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SIMULATION OF REFLECTED SOLAR RADIATION FOR ATMOSPHERE GAS COMPOSITION EVALUATION FOR OPTICAL REMOTE SENSING FROM SPACE

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ABSTRACT

At present, in optical remote sensing of atmosphere from space, a new problem class appears: to determine little gas components (carbon dioxide, methane, etc.), which cause greenhouse effect. Concentration of these gases in atmosphere is less than one percent, which rigidly limits accuracy of satellite measurements and of simulating spatial concentration of the radiation (signal) flow reflected by Earth. In the article, a description of simulating signals received by satellite spectrometer in near-infrared spectrum region is given. The signals are solar radiation passed through an atmosphere layer and reflected from Earth surface. It is calculated based on parametrical radiation atmosphere scattering and absorption model, which takes into consideration both multidimensional atmosphere parameter structure and Earth surface relief. Accounting such information allows you to go from measurement of spatial radiation flux to calculations of gas concentration for an arbitrary geographical Earth surface point and for any time point. As an example, calculations for Fourier spectrometer for spectrum measurement near IR region with an average spectral resolution are presented. The spectrometer was installed on the *GOSAT* satellite of the Space Agency of Japan. A comparison of computed and of really measured values of the signal received by the satellite shows that deviation for the Sun zenith angle equal to 30^{o} does not exceed 3 %.

Keywords: atmosphere, absorption, scattering, numerical model

1. INTRODUCTION

Satellite environment monitoring is a comprehensive and regular environment state observation system (Earth atmosphere and surface). Processing and analysis of the measurement results obtained during various time periods allows estimate trends of changing the state of Earth atmosphere or surface parameters under influence of natural and anthropogenic factors. A success of these data application in various science and practice fields depends on many components: on mathematical simulation of instrument measurement base, on radiation expansion in atmosphere (account of scattering and absorption effects), on reflections from Earth surface, on methods of the reverse problem solution, etc.

There are various ways of optical classification methods of atmosphere gas composition control from space. Depending on the used radiation source, optical methods are divided into passive (extra-atmospheric radiation sources, own and scattered atmosphere radiation) and active (laser and thermal sources). By physical effects of radiation interaction with environment, passive methods can be divided into three groups: 1) transmission (transparency method); 2) emission (own radiation method); 3) scattered radiation method. By experiment geometry, nadir and limb methods can be mentioned (Fig. 1). Active methods are divided into local and remote. Local (*in situ*) methods are measurements of some gas concentration in a given local point in relation to the obtained air specimens.

Difficulties of gas composition analysis using optical methods are as follows:

a) There are constantly two absorbing components in atmosphere (H_2O and CO_2), which absorption spectra cover practically all IR range, where main absorption bands of other atmospheric gases, both basic and anthropogenic are located;

b) Earth atmosphere is non-uniform in time and space by thermal, gas and aerosol composition;

c) Along with height structure of gas composition and atmosphere temperature, turbulent environment fluctuations are constantly present;

d) There is a mixture of aerosol particles in atmosphere, which is unstable and complex by the composition. These particles absorb and scatter radiation;

e) Most atmospheric gases have very little concentrations.

Nevertheless, optical methods are broadly applied in practice of atmosphere gas composition monitoring [1–5].

Among all mentioned methods, most widespread are passive methods of measuring atmosphere parameters. They have a number of advantages: a high sensitivity, a high spectral resolution and high measurement accuracy, absence of exposure on the examined objects, a high level of instrument base development, etc. The scheme B (Fig. 1) should be noticed, in which detector of the satellite device “looks” through atmosphere directly at the Sun, unlike scheme *C* (Fig. 1). Among all measurement geometries, an advantage of nadir version consists in a possibility to obtain continuous spatial fields of various atmosphere parameters with a good periodicity (from several hours to several days).

Optical measuring devices located onboard of spacecrafts are divided into multichannel devices (from several units to several tens channels) and hyper-spectral devices. Spectrometers and radio metres of various classes are referred to the first device type, and Fourier spectrometers most often belong to the second type. The Fourier spectrometers namely allow obtaining thousands of points with a high precision in spectral intervals from visible to infrared spectrum region. The obtained information reflects all peculiarities of radiation expansion in atmosphere.

