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THE USE OF SPACE INFORMATION ABOUT THE EARTH

Analysis of Capabilities for Satellite Monitoring of Atmospheric Gaseous Composition Using IRFS-2 Instrument

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Abstract—Capabilities of the total column monitoring of different minor gaseous compounds of the atmosphere with the satellite IRFS-2 Fourier interferometer have been studied. The possibilities of determining the CO_2, O_3, CH_4, HNO_3, N_2O, CH_3OH, HCFC-22, CFC-11, CFC-12, PAN, and CCl_4 total columns have been investigated on the basis of line-by-line calculations of the forward problem operator and calculation of error matrices by the optimal estimation method. It has been shown that the IRFS-2 device could be used to measure the total columns of CO_2, O_3, N_2O, CH_4, and HNO_3. In the information-gathering mode, it is also possible to retrieve the CH_3OH, HCFC-22, CFC-11, CFC-12, PAN, and CCl_4 total columns due to the suppression of random measurement errors.

Keywords: trace atmospheric gases, remote sensing of the atmosphere, Fourier interferometry, atmospheric composition

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INTRODUCTION

In the last few decades, considerable attention has been paid to the creation and usage of specialized equipment for the space monitoring of the atmospheric gas composition (Timofeev, 1989). Such attention is due to the increasing anthropogenic impact on the gas composition of the troposphere and stratosphere and, as a result, on climate, weather, and environmental conditions (WMO, 2007). A large amount of information on the gas composition of the atmosphere was obtained in recent years with the method of thermal radiation and TES, AIRS, IASI, etc., implementing the method for nadir geometry (Beer et al., 2001; Worden et al., 2004; Crevoisier et al., 2003; Clerbaux et al., 2003, 2009). In Russia, a modern satellite Fourier spectrometer IRFS-2 (Zavelevich et al., 2009) was designed primarily for the temperature-humidity sounding of the atmosphere, as well as for obtaining information on the temperature of the underlying surface, ozone content, and a number of greenhouse gases. The first examinations of information capabilities of the device and its accuracy characteristics are presented in (Polyakov et al, 2009, 2010). The experience of using the IASI-satellite Fourier spectrometer has shown that measurements of the spectra of outgoing thermal radiation with a relatively high spectral resolution and low level of random noise can detect and determine the content of many important atmospheric gases (Clerbaux et al., 2003, 2009). Knowing the corresponding characteristics of the IRFS-2 device allows one to evaluate its capabilities in satellite experiments (Zavelevich et al., 2009).

In this paper we continue investigating the capabilities of this instrument for monitoring the contents of atmospheric gases that have emission bands in the spectral region of the instrument.

METHOD OF NUMERICAL ANALYSIS

At the first stage of the research, in order to limit the list of analyzed atmospheric gases (there are dozens of them), comparisons of calculated variations in the outgoing heat radiation due to variations in the gas content were made with a random noise of the instrument measurements. Calculations of the intensity of outgoing radiation and its variational derivatives with respect to the contents of various gases were carried out using the well-known LBLRTM computer code (Line-by-Line Radiative Transfer Model (Clough et al., 2005)). The initial ensembles of atmospheric states (vertical profiles of temperature, humidity, and gas content) were generated from the WACCM4 numerical model (The Whole Atmosphere Community Climate Model) (Marsh et al., 2013) (http://www.cesm.ucar.edu/working_groups/WACCM/)) and contained 492 profiles for the midlatitudes of the Northern Hemisphere. It was assumed that satellite measurements are conducted in a cloudless atmosphere.

Table 1. Informativeness of measurements of atmospheric gases

Gas	Relative variability of the total content, %		Numbers of degrees of freedom, *ds*
	apriori	aposteriori (error)	
O_3	15.0	0.6	3.2
CO_2	5.8	0.5	1.1
N_2O	3.0	0.9	1.0
CH_4	3.9	1.1	1.0
HNO_3	19.4	7.7	1.0
CH_3OH	73.8	53.6	0.5
HCFC-22	48.3	17.9	0.9
CFC-11	13.2	4.5	0.9
CFC-12	15.5	4.2	0.9
PAN	27.8	19.1	0.7
CCl_4	13.3	9.6	0.5

Calculations of the outgoing thermal radiation were carried with and without taking into account contents of the following trace atmospheric gases (TAG): O_3, CO_2, CH_4, N_2O, C_2H_4, CH_3OH, HCOOH, HNO_3, NO, NO_2, CFC-11, CFC-12, HCFC-22, PAN, and CCl_4. A comparison of these variations with random measurement errors of the IRFS-2 equipment made it possible to exclude from consideration a number of gases whose contribution to the formation of the outgoing radiation is small in comparison with these errors.

