Research of detection range of LWIR dispersive imaging spectrometer

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ABSTRACT

Among various types of long-wave infrared spectrometers, dispersive spectrometer has the simplist structure and has shown good service behavior in all kinds of imaging spectroscopy applications. For the technology of infrared remote imaging spectroscopy, an excellent designed imaging spectrometer is the key factor. Of all the designing factors, the tradeoff between the detection performance and the structure size is always the main topic. In this paper, according to the performance parameters of the used infrared sensor, characteristic of energy transmission of dispersive spectrometer, characteristic of target radiation and the effect of atmospheric transmission, a comprehensive research is done to construct a perfect receiving radiation model of LWIR dispersive spectrometer, providing theoretical foundations for accurately determining the relationship between instrumental structure parameters and the detection range. A designing model with an uncooled microbolometer as its detector is calculateded to analyse its potential in the application of long-wave remote imaging spectroscopy.

Keywords: LWIR, imaging spectrometer, dispersive spectrometer, detection range, hyperspectral, remote sensing

1. INTRODUCTION

Nowadays, LWIR(8~14μm) remote sensing imaging spectrometers have been widely used in fields of geographical remote sensing, pollutants remote sensing, as well as detection and surveillance of military targets, playing more and more important roles. According to the different working mechanisms, LWIR spectrometers can be constructed into various styles. Of all kinds of such spectrometers, the dispersive spectrometer has substantial structure, high spectral and spacial resolutions and good real-time quality, which is especially suitable for airborne and satellite-borne applications in hard environments.

Since objects with normal temperature in nature radiate at a low level; dispersive spectrometer with a prism or a grating as the dispersive component, resolve the incident radiation into a series of narrow bands, leading to very low radiation in every narrow band; the sensors working in LWIR have usually low sensitivities and relatively high noise; and also the incident radiation is attenuated by the atmosphere in transmission, all the above factors make LWIR dispersive spectrometers have to increase its aperture of telescope objective to receive enough radiation, which leads to a large instrument volume. To accurately determine the relationship between instrument structure parameters and the detection range, a comprehensive research is needed to do with the considerations of performance of LWIR sensor used, characteristic of energy transmission of dispersive spectrometer, characteristic of target radiation and the effect of atmospheric transmittance. In this paper, all the main factors concerned with the radiation transmission are considered in theory, constructing a general analytical model, giving the relationship equation between the detection range and all the involved factors.

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2. RADIATION TRANSMISSION MODEL AND DETECTION RANGE EXPRESSION

2.1 Radiant illumination incident on entrance slit

The radiant illumination incident on the entrance slit can be expressed by the following equation:

$$E_i(\lambda) = \pi L(\lambda)\tau_a(\lambda)D^2 / 4f^2 \quad (1)$$

in which D is the receiving telescope objective diameter, f is the focus of telescope objective, $L(\lambda)$ is the spectral radiance of the target, and $\tau_a(\lambda)$ is the atmospheric transmittance. When a Cassegrain objective is used in the instrument, the radiant illumination incident on the entrance slit can be expressed as:

$$E_i(\lambda) = \pi L(\lambda)\tau_a(\lambda)({D_1}^2 - {D_2}^2) / 4f^2 \quad (2)$$

where D_1 is the diameter of the main mirror, and D_2 is the diameter of secondary mirror.

2.2 Characteristic of energy transmission of dispersive spectrometer

The receiving radiant flux focused on the entrance slit is dispersed by the grating component, and the spectral illumination $E_o(\lambda)$ incident on the sensor pixel can be expressed by equation [1]:

$$E_o(\lambda) = \beta\tau_m E_i(\lambda){f_1}^2 / {f_2}^2\gamma \quad (3)$$

where β is the diffraction efficiency on the first order of diffraction, τ_m is the transmittance of mirrors, f_1 is the focus of the collimating object lens, f_2 is the focus of the imaging lens. γ is the transverse magnification of the grating dispersive component, which is expressed by the equation:

$$\gamma = \cos i / \cos\theta \quad (4)$$

where i is the incident angle, and θ is the diffraction angle.