Development of the instrument base and processing of the measurement results are connected with application of models including characteristics of the device, of atmosphere and of Earth surface. The models, as a rule, take into consideration influence of various factors not completely (dependence on latitude and longitude, on measurement time, etc.) and influence of physical processes (device noise, atmosphere fluctuations, height and space-time parameter value variation, etc.). From the other hand, account of many factors highly complicates the calculation models and requires a development of the special algorithms and involving of the correspondent computing facilities.

In this regard, there is a need to develop models, which with a sufficient accuracy allow imitating the signals measured by satellite optical devices, as well as applying this information to exercise methods of solving reverse problems of atmosphere optics [6, 7].

Abilities of modern hyper spectral satellite devices make it possible to solve fundamental problems of atmosphere physics, of climate, ecology, etc. During recent years, several devices of a high resolution were launched: *IASI* (MetOp satellite, the European Union) [8], SCIAMACHY (ENVISAT satellite, the European Union) [9], TANSO-FTS (GOSAT satellite, Japan) [10], which purpose is a recovery of information on atmosphere gas and aerosol composition.

Study of climate-forming parameters is an important fundamental problem. Gas and aerosol composition play an important role in forming various atmospheric processes. Study of aerosol influence on recovery of atmosphere gas composition information in global scale was a limiting factor, and there were no regular measurements covering a big territory.

Increase in concentration of some greenhouse gases (CO_2, H_2O, CH_4, N_2O, etc.) leads to changes of radiation properties of atmosphere and as a result, to Earth climate changes. Modern evaluations of various gases to atmosphere heating process contribution show that relative contribution of CO_2, CH_4, and N_2O is 60, 20 and 6 percents respectively. One of the climate change criteria is global warming, which is a process of gradual increase in average annual temperature of Earth atmosphere and of the World Ocean. A position of the Intergovernmental Panel on Climate Change (IPCC) of the UN is that since the beginning of industrial revolution (the second half of the 18th century) average on Earth surface temperature increased by 0.8 °C [11] and that a big part of the warming observed during the last fifty years is caused by the human activity [12, 13]. Primarily, it was gas emission leading to the greenhouse effect: carbon dioxide (CO_2) and methane (CH_4). As a whole, reasons of climate changes remain unknown and require a study of radiation flows (ascending and descending), of gas and aerosol composition in atmosphere. In doing so, measurement points regularly and uniformly located over Earth surface are necessary. Such measurements are only possible using space methods.

And the former methods of interpreting satellite photometric information based to various extents on the curve-fitting method are hardly applicable since curve coincidence in thousands points cannot be achieved. From the other hand, measurement accuracy in each channel equal to not less, than 1 %, makes new strict requirements to radiation transfer model in atmosphere: the calculation accuracy should be also not less than 1 %. This leads to the fact that well developed methods of solving the radiation transfer problem for a plain layer of turbid environment become unacceptable. Under such conditions, a strict account of light scattering features in a three-dimensional environment is necessary: a vertical non-uniformity of atmosphere, a ragged cloud cover, an underlying surface profile.

Formerly, we made attempts to solve the problem of simulating solar radiation reflected from the surface [14]. In the proposed article, a development of some program is considered, which allows for any season and for any point of Earth surface computing the reflected solar radiation taking into account three-dimensional atmosphere structure.

2. PROBLEM DEFINITION

Radiation coming to a Fourier spectrometer receiver "looking" at nadir on Earth surface consists of two flows: solar radiation reflected by Earth surface, and solar radiation scattered over all atmosphere thickness. The ratio of these flow values depends on the solar declination angle: the more declination is, the more is contribution of the flow scattered in atmosphere. Having passed the way in atmosphere twice, total radiation flow received by the Fourier spectrometer contains information on gas composition and on atmosphere aerosol filling. A purpose of this work is calculation of solar radiation flows received by a satellite Fourier spectrometer in the spectrum near IR area [15], and comparison of the obtained values with the measurement results obtained by the GOSAT satellite[1]. When calculating the signal received by the satellite, use of new physical and mathematical models and methods is supposed. They not only increase the accuracy but also considerably accelerate the calculations.