In the second stage of the study, the errors in determining the vertical profiles of the selected TAG for the linearized form of the thermal-radiation transfer equation were calculated (Turchin et al., 1971; Rodgers, 2000). When calculating the residual covariance matrix (error matrix), the variability of the water-vapor profile and temperature (their determination error) was taken into account. It was assumed that all three vectors (the investigated gas, temperature, and water vapor) are restored simultaneously. Calculations were carried out for the entire spectral interval 600–2000 cm^{-1} (2701 spectral channel of measurements of the IRFS-2 device). The residual covariance matrix (error matrix) was calculated by the formula (Turchin et al., 1971; Rodgers, 2000)

$$\tilde{D} = (A'\Sigma^{-1}A + D^{-1})^{-1},$$

where $D = \begin{bmatrix} D_q & 0 & 0 \\ 0 & D_{H_2O} & 0 \\ 0 & 0 & D_T \end{bmatrix}$ is a covariance matrix of the parameters to be retrieved, D_q is a covariance matrix of the gas under investigation, D_T and D_{H_2O} are covariance matrices of temperature and water-vapor profile (correlations between different retrieved parameters were not taken into account), Σ is a covariance matrix of measurement errors (the corresponding a priori covariance matrices were calculated from the WACCM4 numerical model (Marsh et al., 2013)), and $A = [A_q \;\; A_{H_2O} \;\; A_T]$ is the forward problem operator. The error in the total content (TC) retrieval of the gas under study was calculated from

$$\delta = w^T \tilde{D}_q w,$$

where w is a vector of weighting factors (the quadrature for calculation of the total gas content) and $\tilde{D}_q$ is part of the residual covariance matrix corresponding to the gas component under study.

Apart from the errors in determining TC of gases, it is of interest to find the number of degrees of freedom d_s of a useful signal relative to a given gas, which are contained in spectral measurements (Rodgers, 2000). This value can be interpreted as the number of independent parameters that can be distinguished in the gas profile based on the measurements in question, or, in other words, as the number of atmospheric layers in which the average gas content can be determined. In particular, if this value is close to unity, only the TC can be obtained; if it is close to two, then (in a somewhat simplified sense) the contents in two layers can be obtained, for example, in the stratosphere and troposphere, etc.

To calculate the number of degrees of freedom, we used the formula (Rodgers, 2000)

$$d_s = tr(H),$$

where $H = RA$ is the averaging core; $R = (A'\Sigma^{-1}A + D^{-1})^{-1}A'\Sigma^{-1}$ is the solution operator of the optimal estimation method (in our case).

RESULTS OF CALCULATIONS

Table 1 shows the name of the gas component, the a priori relative variability of the total gas content (expressed as a percentage), the relative error in determining the total content using the IRFS-2 device, and the number of degrees of freedom of the signal.

As follows from the data, there are five gas components (O_3, CO_2, N_2O, CH_4, and HNO_3), the number of degrees of freedom of the signal for which is equal to or exceeds unity. Thus, for these five gases, IRFS-2 makes it possible to determine the general contents. For ozone, it is possible to determine three parameters of its vertical distribution, for example, its content in three layers. For the other six gases, individual measurements of the outgoing thermal-radiation spectra do not allow determining their TC (the number of degrees of freedom is less than one). However, this is possible when multiple measurements over certain areas are used due to the suppression of random measurement errors.

MAIN RESULTS AND CONCLUSIONS

Numerical studies of capabilities of the IRFS-2 satellite for determining the content of a number of TAG have been carried out. Calculations of outgoing radiation, its variations, variational derivatives with respect to the content of TAG, errors in retrieval of the total contents, and the number of independent parameters determined from measurements of the outgoing radiation spectra have shown that

(a) IRFS-2 can determine the O_3, CO_2, N_2O, CH_4, and HNO_3 total contents. Their relative errors range from 0.5 to 7.7%;

(b) it is possible to determine three parameters for the vertical distribution of ozone content;

(c) when averaging the measured spectrum of outgoing radiation for specific areas, there are potential possibilities for determining the total contents of CH_3OH, HCFC-22, CFC-11, CFC-12, PAN, and CCL_4.

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