lambda, -\mu', \theta_s, \phi_s)d\mu' d\phi' \quad (3)$$

where, f_r is bidirectional reflectance distribution function(BRDF), $E_s(\lambda)$ is the solar spectral irradiance on the surface of the earth, the second item on right hand side is the integral of atmospheric downward radiation in all directions.

It can be seen that, there are too many factors to be determined for earth infrared radiance. However, simplification is practicable that the surface BRDF's anisotropy can be neglected, because emissivities of most ground materials varies very small along with viewing angle [14]. The model's efficiency also can be improved if the surface thermal radiative intensity only depends on the wavelength. Moreover, the earth's surface can be assumed as ideal Lambertian surface, thus the surface radiative intensity would be irrelevant to viewing angle. As a result, Eqs. (2) and (3) can be simplified as follows:

$$I_e(\lambda) = \varepsilon(\lambda) I_B(\lambda, T) \quad (4)$$

$$I_r(\lambda, \theta_s, \phi_s) = \frac{\rho}{\pi}[\cos\theta_s E_s(\lambda) + E_{atm}(\lambda, \theta_s, \phi)s] \quad (5)$$

where ρ is the diffuse reflectance of ground surface, E_{atm} is the irradiance on the surface of the atmospheric downward radiation from all directions.

It can be found in the calculation equation that the earth spectral infrared radiance on top-of-atmosphere (TOA) is not only depended on the viewing angle, but also on the solar orientation. We simulate all the constituents of earth infrared radiance by using MODTRAN code to see the proportion of each factor, as shown in Fig. 2. The separate constituents are thermal path radiance, surface emission radiance, scattered solar radiance, and reflected radiance by ground surface. Among them, the surface emission and reflection has been multiplied with atmospheric transmittance. In this case, the temperature of ground surface is set as 300 K, and the reflectivity is 10%, and the solar zenith angle is 0°, and the atmospheric model is mid-latitude summer.

From the Fig. 2, the surface emission is the main influence factor when the wavelength is less than 4.3 μm, and from this wavelength the atmosphere path thermal radiation begins to rise. The surface emission and reflection is non-transparent between 5.0 μm and 8.0 μm, while the atmosphere path thermal radiation is the only one to be considered. In the band 8.0–14.0 μm the surface emission plays the most important role in total radiance and the atmosphere path thermal radiation is significant, too.

Fig. 2 reveals that the scatted solar radiance is insignificant which can be neglected in whole thermal infrared band. It also shows obviously that the reflected radiance is so weak and negligible in all calculated infrared band, because of the low reflectivity. It is reasonable that most earth surface materials are highly emissive in thermal infrared wavelength.

As analyzed, the solar scatted radiation and reflected radiation have faint impacts on the total TOA radiance, thus it need not to consider the solar orientation in the calculation. Atmospheric

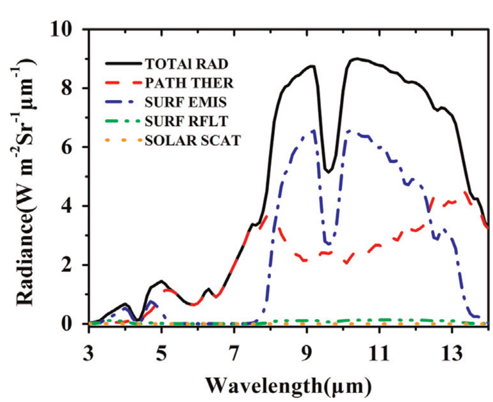

Fig. 2. Spectral TOA infrared radiance in mid-latitude summer (total and constituents).