Alike the analysis of energy transmission of grating dispersive spectrometer, in the prism dispersive spectrometer, the outgoing spectral illumination $E_o(\lambda)$ can be expressed by the following equation:

$$E_o(\lambda) = \tau_p(\lambda)\tau_m(\lambda)E_i(\lambda)(\sin\varepsilon){f_1}^2 / {f_2}^2\gamma \quad (5)$$

where $\tau_p(\lambda)$ is the spectral transmittance of the prism, which is determined by the used prism , and ε is the angle of inclination between the imaging plane and the optical axis of the imaging system.. γ is the transverse magnification of the prism dispersive system, which can be expressed by the equation:

$$\gamma = \cos i_1 \cos i_2 / \cos i_1' \cos i_2' \quad (6)$$

in which i_1 is the incident angle with its refraction angle of i_1', i_2 is the exit angle with its refraction angle of i_2' as well.

2.3 Effect of atmospheric transmission

Although the LWIR band is one of the atmospheric windows, the absorption of water and CO_2 is the key factor in determining the detection range when it is too far away.

Theoretically, it is assumed that the atmospheric composition at the altitude of h is stable. In the distance of l, the transmittance of this atmospheric layer can be calculated by the following equation:

$$\tau_{\lambda,h}(l) = e^{-\alpha(\lambda,h)l} \quad (7)$$

where $\alpha(\lambda, h)$ is the atmospheric attenuation coefficient at the altitude of h.

When in oblique or vertical remote sensing with the altitude of H and the sensor viewing angle of θ, the atmospheric transmittance from the object to the infrared spectral remote sensor can be expressed by the equation:

$$\tau_{\lambda,\theta}(H) = e^{-\int_0^H \alpha(\lambda,h)\sec\theta dh} \tag{8}$$

In the calculation of the atmospheric transmittance, it is needed to obtain the accurate distribution of the atmospheric attenuation coefficient $\alpha(\lambda, h)$. At present, in the fields of atmospheric remote sensing and photoelectric detection technologies, the atmospheric code LOWTRAN and MODTRAN have been used widely in the design of photoelectric detection instruments and the calibration of spectral data. LOWTRAN is the low-resolution atmospheric code with the spectral resolution of 20cm^{-1}, and MODTRAN is the moderate-resolution atmospheric code with the spectral resolution of 2cm^{-1}, which show the excellent performances in applications.

2.4 Characteristic of LWIR radiation from objects

Since the solar radiation in the LWIR band is very low, the effect of the solar radiation can be dismissed. Thus, the compositions of the LWIR radiation from the object are composed of three parts which are respectively the spontaneous thermal radiation of the object, the reflection part of the downward atmospheric radiation from the object, as well as the route scattering part and its radiation part. Therefore, the spectral radiance can be expressed by the equation [2]:

$$L(\lambda) = L_t(\lambda) + L_a(\lambda) + L_{r\uparrow}(\lambda) \tag{9}$$

Knowing the object emissivity $\varepsilon(\lambda)$, the spectral radiance from the object to the sensor can be expressed by the following equation:

$$L(\lambda) = \varepsilon(\lambda)L_B(\lambda,T) + [1-\varepsilon(\lambda)]L_{a\downarrow}(\lambda) + L_{r\uparrow}(\lambda) \tag{10}$$

where $\varepsilon(\lambda)$ is the emissivity of object, $L_a(\lambda)$ is the radiance part caused by the downward atmospheric radiance $L_{a\downarrow}(\lambda)$, $L_{r\uparrow}(\lambda)$ is the route atmospheric radiance. $L_B(\lambda,T)$ is the spectral radiance of the blackbody with its absolute temperature of T, which is express as:

$$L_B(\lambda,T) = 2hc^2 / \lambda^5 (e^{hc/\lambda KT} - 1) \tag{11}$$

where h is the Planck constant, and K is the Boltzmann constant.

2.5 Detection range of the LWIR hyperspectral remote sensing sensor

To obtain accurate spectral data, the SNR between the signal voltage transformed by the infrared sensor and the noise voltage has to be greater than a threshold SNR_{th} which is defined according to a required detection probability.

