FORMATION MECHANISM AND EVALUATION MODELS OF VERTICAL SPACE CHARACTERISTIC FOR FY-4A INFRARED HYPERSPECTRAL ATMOSPHERIC TEMPERATURE SOUNDING

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ABSTRACT: Remote sensing space characteristic is an important aspect of remote sensor performance, and space-borne infrared hyperspectral vertical sounding is the frontier of atmospheric sounding. In this paper, to evaluate the vertical space characteristics (VSC) of the atmospheric temperature sounding by FY-4A geostationary interferometric infrared sounder GIIRS, the formation mechanism of the VSC of the space-borne infrared hyperspectral atmospheric sounding data is analyzed, the VSC indicators and their mathematic models are established. The results show that, the sounding altitudes of most long-wave band channels distribute in ≤9km, meanwhile there are several long-wave band channels whose sounding altitudes distribute in 16~29km, and the sounding altitudes of medium-wave band channels all distribute in ≤14km. As a whole, FY-4A GIIRS can sound the change of atmospheric temperature profile below 35km with sounding resolution taken into consideration.

1. INTRODUCTION

Spatial characteristics of satellite remote sensing has two meanings: one is the spatial characteristic of remote sensing data, the other is the spatial characteristic of inversion product. Generally, satellite earth observing sensors includes imager, aiming to obtain the horizontal images of atmospheric and earth surface features, and the atmospheric vertical sounder which focuses on obtaining the vertical distribution profiles of atmospheric parameters. The first infrared hyperspectral atmospheric sounder on geostationary satellite, GIIRS (Geostationary Interferometric Infrared Sounder) with 1650 spectral channels is loaded on FY-4A meteorological satellite, which is China's second-generation geostationary meteorological satellite launched in December 2016. GIIRS is an interference spectrometer, covering long-wave band 700-1130cm^{-1} and medium-wave band 1650-2250cm^{-1}. Launched in November 2017, the polar-orbiting meteorological satellite FY-3D also carried an infrared hyperspectral atmospheric sounder HIRAS with 1370 spectral channels. (Liu, 2019, Dai et al, 2019, Hua and Mao, 2018, Song et al, 2019, Dong et al, 2013, Zhang et al, 2017, Yang et al, 2018).

The spatial characteristics of imaging data is usually described by pixel position, pixel size, pixel shape and the coverage of all pixels etc., which completely depend on optical and mechanical design of imager, design of satellite orbit and other geometric designs, and have nothing to do with the underlying surface parameters interested (Hu et al, 2018, 2002, Niclòs et al, 2014, Qi et al, 2019). As for the spatial characteristics of inversion products obtained from imaging data, the inversion method, such as sub-pixel decomposition technique, has been studied extensively.

The data of infrared hyperspectral atmospheric sounder has the horizontal space characteristic (HSC) with the same formation mechanism as imager. More importantly, it has vertical space characteristics (VSC). So far, there have been a few studies on the VSC related to the infrared hyperspectral atmospheric sounding, which mainly focus on the inversion products, rather than on the vertical sounding data. Zeng (1974) defined measurable altitude as altitude of the effective radiation layer and the vertical resolution as a discernible vertical scale depending on the effective information content of selected channels. and other researchers have also studied the spatial characteristics of retrieval products of atmospheric parameters (Conrath,1972, Thompson et al., 1976, Newman, 1979, Purser and Huang, 1993, Wang et al., 2007, Maddy and Barnet, 2008, Dong et al., 2013). However, there is a lack of research on the atmospheric space characteristic information contained in the sounding data itself.

In this paper, the formation mechanism of VSC of the infrared hyperspectral atmospheric sounding data is analyzed systematically in section 2. On this basis, indicators of VSC are defined and their mathematical models are established in section 3. Followed the VSC of FY-4A GIIRS data for atmospheric temperature is evaluated in section 4.

