FIRE-ARMS software package and its application to passive IR sensing of the atmosphere

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FIRE-ARMS (Fine InfraRed Explorer for Atmospheric Radiation MeasurementS) software package for simulation of atmospheric radiation spectra, analysis of weighting functions, and solution of the inverse problem of passive IR sensing of the atmosphere has been developed. Some results of IR spectra processing with FIRE-ARMS are presented. The spectra have been obtained with IMG (Interferometric Monitor for Greenhouse gases) Fourier spectrometer operating from onboard an ADEOS (Advanced Earth Observing Satellite) launched in August of 1996 by NASDA (Japan). Using FIRE-ARMS, we have identified some peaks and dips in the IMG spectra, which proved to correspond to $^{12}C^{18}O^{16}O$, $^{13}CO_2$, and HDO isotopic species. The presence of SiO_2 aerosol above the Sahara Desert has been revealed from these spectra. The possibility of estimating the cloud top height is also demonstrated.

Introduction

Since the beginning of space research various methods of Earth sensing from space in the infrared (IR) spectral region have been intensely developed.[1] A new generation of high-resolution IR Fourier spectrometers operated from spaceborne platforms open new possibilities for measurements of the Earth's surface – atmosphere system parameters. IMG/ADEOS device[2] is the first space-based Fourier spectrometer with a wide spectral range of operation from 600 to 3030 cm^{-1} and high resolution (~0.1 cm^{-1}). Such a resolution is quite sufficient for reliably resolve rotational structure of the molecular absorption bands of atmospheric gases. The IMG (Interferometric Monitor for Greenhouse gases) instrument has been developed at the Ministry of International Trade and Industry (MITI), Japan, for global mapping of greenhouse gases.

During eight-month of the IMG operation, a great number of IR spectra have been recorded. Besides, a number of methods have been developed to reconstruct atmospheric profiles of air temperature, humidity, and minor gaseous constituents from such spectroscopic data.[3–6] The methods are based on computational algorithms for solving direct problems (that is, the problem of IR spectrum simulation based on the known temperature profiles, and so on) and the inverse problem.

Solution of an inverse problem requires sufficiently large bulk of *a priori* information to be available. In this paper we present the FIRE-ARMS software package,[7] as well as some results of its application to analysis of IMG spectra.

Basic capabilities of the *FIRE-ARMS*

Basic capabilities of the FIRE-ARMS software package include:

– simultaneous use of several non-overlapping spectral ranges from the region of 0 to 5000 cm^{-1},

– use of the algorithms for solution of the direct and inverse problems of atmospheric sensing with spaceborne, airborne, and ground-based spectrometers (with the resolution higher than 1 cm^{-1}) for observation angles ranging from 0 to 70° (downward direction corresponds to observation of the Earth's surface),

– reconstruction of temperature profiles and profiles of atmospheric gases content both in turn and simultaneously when sensing in properly chosen spectral regions,

– use (optional) of the regularization approach to solution of the inverse problem,

– analysis of the weighting functions when selecting optimal spectral regions for profile reconstruction and assessing whether or not the spectral resolution of a device is sufficient for reliable reconstruction of one or another profile.

FIRE-ARMS computational aspects

The spectrum of thermal radiation of the atmosphere at observation along the nadir direction can be derived from solution of the transfer equation[2]:

$$W(\nu) = \varepsilon(\nu)\, B(\nu, T_0) \exp\left(-\int_0^H K_{\rm atm}\, {\rm d}h\right) +$$

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$$+\int_0^H K_{\rm atm}\, B(\nu, T)\, \exp\left(-\int_h^H K_{\rm atm}\, {\rm d}h'\right){\rm d}h. \qquad (1)$$