According to above analysis, the signal voltage can be calculated by the following equation:

$$V_s = A_d S(\lambda)\pi L(\lambda)\tau_a(\lambda)\tau_s(\lambda)D^2/4f^2 = A_t S(\lambda)\pi L(\lambda)\tau_a(\lambda)\tau_s(\lambda)D^2/4R^2 \tag{12}$$

where R is the detection range, A_d is the sensitive area of the sensor, A_t is the object area, $S(\lambda)$ is the spectral response, and $\tau_s(\lambda)$ is the system transmittance of the spectrometer. V_n is the RMS noise voltage of sensor which can be obtained by the following equation:

$$V_n = S(\lambda)\sqrt{A_d \cdot \Delta f} / D^* \tag{13}$$

where Δf is the system bandwidth, and D^* is the detectivity of sensor.

Considering the limit of $SNR \geq SNR_{th}$, detection range can be finally expressed as following:

$$R \leq \left[\frac{\pi A_t D^2 D^* L(\lambda) \tau_a(\lambda) \tau_s(\lambda)}{4\sqrt{A_d \Delta f} SNR_{th}} \right]^{1/2} \tag{14}$$

3. SIMULATION AND RESULTS

Using the expression of detection range, the structure parameters of a kind of small remote imaging spectrometer, of which uncooled microbolomerer FPA is used as the detector, have been calculated in this section. As known to all, uncooled microbolometer without the bulk cryogenerator can be designed into small thermal infrared imaging system. But the low detectivity limits its remote-sensing applications. However, with the development of the microbolometer technology, the performances have been improved a lot and its potential in remote sensing is becoming increasing. The application feasibility of uncooled microbolometer FPA in imaging spectroscopy is analyzed in this section.

This simulation is considered as the remote sensing imaging spectrometer for a small flying platform working at low altitude, such as UMV, to do remote observation of land scene. The working parameters used here in the calculation are set as follows: working altitude>1km, flying speed=120km/h, ground resolution=1m^2 , the range of working spectrum: 7.8~13.4μm , spectral resolution=0.1μm, the ground surface temperature=300K. The performance parameters of uncooled microbolometer FPA refer to documents [3, 4]. Here, it is thought that the spectral response and detectivity of microbolometer are invariable. The main request of system and the device parameters are listed on Table 1.

Table. 1. Request of small imaging spectrometer and performance parameters of uncooled-microbolometer FPA.

Request of small dispersive imaging spectrometer	
Altitude	≥1 km
Flying speed	120 km/h
Spectral resolution	0.1μm
Number of wave bands	56
Ground resolution	1 m^2
Performance parameters of uncooled-microbolometer FPA	
Responsivity	3.5×10^4 V/W
Detectivity	1.6×10^9 cmHz$^{1/2}$/W
Pixel area	39μm×39 μm
Frame frequency	30 Hz

For the purpose of precise imaging spectral detection for various ground objects, it is needed to obtain reliable signal with high SNR in every narrow band. To realize this objective, it is necessary to comprehensively consider the emissivity of all the objects of interest, using the minimum value of emissivity in design calculation. The long-wave emissivity of several material objects are shown in figure 1, the data come from [5]. As shown in the figure, most objects in nature have similar high emissivity in LWIR band. But for the sand, there is an obvious absorption peak at near 9μm. As the difference of long-wave infrared emissivity between most objects are rather low, in order to distinguish the spectrum emissivity of different objects, it is needed to set a high SNR. According to the relative documents [6, 7], the SNR is set as 500. At the meantime, for the sake of simplifications, the transmittance of imaging spectrometer system is set to be 0.5, which is careful and cautious.