Interaction of solar radiation with atmosphere leads to scattering and absorption. This interaction is quantitatively determined by properties of atmosphere gas composition and by aerosol types. The radiation, which was reflected from Earth surface or from clouds, depends on the surface relief, on the reflecting properties and on the temperature.

Some part of solar radiation, which has reached the satellite device, depends on the atmosphere absorbing properties and thus can be used to determine atmosphere gas composition.

3. MODEL DESCRIPTION

Solar radiation $I_0(\lambda)$ penetrates to Earth atmosphere under different angles depending on the season being subject to absorption and scattering by gases and by aerosol particles of atmosphere, as well as to reflection from clouds. Further reflection from Earth surface takes place, which is characterised by types, every of which has its own spectral distribution of reflection factor, and by the relief. The reflected radiation passing through atmosphere and incident to the satellite device input, which is consist of many components (Fig. 1). The scattering can be single-stage and multiple, and reflections can be not only from observed Earth surface but also from clouds, from a surface beyond visual field of the device, etc. Different components make different contributions to the signals received by the device [16].

In the signal $I(\lambda)$ received by the device installed at the *GOSAT* (further the GOSAT device), one can distinguish two main components: solar radi-

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[1] *GOSAT* (*Ibuki*) is a satellite of remote Earth sensing, which aim is monitoring of greenhouse gases (*GOSAT* and *Ibuki* are the same but the first name is connected with an English phrase "*Greenhouse gases Observing SATellite*", and *Ibuki* in Japanese is breath). The *GOSAT* is equipped with infrared detectors, based on which data determination of general concentration of carbon dioxide and of methane in atmosphere is possible. These are detector of greenhouse gas observation (TANSO-FTS) and detector of clouds and aerosols (TANSO-CAI). In the spectrum registered by *TANSO-FTS*, 1.6 µ and 2.0 µ bands in the spectrum near IR interval are used for observation of general concentration of CO_2 and CH_4. Total number of the spectral observation channels reaches 18,500.

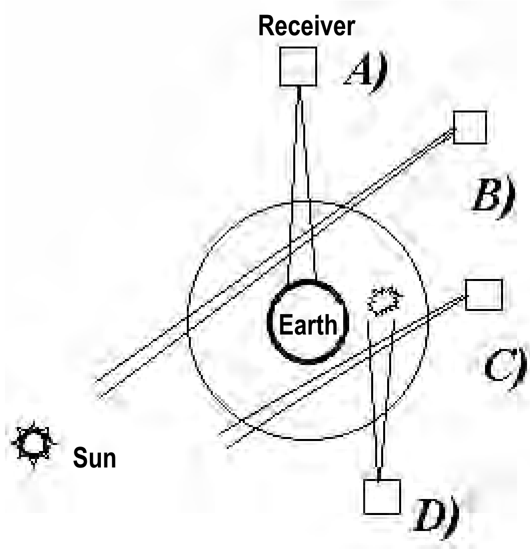


Fig. 1. Various versions of sounding atmosphere: *A)* nadir (method of thermal radiation – MTR); *C)* tangent (transparency method –TM); *C)* limb (MTI or method of reverse scattering – MRS) and *D)* emission

ation flow $I_1(\lambda)$ reflected from the surface and radiation single-stage flow $I_2(\lambda)$, which is scattered in atmosphere (Fig. 2), whereas other components make a little contribution (less than one percent) within $10^{o} < \theta_0 < 60^{o}$ interval of the Sun zenith angle change.