Here W is the spectral density of radiance, in $W/(m^2 \cdot cm^{-1} \cdot sr)$; h is the height; $K_{\rm atm}$ is the absorption coefficient of atmospheric gases, it is calculated by the line-by-line method using the HITRAN-96 (Ref. 8) or GEISA (Ref. 9) data banks; $B(\nu, T)$ is the black body function; $\varepsilon(\nu)$ is the emissivity of the Earth's surface; T_0 is the surface temperature; H is the atmospheric top height. For calculation of integrals in Eq. (1) FIRE-ARMS employs a numerical integration technique proposed in Ref. 10 and the adaptive selection of a height step. High-resolution spectral calculations are followed by integral convolution of the calculated spectrum with the instrumental function of a spectral device specified by a user. In the general case, the algorithm for solution of the inverse problem, utilized by FIRE-ARMS, minimizes the goal function[11]:

$$F = \frac{1}{2}(F_1 + F_2), \qquad (2)$$

where

$$F_1 = \sum_{i=1}^{M}\left[\frac{W_i^{\rm obs}}{W_i^{\rm calc}} - \frac{W_i^{\rm calc}}{W_i^{\rm obs}}\right]^2,$$

$$W_i^{\rm calc} \equiv W^{\rm calc}(T, P, n_\alpha, \nu_i)|_{h=H}; \qquad (3)$$

$$F_2 = \mu^T \sum_{j=1}^{N}\left[\frac{t_j}{t_j^{\rm ref}} - \frac{t_j^{\rm ref}}{t_j}\right]^2 + \mu^P \sum_{j=1}^{N}\left[\frac{p_j}{p_j^{\rm ref}} - \frac{p_j^{\rm ref}}{p_j}\right]^2 +$$

$$+ \sum_{\alpha=1}^{N_{\rm gas}} \mu^\alpha \sum_{j=1}^{N}\left[\frac{n_{\alpha j}}{n_{\alpha j}^{\rm ref}} - \frac{n_{\alpha j}^{\rm ref}}{n_{\alpha j}}\right]^2. \qquad (4)$$

The fitting parameters here are t_j, p_j, and $n_{\alpha j}$, i.e., the values of temperature, pressure, and gas concentration at the jth node of the altitude grid; F_1 is the standard functional of the least-square method, which should be reduced to minimum to find the optimal set of fitting parameters; $W_i^{\rm obs}$ and $W_i^{\rm calc}$ are the observed and calculated spectra, respectively; M is the number of spectral points; N is the number of points on the vertical profile; $N_{\rm gas}$ is the number of atmospheric gases considered. The solution stabilizer F_2 depends on both the reference profiles $t_j^{\rm ref}, p_j^{\rm ref}, n_j^{\rm ref}$, and dimensionless regularization parameters μ^T, μ^P, μ^1, ..., $\mu^{N_{\rm gas}}$. Equation (1) is minimized by the Fletcher–Rivs method.[12] An important feature of FIRE-ARMS is the possibility to select several spectral ranges for reconstruction of atmospheric profiles based on the analysis of the weighting functions of the direct model.[13]

Some results of applying the *FIRE-ARMS*

The IMG/ADEOS IR spectra recorded in the first half of 1997 (Ref. 14) have been used for reconstructing some atmospheric parameters. Figure 1 shows an example of the temperature profile reconstructed from the IR spectrum recorded in the 680–765 cm^{-1} region, which corresponds to the 15-μm wing of the CO_2 absorption band.

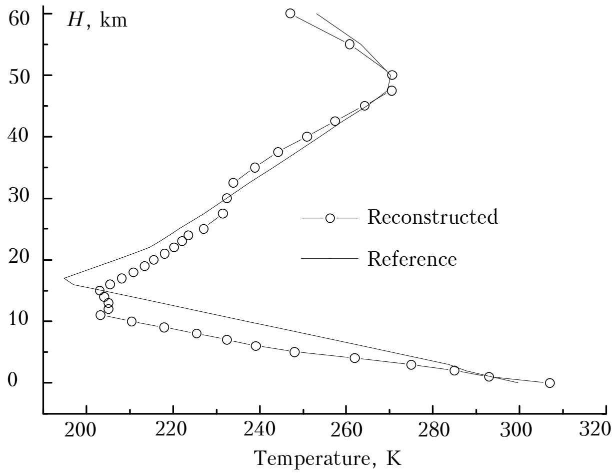

Fig. 1. An example of the reconstructed temperature profile under clear-sky conditions.

