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Application of FY-4 atmospheric vertical sounder in weather forecast

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Abstract: As the main instrument of FY-4 which was launched on Dec. 11th, 2016, Geostationary Interferometric Infrared Sounder (GIIRS) is the first hyperspectral infrared atmospheric vertical sounder working on geostationary orbit internationally. This instrument is mainly used for vertical atmospheric sounding and gains atmospheric temperature, humidity, and disturbances. The observed data of FY-4 GIIRS is assimilated into the GRAPES Global Forecast System in real time. It is the first time to realize the satellite hyperspectral detection and real-time data assimilation of wide range sensitive area sat a high frequency and will have a significant impact on the current meteorological forecasting capability, in particular, for the prediction of typhoon intensity and track, the accuracy can be greatly improved. In this paper, we present the measuring principle of the atmospheric vertical sounder and the on-orbit performance and operation of GIIRS, and the development of hyperspectral infrared atmospheric vertical sounder in the future is also prospected.

Key words: systematic application of information technology, atmospheric vertical sounder, Fourier hyperspectral detection, weather prediction
PACS: 93.85.-q, 07.07.-a, 07.07.Df, 42.68.-w, 42.68.Ca

风云四号大气垂直探测仪在气象预报中应用

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摘要:发射于2016年12月11日的风云四号卫星上搭载了国际上首台工作于静止轨道的高光谱红外大气垂直探测仪(GIIRS),该仪器主要用于探测地球大气的温度和湿度的垂直分布和变化,观测的数据实时同化到GRAPES全球预报系统,首次实现了大范围、高频次针对敏感区的卫星高光谱探测和实时资料同化应用,对目前的气象预报能力产生显著影响,尤其对台风强度和路径的预报更加精准.本文简要介绍了风四大气垂直探测仪的测量原理和在天气预报中的应用情况,并对未来的发展趋势给予了展望.

关　键　词:信息技术系统性应用;大气垂直探测仪;傅里叶高光谱探测;气象预报

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Introduction

By utilizing the infrared radiation coming up from the atmosphere and earth's surface, the atmospheric vertical sounder can continually measure the specific infrared spectrum of Earth's atmosphere with high precision from space. After the physical inversion, we can obtain the global atmospheric 3-dimensional distribution and the change of temperature and humidity[1].

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On December 11_{th}, 2016, the FY-4A was successfully launched at the Xichang satellite launch center, and reach at the position of 99.5 degree east of the 0 degree longitude line above the equator on December 17_{th}.

As one of the main instruments onboards the FY-4A satellite, GIIRS is the first interferometric infrared sounder working on geostationary orbit internationally. It can take continuous measurement of time varying atmospheric distribution of temperature and humidity by high frequency. It is the first time to realize the "Four-Dimensional observation" of atmosphere on geostationary orbit in the world[2]. It is the first use of GRAPES Global Four-Dimensional Variational Assimilation Forecasting System (4DVAR) for GIIRS data processing in China, which greatly improves the capability of domestic weather prediction[3].

1 Measuring principle of atmospheric vertical sounder

The vertical detection, measuring the distribution of temperature and humidity, is achieved by observing the infrared spectral spectrum which has specific absorption characteristics. Using the earth's surface temperature, atmospheric temperature distribution, gas composition vertical distribution and atmospheric transmittance parameters for mathematical modeling, we can easily calculate the amount of radiation from the earth and atmosphere to the satellite sounder, this is the forward modeling. Conversely, if the observed radiation of satellite sounder in different spectral bands is a known quantity, and we can also deduce the distribution of atmospheric temperature and absorbed gas, this is the inversion modeling. Through the use of the atmospheric vertical sounder, vertical distribution of atmospheric temperature and humidity can be retrieved by measuring the radiance of different spectral channels[4].

Suppose that the earth's surface temperature is T_s, $B(\nu, T_s)$ is the emission of infrared radiation form of Planck's law, where ν is wavenumber, $\tau(\nu, p_s)$ is Earth's atmospheric transmittance and p_s is the atmospheric pressure, which is related to the height. Then the earth's surface radiation reaching the atmosphere can be calculated by $B(\nu, T_s)\tau(\nu, p_s)$.

When the earth's surface radiation passes through the atmosphere, water vapor, carbon dioxide, ozone and other gases absorb this radiation and emit infrared radiation. According to the principle of atmospheric radiation transfer, the secondary radiation in the atmospheric layer at a certain height from the ground is $B(\nu, T)\tau(\nu, p)$, the infrared radiation received by the satellite infrared sounder includes the ground radiation and the secondary radiation from the atmospheric layer at different altitudes.