2. THE VSC FORMATION MECHANISM OF INFRARED HYPERSPECTRAL ATMOSPHERIC SOUNDING DATA

2.1 Atmospheric Sounding Equation

Assuming that the atmosphere is a plane parallel molecular layer in state of local heat balance, and the sounding band is medium-wave infrared band (excluding its molecular scattering segment) and long-wave infrared band, the radiation observed in the direction of substellar point is:

$$I_\nu = \int_{p_s}^{0} \left[B_\nu(T_p) - \varepsilon_{s\nu} B_\nu(T_s) \right] \frac{dH_\nu(p)}{dp} dp + \varepsilon_{s\nu} B_\nu(T_s) + I'_{\nu-sun} + \varepsilon'_\nu \qquad (1)$$

Where, I_ν is radiation intensity measured by sounder, ν is wavenumber, T_p is the temperature at pressure p, $B_\nu(T_p)$ is the blackbody radiation intensity at T_p, $H_\nu(p)$ is the transmittance from p to the top of atmosphere, $\varepsilon_{s\nu}$ is the surface emissivity, T_s is the surface temperature, $B_v(T_s)$ is the surface blackbody radiation intensity, p_s is the surface pressure, $H_v(p_s)$ is the transmittance from surface to the top of atmosphere.

Similar to the HSC of imaging data which concerns where the surface being looked at and doesn't concern at what extent the surface being seen clearly, the VSC of infrared sounding data is also defined to pay attention to where the atmosphere being looked at and doesn't pays attention to at what extent the atmosphere being seen clearly. Thus, if there are m channels and the central wavenumbers are $v_i\,(i=1,2,\cdots m)$, the equation used to analyze the VSC of sounding data is:

$$L_{v_i}=\left[\int_{p_s}^{0}B_{v_i}(T_p)-\varepsilon_{sv_i}B_{v_i}(T_s)\right]\frac{dH_{v_i}(p)}{dp}dp \qquad (2)$$

All the quantities in Eq. (2) related to wavenumber mean the average for bandwidth of spectral resolution centered at v_i .

The altitude distribution of atmospheric temperature and atmospheric absorption gases is reflected in L_{v_i} by influencing atmospheric radiation and transmittance. It should be noted that the expression of an atmospheric parameter may be changed. To illustrate, Li et al. (1994) used the logarithm of the mixing ratio rather than the mixing ratio for water vapor.

Supposing $a_j(p)\quad(j=1,2,\cdots n)$ are the altitude distribution of atmospheric parameters, the signal response of the jth atmospheric parameter variation in the ith spectral channel is:

$$\delta L_{v_i}^{j}=\int_{0}^{p_s}K_{ij}(p)\delta[a_j(p)]dp \qquad (3)$$

Where, $\delta[a_j(p)]$ is the variation of the jth atmospheric parameter at p, $K_{ij}(p)$ is the response weighting function of the ith spectral channel for $\delta[a_j(p)]$. For an atmospheric parameter, if its expression is changed, the corresponding response weighting function will also be changed.

Thus, the VSC of atmospheric sounding data should specify the interested atmospheric parameter, its expression form and variation meaning. The variation of atmospheric parameter can be either absolute or relative. The relative variation concerned by optimal selection of infrared hyperspectral atmospheric sounding channels (Rodgers, 1996).

If relative variation of atmospheric parameter is considered, Eq. (3) can be rewritten as,

$$\delta L_{\nu_i}^{j} = \int_{0}^{p_s} W_{ij}(p)\delta[b_j(p)]dp \quad (i=1,2,\cdots m,\ j=1,2,\cdots n) \qquad (4)$$

Where,

$$W_{ij}(p) = K_{ij}(p)\sqrt{\delta^2[a_j(p)]}\ , \quad \delta[b_j(p)] = \delta[a_j(p)]/\sqrt{\delta^2[a_j(p)]} \quad (5)$$

The altitude in above equations is expressed by pressure p, it can also be expressed by geometric height. Thus, if z is used as altitude parameter, Eq. (4) can be rewritten as,

$$\begin{aligned}\delta L_{\nu_i}^{j} &= \int_{z_{top}}^{0} \left\{ W_{ij}(p)\frac{dp}{dz} \right\} \delta[b_j(p)]dz \\ &= \int_{z_{top}}^{0} \left\{ K_{ij}(p)\sqrt{\delta^2[a_j(p)]}\frac{dp}{dz} \right\} \delta[b_j(p)]dz \quad (i=1,2,\cdots m,\ j=1,2,\cdots n)\end{aligned} \qquad (6)$$

We should note that the unit of $W_{ij}(p)$ and $W_{ij}(p)\frac{dp}{dz}$ is “the unit of radiation change / the unit of altitude)”.