It should be noted that reconstruction of the temperature profile is among the simplest tasks. With the optimally selected spectral region, three to five iterations are usually sufficient to reconstruct the atmospheric temperature profile. Under the overcast conditions, reconstruction of temperature is not correct, but it allows estimation of the cloud top height.[15] This case is illustrated by the data presented in Fig. 2. In contrast to devices observing the Earth's surface in the visible and near infrared, the IMG device is capable of acquiring certain information about cloudiness even during nighttime.

FIRE-ARMS allows simulation of spectra of any set of isotopic modifications of a molecule specified by the user (of course, if the species is in the data bank). This, in turn, allows identification of spectral features (peaks) corresponding to one or another molecule. Figure 3 exemplifies identification of the peaks and dips corresponding to $^{12}C^{16}O^{18}O$, $^{13}CO_2$, and HDO molecules.

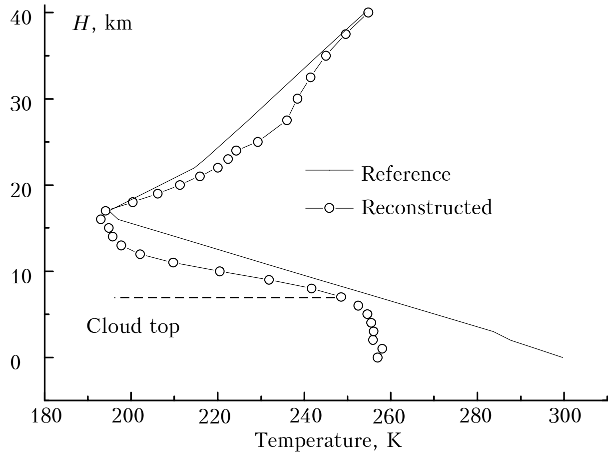

Fig. 2. Reconstruction of the temperature profile under overcast conditions. The point, below which the reconstructed profile remains unchanged with height, correspond to the cloud top height.

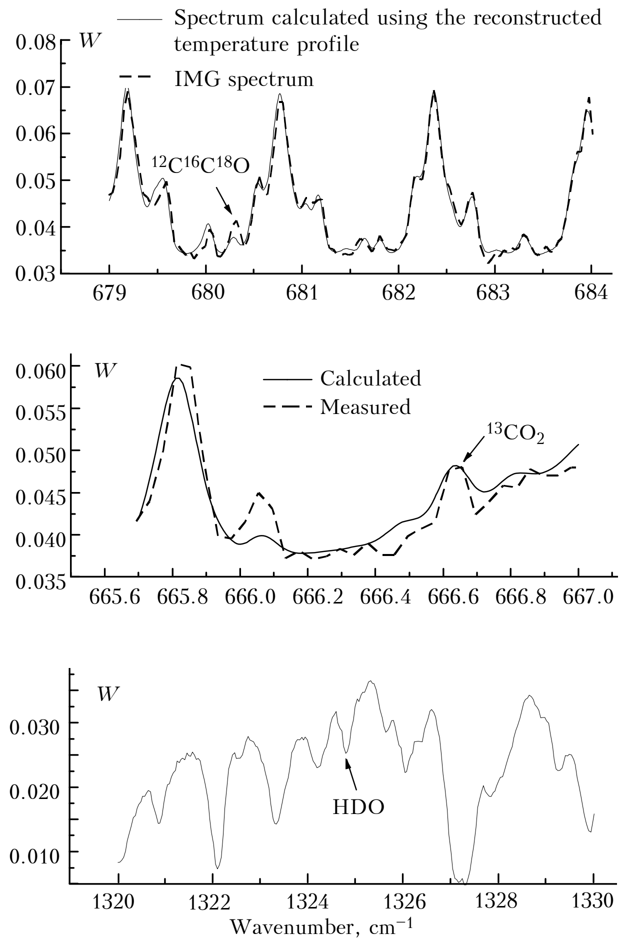

Fig. 3. Identification of the peaks and dips in the IMG spectra, which correspond to different isotopic species of atmospheric gas molecules.