So the infrared radiation intensity at the satellite altitude is:

$$\begin{aligned} I(\nu) &= B(\nu,T_s)\tau(\nu,p_s) + \int B(\nu,T)\,d\tau(\nu,p) \\ &= B(\nu,T_s)\tau(\nu,p_s) + \int B(\nu,T)K(\ln p)\,d(\ln p) \end{aligned} , \quad (1)$$

Eq. 1 is the atmospheric transport equation. The weight function $K(\ln p) = \frac{\partial \tau(\nu, p)}{\partial(\ln p)}$ in the formula is related to height or atmospheric pressure. It characterizes the contribution of atmospheric radiation at different altitudes to the final detection result.

In the absorption spectrum bands of carbon dioxide, as the main absorption gas, carbon dioxide has a constant atmospheric mass mixing ratio. Thus, the weight function $K(\ln p)$ has a functional relationship with the variation of atmospheric pressure or height. When wavenumber ν is a constant, $K(\ln p)$ obtains its peak value at a certain height or pressure. At the weak absorption band, its effective radiation layer is in the lower atmosphere, and the peak height is in the lower atmosphere; at the strong absorption band, the peak height is in the upper atmosphere.

Eq. 1 shows that the radiation detected by the remote sensing instrument comes from the emission energy of the ground and the atmosphere, but the main part is the atmosphere whose height is equivalent to the peak value of $K(\ln p)$. The vertical distribution of temperature can be retrieved by simultaneous measurement of multiple bands in the CO_2 absorption band.

Suppose that we detect the radiation $I(\nu)$ of a spectral channel ν by satellite, and solve $B(\nu, T)$ by the atmospheric transport equation to obtain the vertical temperature distribution $T(H)$ or $T(p)$, this is the inversion deduction. In the same way, we can use infrared radiation spectrum and atmospheric transport equation to determine the vertical profile of other absorbing gases such as water vapor and ozone. Therefore, the vertical detection of atmospheric temperature and humidity are accomplished by measuring infrared radiation with atmospheric vertical sounder and inversion calculation[5].

Spaceborne interferometric atmospheric vertical sounder is a remote sensing instrument based on Fourier spectroscopy principle, which can be installed on both polar orbit meteorological satellite and geostationary meteorological satellite platforms. The principle of detection is shown in Fig. 1.

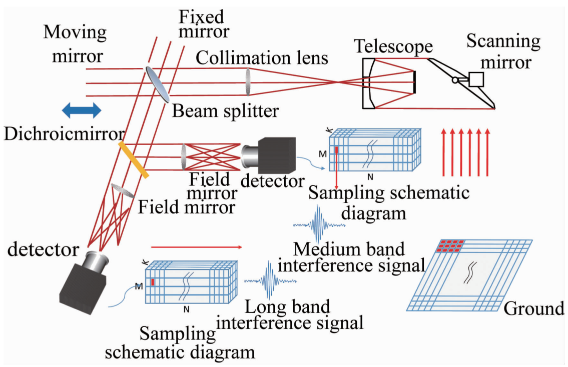

Fig. 1 Schematic diagram of atmospheric vertical sounder (GIIRS)
图 1 大气垂直探测仪(GIIRS)原理图

The infrared radiation from earth is reflected by scanning mirror to the telescope which compresses the diameter of beams, and then it reaches the collimator and changes into parallel rays. The parallel rays are divided into two paths through the beam splitter. One path is reflected to the reference arm (fixed mirror), and the other is transmitted to the measuring arm (moving mirror). Reflected back by a moving mirror and fixed mirror respectively, the light is recombined on the beam splitter and then reflected towards the splitter. After passing through the splitter, the beam split into long wavelength band and mid wavelength band, one of the spectral ranges 700 ~ 1 130 cm^{-1} (8.85 ~ 14.3 μm) and another ranges1 650 ~ 2 250 cm^{-1} (4.44 ~ 6.06 μm). After passing through the aft optics assembly, finally these infrared rays reach to detectors.

While the moving mirror is constantly moving back and forth, the total optical path difference between two beams changes with the motion. After light passes through the interferometer, interferometric modulation signals of different light path positions are generated, which are collected by a detector to form the interferogram.