Taking into account geometrical factors, surface types and seasons, the signal received by the satellite is a multidimensional function of such parameters as spatial co-ordinates (*x*, *y)*, wavelength λ, the Sun zenith angle θ_o, season *t* and altitude above sea-level *h*. With due regard for multidimensional formation of the signal registered by the satellite, it can be presented as [17],

$$I(\lambda) = I_1(\lambda) + I_2(\lambda), \tag{1}$$

where:

$$I_1(\lambda) = I_0(\lambda)\cos(\theta_0(t))r(\lambda,x,y) \\ R_{surf}(x,y)T(\lambda,x,y,\theta_0,H,t), \tag{2}$$

(See eqn 3 below)

$$\cos(\gamma) = \\ = -\mu_{sun}\mu_{sat} - \sqrt{(1-\mu_{sun})(1-\mu_{sat})}\cos(\theta_0), \tag{4}$$

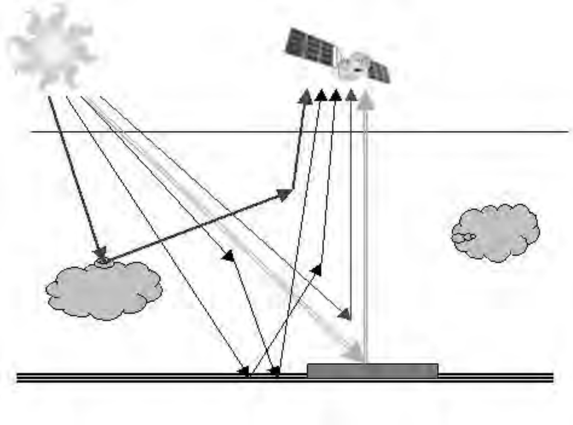


Fig. 2. Main components of the signal received by a satellite

where

$I_0(\lambda)$ is the radiation of the Sun beyond Earth atmosphere; $r(\lambda, x, y)$ is the spectral reflection factor of the surface; $R_{surf}(x, y)$ is the parameter responsible for relief; $T(\lambda, x, y, \theta_{0,} H, t)$ and $T(\lambda, x, y, \theta_0, h, t)$ are the atmosphere transmission along all optical route in atmosphere and at a given height *h*; θ_0 is the zenith angle of solar declination (in this work azimuth angle is not taken into consideration); *t* is the time, λ is the wavelength; x, y are co-ordinates of the point, α_{aer} and α_{mol} are attenuation factors due to aerosol and molecule scattering respectively; Ψ_{aer} and F_{aer} are characteristics of radiation scattering by aerosol (single-stage albedo and scattering function respectively); μ_{sun} and μ_{sat} are directions to the Sun and to the satellite for an observation point respectively ($\mu = 1/cos(\theta)$), *H* and H_0 are thickness of atmosphere (100 km) and height of a local place above sea level respectively.

Atmosphere transmission can be found according to the expression:

$$T(\lambda,x,y,\theta_0,h,t) = \\ +\exp\left(-m(\theta_0)\cdot\tau(\lambda,x,y,h,t)\right), \tag{5}$$

$$\tau(\lambda,x,y,h,t) = \\ = \int_{H_0}^{h} \begin{pmatrix} \alpha_{gas}(\lambda,x,y,h',t) + \\ +\alpha_{aer}(\lambda,x,y,h',t) + \\ +\alpha_{mol}(\lambda,x,y,h',t) \end{pmatrix} dh', \tag{6}$$

$$I_2(\lambda) = \frac{I_0(\lambda)}{\mu_{sun}} \int_{Ho}^{H} \left(\alpha_{mol}(\lambda,x,y,h,t) + \alpha_{aer}(\lambda,x,y,h,t)\psi_{aer}F_{aer}(\gamma)\right)T(\lambda,x,y,\theta,h,t)dh, \tag{3}$$