In some IMG/ADEOS spectra recorded over the Sahara Desert, a wide peak with the maximum near 1157 cm^{-1} has been detected (Fig. 4). We failed to assign this peak to molecules included in the HITRAN–96 data bank. At the same time, atmospheric spectra in this spectral region may have some peculiarities due to aerosol components.[16] The presence of one or another atmospheric component can be judged from these peculiarities. According to Ref. 17, such a silicate (SiO_2) species as amorphous silicon dioxide and α-quartz have absorption peaks near 1157 cm^{-1}. These substances are abundant in the desert region. Appearance of such a peak in the spectrum is indicative of a dust storm. Figure 4*a* shows the entire spectrum, while Fig. 4*b* presents its fragment in the vicinity of 1157 cm^{-1} frequency. Solid line in this figure shows the observed spectrum, while the dashed line is the spectrum calculated using the reconstructed temperature profile. Spectral line structure superimposed on the broad peak is due to N_2O molecule.

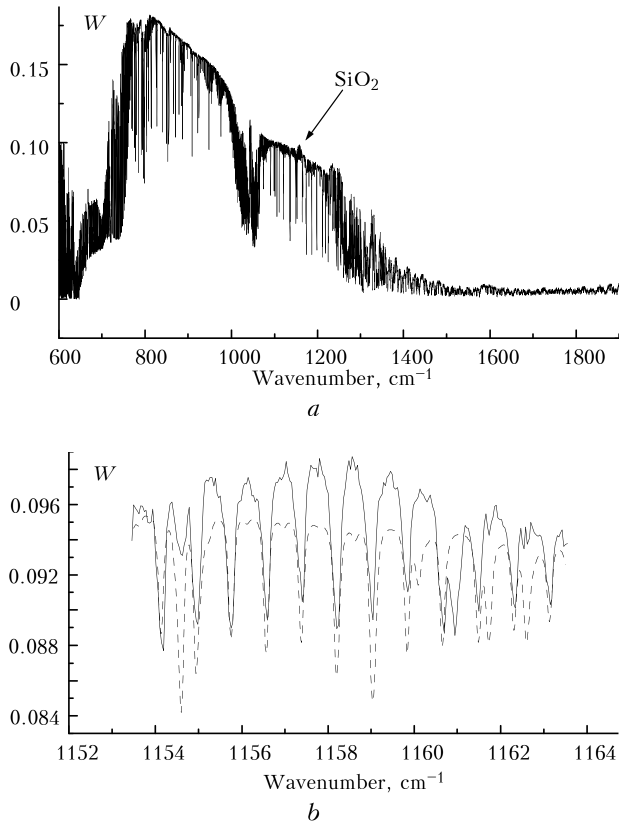

Fig. 4. IMG/ADEOS spectrum recorded on June 19, 1997, at 10:37 UTC over the point 21.29°N, 4.33°E.

Conclusions

In this paper some examples of the atmospheric temperature profiles reconstructed from the IR spectra recorded from space with the resolution of ~0.1 cm^{-1} are used to demonstrate the possibility of detecting the clouds and estimating the cloud top height. The cloud top height can be judged from the characteristic break in the temperature profile (see Fig. 2). The break means that IMG sensor recognizes the overcast clouds below this point as the black body with the surface temperature corresponding to the beginning of the profile break. It should be noted that this method of cloud top height estimation can be applied to both daytime and nighttime observations. The possibility of identifying minor atmospheric constituents, such as isotopic species of carbon dioxide and water vapor, in IMG/ADEOS spectra is demonstrated as well. One more example of the method capabilities is the identification of SiO_2 peaks in the spectrum recorded over the Sahara Desert. The appearance of these peaks in the spectra is likely to be associated with the dust storms.

The FIRE-ARMS software package has been developed for processing data from spaceborne, airborne, and ground-based Fourier spectrometers with the spectral resolution higher than 1 cm^{-1}. Processing of IMG/ADEOS spectra is the first application of the FIRE-ARMS package. We look forward to further successful application of this software to solution of different problems in remote IR sensing of the atmosphere. We also believe that it can be considered as a useful part of future orbital complexes.

Demo version of the FIRE-ARMS software can be downloaded from www.chat.ru/~atmsci.

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