2.2 The Response Analysis of Atmospheric Parameter Variations

If a certain atmospheric parameter expressed properly, the ith channel is the absorption channel of this parameter, there will be a special altitude where the variation of this parameter will be responded most sensitively by the ith channel compared with other altitudes. That is, the weighting function is the maximum at this special altitude.

Figure 1(a) and Figure 1(b) show respectively the change of weighting function with geometric altitude for temperature relative change sounding applying spectral channels 720cm^{-1}, 720.625cm^{-1}, 790cm^{-1}, 790.625cm^{-1}, 791.25cm^{-1}, 1048.125cm^{-1}, 1651.875cm^{-1}, 1748.75cm^{-1} and 1771.25cm^{-1}, and for water vapor mixing ratio relative change sounding applying spectral channels 1048.125cm^{-1} and 1651.875cm^{-1}. It can be seen that, the weighting functions of different atmospheric parameters are different in their altitude positions, altitude range sizes and shapes. Taking channels 1048.125cm^{-1} and 1651.875cm^{-1} as examples, the shape and peak position of the weighting function change with altitude for temperature are different from that for water vapor.

In a word, the formation mechanism of the VSC of infrared hyperspectral atmospheric sounding data is complex and completely different from that of HSC of imaging data.

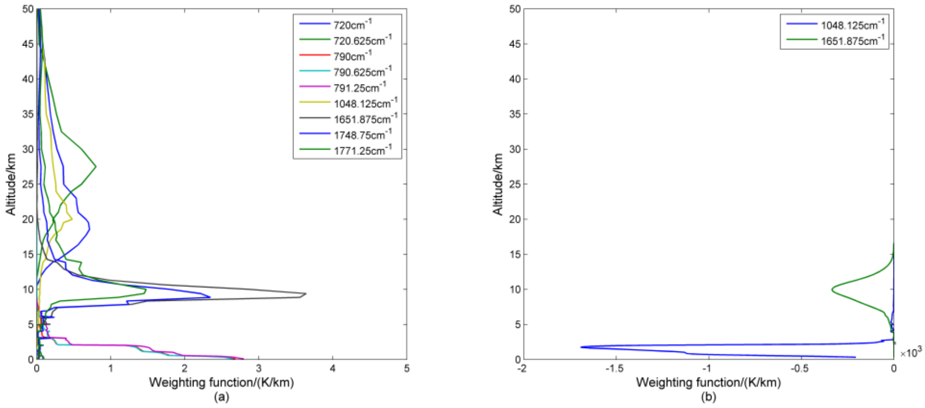

Figure 1 (a)Temperature weighting functions (b) water vapor weighting functions

3. THE VSC INDICATORS AND THEIR MATHEMATICAL MODELS OF INFRARED HYPERSPECTRAL ATMOSPHERIC SOUNDING DATA

Hereafter, h and $Q_{ij}(h)$ are used uniformly to represent altitude and response weighting function. Given a spectral channel, with appropriate expression and variation definition of interested atmospheric parameter, the change of weighting function with altitude generally has the features: 1) increase first and then decrease; 2) increase monotonically; 3) decrease monotonically. The latter two features can also be regarded as special cases of the first feature in the case of upper boundary (h_{top}) cutoff and lower boundary (h_{ground}) cutoff. (see Figure 2).