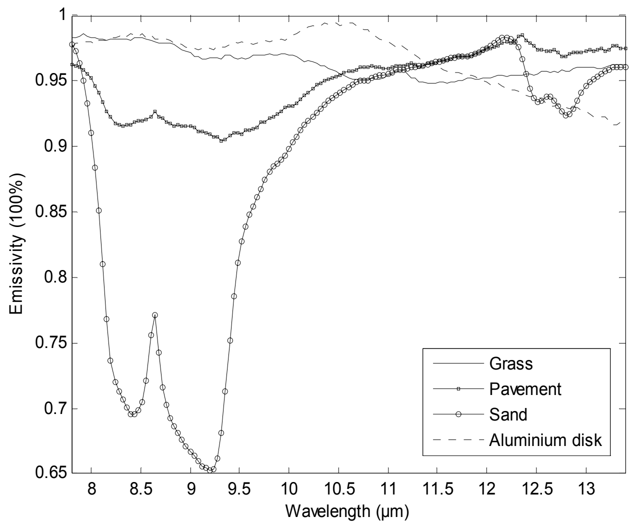

Fig. 1. Spectral emissivity of several materials in LWIR band.

In the simulation, since reflectance of most of ground objects and the atmospheric route radiation are both very low in LWIR region, the effect of atmosphere is not taken into consideration, and the receiving radiation is only produced by the spontaneous thermal radiation. Here, we use LOWTRAN code to calculate the atmospheric transmittance of several application environments, and the main parameters are set as follows: 1976 American Standard Atmospheric Model; country extinction coefficient aerosol model, with meteorological visual range equal to 23km; spring-summer troposphere/stratosphere profile; zenith angle of 0. The Figure 2 shows the curve of atmospheric radiation transmittance at different observation altitude.

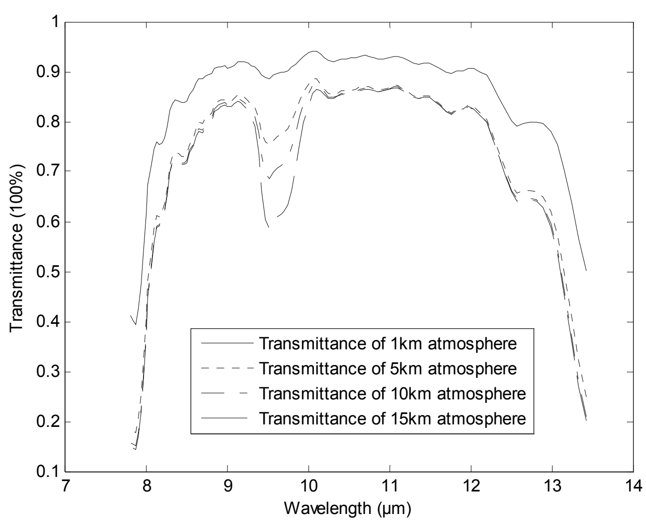

Fig. 2. Curves of atmospheric transmittance at different observation altitude.

The aperture dimensions of telescope objective at different detection height are calculated through the above formulas, and the results are shown on Table 2. When the detection height is 1km, the objective aperture needs to be 19cm. It can be seen that this dimension is practically feasible to a remote-sensing imaging spectrometer using uncooled microbolometer FPA. But when higher than 5km, the system has to increase the receiving objective aperture over 1m. In the sense of engineering, this has lost its practicability, and the cooled photon FPA with higher detectivity must be needed. It is needed to point out that the analysis is based on some simplifications. To obtain precise results, the accurate parameters used in the calculation should be known.

Table. 2. Relationship between objective apertures and altitudes.

Altitude (km)	Objective aperture (m)
1	0.19
5	1.40
10	3.04
15	4.65

4. CONCLUSION

According to the performance parameters of infrared sensor used, characteristic of energy transmission of dispersive spectrometer, characteristic of target radiation and the effect of atmospheric transmission, a comprehensive research is done to construct a perfect receiving radiation model of LWIR dispersive spectrometer, providing theoretical foundations for accurately determining the relationship between instrumental structure parameters and the detection range.

The optimization of hyperspecrtral remote sensor, especially LWIR imaging spectrometer, is a key issue in the design of such a kind of sophisticated instrument. A tradeoff has to be considered between the requirements and the instrumental structure. According to this research, the aperture of telescope objective can be determined to be the best advantage.

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