The core component of the Geostationary Interferometric Infrared Sounder (GIIRS) is a Michelson interferometer. The infrared radiation with a wave length ν incident on the beam splitter and split into two equal amplitude α beams. These two beams hit fixed mirror and moving mirror respectively and are reflected back. After travelling in different optical paths δ_1 and δ_2, the two beams are combined at beam splitter and transmitted to the detector, where an interference pattern is produced. Assume that the phase difference between two beams of the infrared light is Φ.

$$\Phi = 2\pi\left(\delta_1 - \delta_2\right)\nu \quad . \quad (2)$$

The amplitude of interferogram received by the detector is A.

$$A = 2\alpha\cos\left(\pi\left(\delta_1 - \delta_2\right)\nu\right) \quad . \quad (3)$$

Owing to the movement of the moving mirror, the total optical path difference between two beams $\delta = \delta_1 - \delta_2$ changes constantly. So the infrared radiation intensity at the detector will be determined by

$$I(\delta) = A^2 = 4\alpha^2\cos^2(\pi\delta\nu) = \frac{1}{2}I(0)\left(1 + \cos(\pi\delta\nu)\right) \quad . \quad (4)$$

In Eq. 4, $I(0) = 4\alpha^2$ is the intensity of incoming infrared radiation. Assuming that the spectral distribution of incident infrared radiation is $B(\nu)$ and thus the incoming infrared radiation is

$$I(0) = \int_0^{\infty} B(\nu)\,d\nu \quad . \quad (5)$$

The intensity of the infrared radiation received by the detector is

$$I(\delta) = \frac{1}{2}\int_0^{\infty} B(\nu)\left(1 + \cos(2\pi\delta\nu)\right)d\nu \quad . \quad (6)$$

The variable quantity in Eq. 6 is called $I'(\delta)$, which is the real part of the Fourier transform of $B(\nu)$.

$$I'(\delta) = \frac{1}{2}\int_0^{\infty} B(\nu)\cos(2\pi\delta\nu)\,d\nu \quad . \quad (7)$$

According to the Eq. 8, spectrum distribution of signal can be obtained by Fourier transform.

$$B_t(\nu) = \int_{-\infty}^{+\infty} I(x)\,w(x)\,exp(-i2\pi\nu x)\,dx \quad , \quad (8)$$

where

$$w(x) = \begin{cases} 1, \text{when} |x| < L \\ 0, \text{when} |x| \geqslant L \end{cases} \quad . \quad (9)$$

However an infinite range of movement of the moving mirror is impossible, so this integration has to be cut off in a finite optical path difference range ($-L$, $+L$), and the result is tantamount to multiplying the time domain signal by a rectangular window function.

The spectral distribution obtained by Eq. 8 shows the spectral characteristics of radiation from a target. After the physical inversion, we can obtain the atmospheric distribution and the change of temperature and humidity, and thus the function of atmospheric vertical detection can be realized. The information transformation process of the atmospheric vertical sounder is shown in Fig. 2.

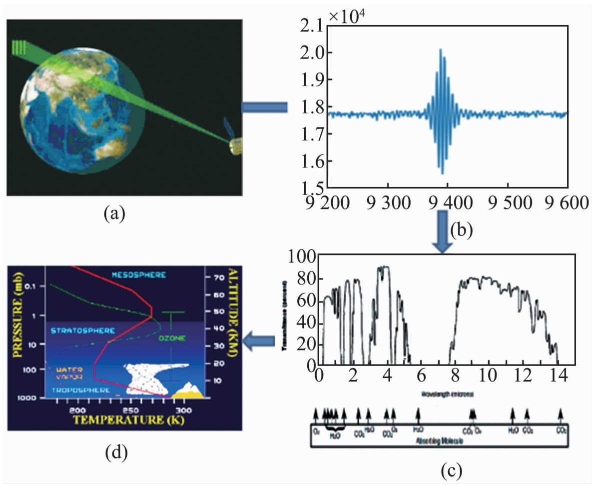

Fig. 2 Flow chart for information transformation of atmospheric vertical sounder, (a) Measurement model of atmospheric vertical sounder, (b) Interference signal, (c) Radiation spectrum, (d) Vertical detection

图 2 大气垂直探测仪信息变换流程图,(a)大气垂直探测仪测量模型,(b)干涉信号,(b)辐射光谱,(d)垂直探测

2 Experimental data on orbit

After the launch of the atmospheric vertical sounder, the following steps are taken to the preparation process: temperature control of the instrument, unlocking the moving mirror, decontamination heating about 45 days and then the cooler starting for cooling. The infrared detector and interferometer begin to work when temperature reach the designed value. Its on-orbit spatial resolution is 16km. Spectral resolution is 0.8 cm^{-1}. Instantaneous field of view is 448ur. Each detector has 32 × 4 sensor elements, and the frequency of observation for specific targets is more than 20 times per day. Despite amplitude of some spectrum-band is reduced slightly, which may be caused by some material gradually releasing little gas, the data acquired by the interferometric atmospheric vertical sounder on orbit are basically consistent with those acquired by the Infrared Atmospheric Sounding Interferometer (IASI).