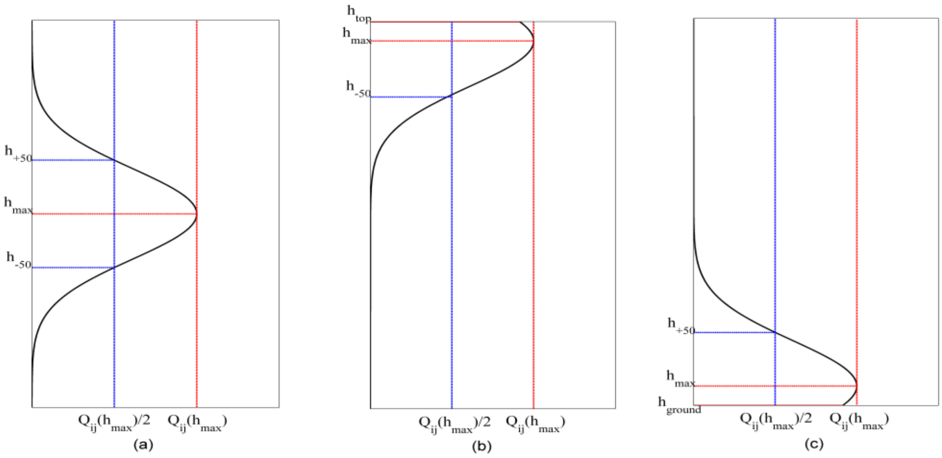

Figure 2 Schematic diagram of weighting function

Similar to the HSC, the four indicators followed can be used to characterize the VSC of infrared hyperspectral atmospheric sounding data for a certain atmospheric parameter including its definitions of expression and variation:

1) Sounding altitude

It reflects the altitude position of the response weighting function curve of a spectral channel.

This indicator is corresponding to the imaging pixel position in the HSC of imaging data. The mathematical model for sounding altitude is defined as the peak altitude of weighting function $h_{\max}$, that is

$$Q_{ij}(h_{\max})=\max_{h_{ground}\le h\le h_{top}}[Q_{ij}(h)] \quad (7)$$

Where,

a) If $h_{ground} < h_{\max} < h_{top}$, $h_{\max}$ is in the concerned atmosphere.

b) If $h_{\max}=h_{top}$, $h_{\max}$ is at the upper boundary.

c) If $h_{\max}=h_{ground}$, $h_{\max}$ is at the lower boundary.

2) Sounding vertical coverage

It reflects combined altitude coverage of the response weighting functions of all spectral channels. This indicator is corresponding to the total ground range observed by imager. If h_{+50}, h_{-50} are respectively the upper and lower altitude corresponding to half max of weighting function, then the mathematical model of the sounding vertical coverage of an infrared band is defined as

$$\mathrm{R}=\bigcup_{h_{ground}\le h\le h_{top}}\left[h_{d5}, h_{u5}\right] \quad (8)$$

Where,

$$h_{u5}=\min(h_{top}, h_{+50}),\quad h_{d5}=\max(h_{ground}, h_{-50}) \quad (9)$$

If there are several infrared sounding bands, the total vertical coverage of sounding data is the union of the sounding vertical coverages of these bands.

3) Sounding altitude resolution

It reflects the altitude range covered by the response weighting function curve of a spectral channel. This indicator is corresponding to the imaging pixel size due to the instantaneous FOV of imager.

4) Sounding vertical asymmetry

It reflects the shape of the response weighting function curve with altitude of a spectral channel. This indicator is corresponding to the imaging pixel asymmetry relative to the imaging pixel position.

4. THE EVALUATION OF VSC FOR ATMOSPHERIC TEMPERATURE SOUNDING WITH FY-4A GIIRS DATA

4.1 FY-4A GIIRS Technical Parameters and The Calculation of Response Weighting Function for Atmospheric Temperature Variation

Atmospheric temperature is taken as the interested sounding parameter and its relative variation is concerned. Here, to illustrate, we focus on the assessment of sounding altitude and sounding vertical coverage of temperature sounding of FY-4A GIIRS data.