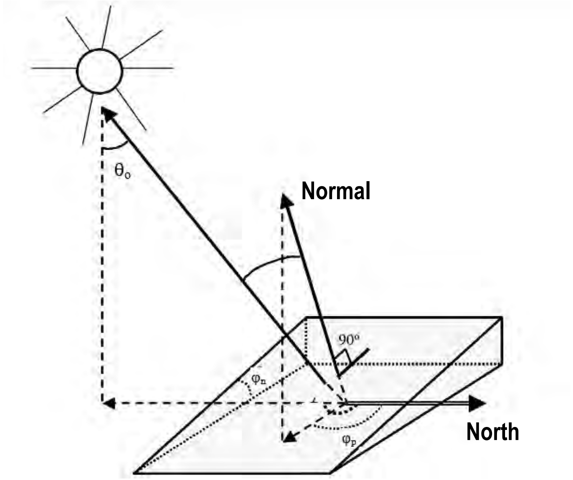


Fig. 3. Orientation layout of a site of Earth surface relative to visual field of the satellite device

where

$m(\theta_0) = 1/\cos(\theta_{sun}) + 1/\cos(\theta_{sat})$;

$\tau(\lambda, x, y, h, t)$ is the optical thickness of atmosphere;

$\alpha_{gas}(\lambda, x, y, h, t)$ is the gas attenuation factor.

Radiation attenuation by gases can be found from the expression:

$$\alpha_{gas}(\lambda, x, y, h, t) = \sum_{j=1}^{N} K_j(\lambda, h)\rho_j(x, y, h, t), \quad (7)$$

where $K_j(\lambda, h)$ is the absorption factor *j* because of gas, $j = 1, \ldots, N$; $\rho_j(x, y, h, t)$ is the concentration profile of *j* gas at a preset height *h* and at a preset time *t*.

Radiation reflected towards the satellite device significantly depends both on the surface type (due to its spectral reflection factor) and on the relief (Fig. 2). Form factor, which takes into consideration relief parameters, is determined by expression [18]:

$$R_{surf}(x, y) = \cos(\varphi_p(x, y))/[\cos(\varphi_n(x, y)\cos(\theta_0)], \quad (8)$$

where θ_0 is the zenith angle of the Sun declination; φ_n is the tilt angle of a selected surface site; φ_p is the rotation angle of a selected surface site (Fig. 3).

4. DESCRIPTION OF THE SOFTWARE STRUCTURE

The problem of simulating radiation received by the satellite device is connected with calculation of direct and once scattered solar radiation and with reflection of radiation from Earth surface in spectral area of 1.5–2.0 µ. For each calculation part, its own priori information is necessary, based on which the calculation is carried out. This information should be global over space and should enclose time including at least one year. It should be noticed that a part of the information is one-dimensional, for example, spectra of reflection from different type surfaces, extra-atmospheric solar spectrum, etc. Another part is two-dimensional (Earth surface relief, Earth surface types (for example, water, wood, field, etc.). And meteorological information is four-dimensional. Therefore, before the calculation is performed, all priori information arrays are reduced to one network interconnected by space (*x*, *y*, *h)*, by wavelength λ and by time *t*. After this, calculation of the radiation received by the satellite Fourier spectrometer is made. A flow chart of the calculation program of the signal received by a satellite is given in Fig. 4.

For three flight days (along a preset trajectory), the GOSAT device obtains information from 12,600 geographical points (diameter of the observation spot is 10 km). In case when account of the points located over land is only carried out (about 4000 points), it is necessary to compute of about half a million points a year. For each geographical point, there are 18,500 spectral lines for three Fourier spectrometer channels. As a result, one should compute about 10^{10} spectral points during an acceptable time limit convenient for work, which, in our opinion, is no more than several hours. The last condition imposes rigid limitations on the calculation speed, with a minimum deviation of the model from real measured values of solar radiation reflected from the surface and received by the spectrometer.

Sets of priori data are formed of known sources of scientific information. For example, relief is taken from the *Shuttle radar topography mission* data [19]. Absorption by gases is calculated based on the *HITRAN* spectroscopic base [20], meteorological parameters are taken from the *NCEP* [21] base, aerosol extinction factor is taken from [22], and solar spectrum is from [23].