Fig. 3 is the interferogram in both mid wavelength and long wavelength collected on orbit by GIIRS on FY-4.

The interferometric atmospheric vertical sounder has more than 1 600 detection channels. The contribution of atmosphere at different altitudes to the infrared radiation

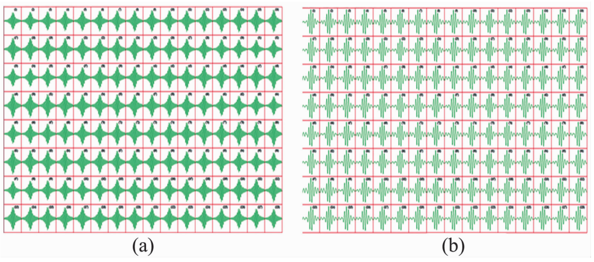

Fig. 3 Interferograms on orbit, (a) Medium wave band interferograms, (b) Long wave band interferograms
图 3 在轨测试干涉图,(a)中波干涉图,(b)长波干涉图

of different detection channels is different. Based on these differences, the three-dimensional structure of atmospheric temperature and humidity can be calculated, just like taking a CT scan for atmosphere. Fig. 4 shows which is the temperature profiles at different altitudes from 8:00 to 10:15 on February 23, 2017, which are calculated with the interferogram data of GIIRS on orbit.

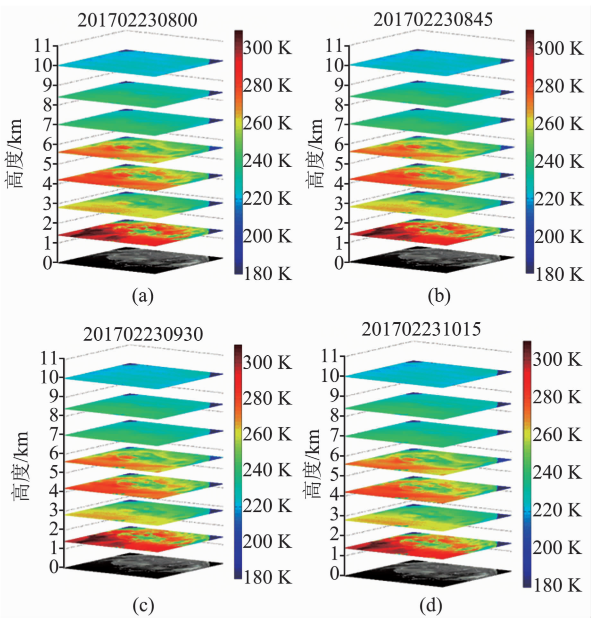

Fig. 4 Temperature profiles at different heights and times
图 4 不同时间高度温度反演分布图

The vertical distribution of atmospheric temperature and humidity can be calculated by data processing of interferogram data collected by atmospheric vertical sounder. Because the revisit period of the sounder is short, it can achieve continuous observation at a high frequency. Therefore, the vertical and horizontal temperature and humidity distributions can be observed constantly, and if taking time dimension into consideration, it is a 4-dimensional detection. The temperature and humidity vertical distribution data obtained by the atmospheric vertical sounder are dynamic over time. Therefore, not only the horizontal movement and flow of the atmosphere but also the vertical movement and flow of the atmosphere can be seen. This is the first time to realize the "four-dimensional observation" of the geostationary atmosphere internationally.

On July 10, 2018, when monitoring typhoon 'Maria', the 15-minute resolution data from the FY-4 GIIRS were assimilated into the GRAPES Global Forecast System, which improved the forecasting of Typhoon 'Maria'. This result shows the improvement of the ability to predict the intensity and the path of the typhoon, which helps to make typhoon warning system more reliable. Fig. 5 is the product based on data from FY-4A atmospheric vertical sounder.

The Geostationary Interferometric Infrared Sounder (GIIRS) on FY-4A entered into the numerical prediction model after the formation of the 'Ambi' on July 19, 2018.

Fig. 6 (a) is a typhoon forecast path without assimilating GIIRS data. Fig. 6 (b) is a typhoon forecast path based on GIIRS data.

Through data analysis, the forecast path of the typhoon 'Ambi' was adjusted northward to make the center position closer to the actual situation. GIIRS has successfully improved the track forecast of typhoon 'Ambi' and has proved that it can provide important support for typhoon track, heavy rainfall and gale forecast[6].