The response weighting function can be calculated by the line-by-line radiative transfer model (LBLRTM). The statistical average profile and standard deviation profile of vertical distribution of atmospheric temperature are as input (Luo and Yin, 2019). The atmosphere 0-100km is divided into 121 layers for running LBLRTM. We focus on the atmosphere below the stratopause (about 50km), in which the water vapor, O_3, CO_2 and other absorbing gases are mainly distributed. Since the atmosphere is divided into layers, the judgment of sounding altitude should include the influence of atmospheric discretization.

4.2 Sounding Altitude

Figure 3 shows the sounding altitude distribution of the 689 channels in long-wave band and the 961 channels in medium-wave band of FY-4A GIIRS. The statistical results of sounding altitude distribution are given in Figure 4. It can be seen that,

1) The sounding altitudes of long-wave band (700-1130cm^{-1}) channels are distributed near 16 altitudes, while the sounding altitudes of medium-wave band (700-1130cm^{-1}) channels are distributed near 15 altitudes. There is no peak response above 30km.
2) For 689 long-wave channels, there are 589 channels with sounding altitude of 1km or less accounting for 85.5%, 85 channels with sounding altitude of (1km,7km] accounting for 13.1% and only 4 channels with peak altitude of (7km, 9km]. The sounding altitudes of the remaining 6 channels are in 16km~29km.
3) For 961 medium-wave channels, there are 349 channels with sounding altitude of <=1km accounting for 36.3%, 420 channels with sounding altitude of (1km,6km] accounting for 43.7%, 187 channels with sounding altitude of (6km,11km] accounting for 19.6%. The sounding altitudes of the remaining 3 channels are in 13km~14km.

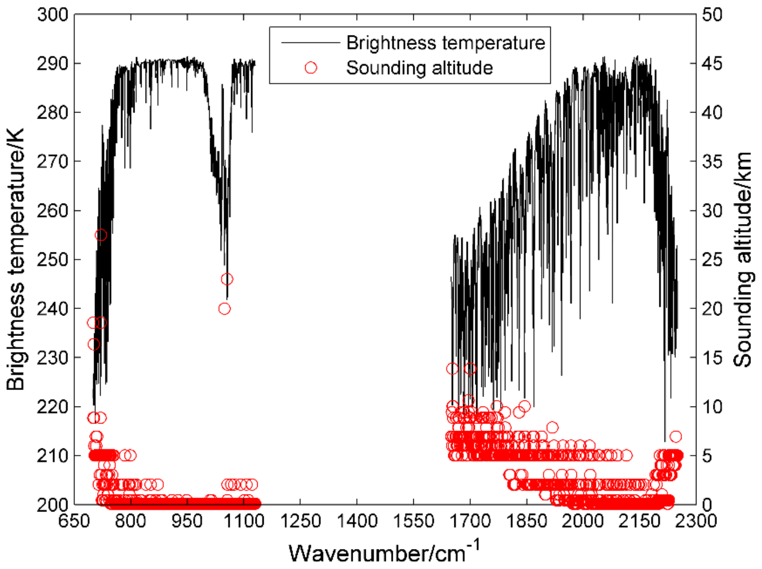

Figure 3 Temperature sounding altitude distribution of FY-4A GIIRS spectral channels

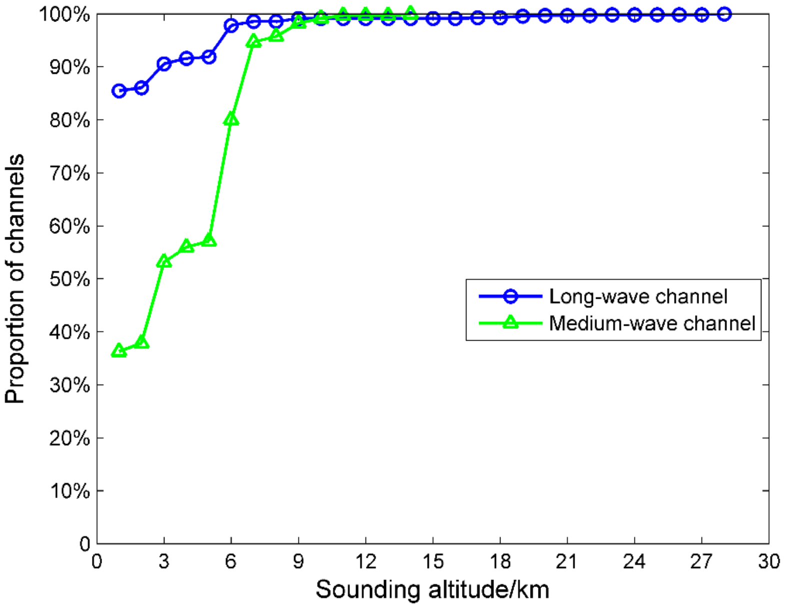

Figure 4 Cumulative temperature sounding altitude distribution of FY-4A GIIRS spectral channels

4.3 Sounding Vertical Coverage

The distribution of upper and lower altitudes where the response weighting function reaches half of peak response, h_{u5} and h_{d5}, with sounding altitude is shown in Figure 5. It can be seen that, 1) Most spectral channels of FY-4A GIIRS are sensitive to the temperature variation in troposphere. 2) There are 9 spectral channels sensitive to the temperature variation in lower stratosphere from 14km-29km. 3) Due to the maximum sounding altitude of FY-4A GIIRS for atmospheric temperature is below 30km, the temperature variation above 35km can't be sounded by FY-4A GIIRS.

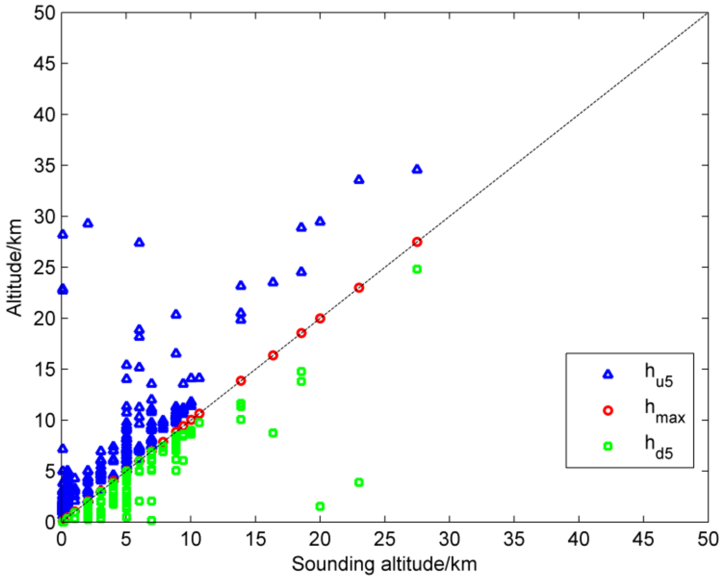

Figure 5 Temperature sounding vertical coverage of FY-4A GIIRS spectral channels

5. CONCLUSIONS

The VSC of sounding data and the HSC of imaging data both concern about where the remote sensing instruments look at, but not about whether the target can be seen clearly, which is answered by inversion data. The difference between VSC and horizontal space characteristic is mainly in that: 1) The latter is determined directly by the instantaneous FOV and total FOV of imager and the height of satellite, while the former is determined indirectly by the spectral channel distribution and wave band coverage of sounder. 2) The latter is independent of surface parameter, while the former is related to the interested atmospheric parameter is interested, and its expression and variation definitions.

The VSC of FY-4A GIIRS data is evaluated with the relative variation of atmospheric temperature as sounding target. The results show, 1) The sounding altitudes of spectral channels in the long-wave band are mostly lower than 9km, and 6 channels with sounding altitudes in 16km~29km。The sounding altitudes of spectral channels in the medium-wave band are all in the troposphere (<14km). 2) The sounding vertical coverage of spectral channels is from ground to 35km. There is no coverage above 35km.

For further research, we will evaluate the VSC of other atmospheric parameters such as water vapor and ozone etc., and compare their features.

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