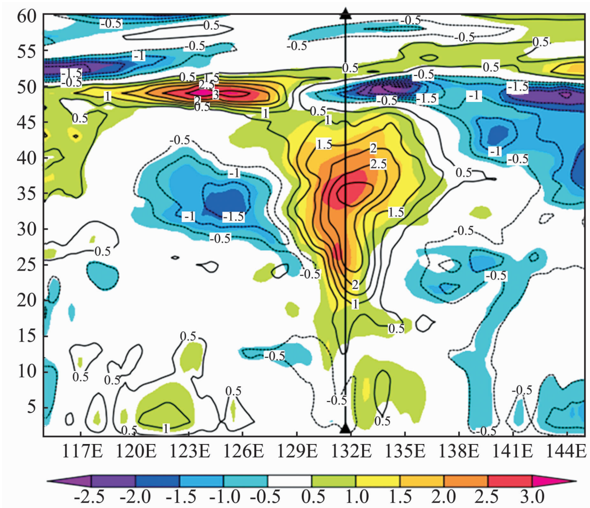

Fig. 5 product based on data from FY-4 Asatellite GIIRS
图 5 风云四号 A 星大气垂直探测仪产品

It is the first time that the space-borne hyperspectral detection and real-time data assimilation for sensitive areas have been realized in China under the real-time operational numerical prediction environment, which has successfully implemented the interactive "observation - prediction" scientific idea put forward by the international THORPEX (2002-2012) scientific plan.

3 Development of hyperspectral atmospheric vertical sounder

At present, the main development direction of space-borne atmospheric vertical sounder is "one width and three height", that is, wide spectral range, high temporal resolution, high spatial resolution, high spectral resolution.

Improving the temporal resolution of spectral detec-

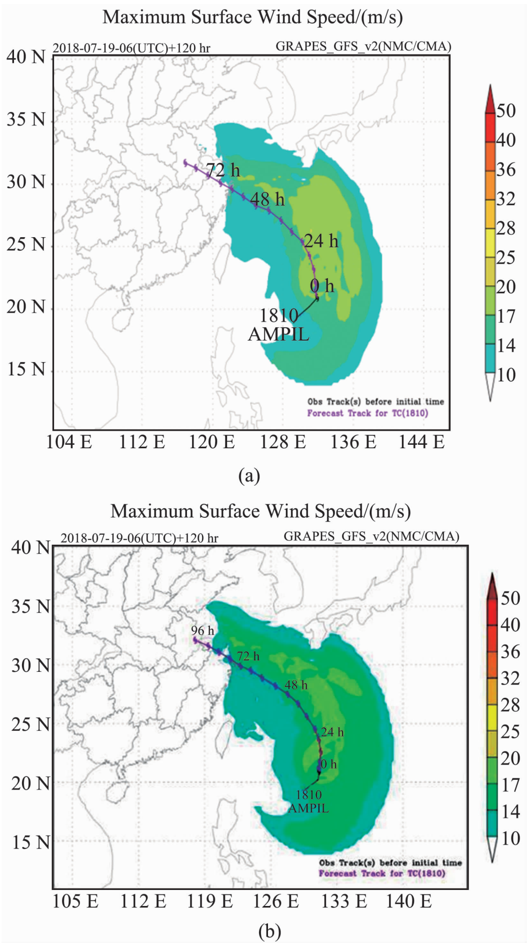

Fig. 6 forecast path of typhoon 'Ambi', (a) is a typhoon forecast path without assimilating GIIRS data, (b) is a typhoon forecast path with assimilating GIIRS data
图 6 台风"安比"的预报路径,(a)未同化 GIIRS 资料预报路径,(b)同化 GIIRS 资料预报路径

tion will directly serve short-term and imminent weather prediction enhance the timeliness of spectral detection and the ability of meteorological observation; broadening the detection spectrum, especially the long wave band (above 14 um), which will greatly enhance the ability of remote sensing information acquisition in China; by improving the spatial resolution and spectral resolution we can promote the ability of fine spectral resolution and meso-small scale meteorological observation.

4 Conclusion

It is the first time that the hyperspectral infrared atmospheric vertical sounder GIIRS is onboarded the FY-4 satellite. It can measure the atmospheric stratification information quantitatively and accurately on the vertical plane, which is equivalent to take a CT scan of the atmosphere. By detecting atmospheric temperature, humidity, atmospheric instability index etc, we can observe the occurrence of severe convective weather in advance[7].

For the first time in China, the real-time assimilation of the GIIRS data on FY-4A into the GRAPES Global Forecasting System has been realized, which has a significant impact on the current meteorological forecasting field, especially on the accuracy of typhoon intensity and track forecasts. The revolutionary progress of meteorological observation capacity will provide more significant meanings of early warning on disastrous weather and reducing the economic losses.

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(上接第 274 页)

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