Within known calculation programs, the signals received by satellites are only calculated for one spatial point. The program, which we propose, allows calculating both for one point and along the satellite flight trajectory. For each point, a set of priori data (Fig. 4) is formed. Then for each set the program performs calculations of the signals re-

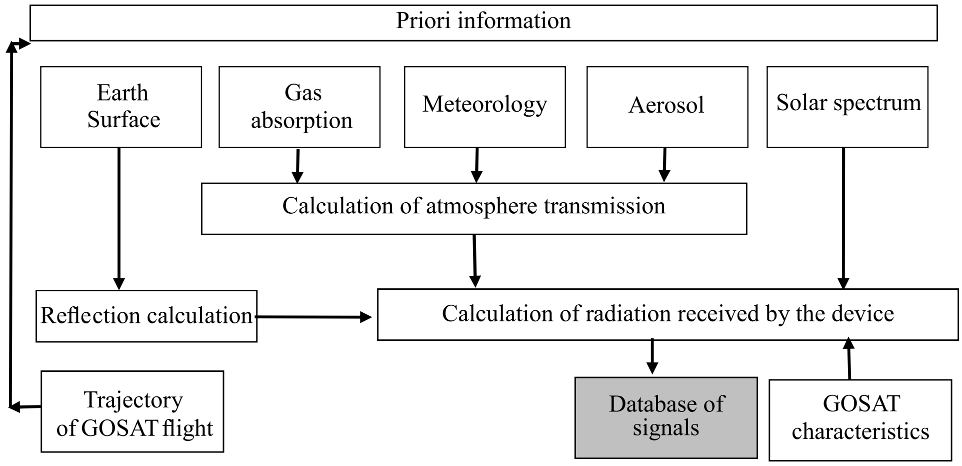


Fig. 4. Flow chart of the calculation program of the signal recieved by the satellite

ceived by satellites [24]. If data read-out and calculation acceleration techniques are not used, then processing time is long. Therefore we applied the *MMF* (Memory-Mapped Files) read out technologies and elements of parallel technologies. The *MMF* technology allows applications working with files as well as they work with dynamic memory. A numerical experiment performed to search number of optimum flows when changing data volume from 64 kb to 1 Gb and with use of the *MMF* technology, shows that for reading from a file, most effective number is 4–6 flows. A paralleling consisted in creation of elementary function groups and data sets for them, so that all computation nodes were loaded by calculations uniformly.

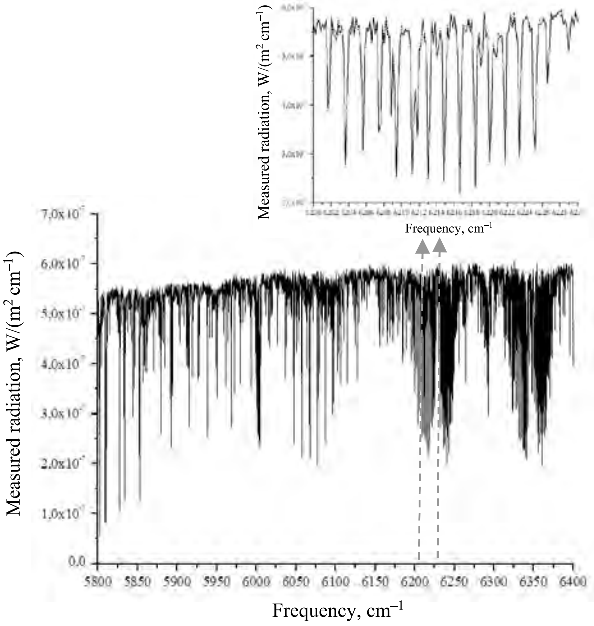


Fig. 5. Comparison of real (solid line) and computed (dashed line) of *GOSAT* signals (co-ordinates of a point are 23.003° N and 14.869° E – Sahara Desert)

5. DESCRIPTION OF THE OBTAINED RESULTS

Because of its versatility, the considered task requires a bigger computational cost, which in its turn requires involving high-speed calculators, program technologies and algorithms. The flow chart presented in Fig. 4 was the basis of a program operating by means of a computing cluster with transfer of a part of algorithms into a parallel operation mode. It made it possible to perform mass calculations for a comparatively small time, which is now equal to 12 h. A comparison of calculation results of the radiation arriving to the GOSAT device with the values, which are really measured for two points under the conditions of an absence of clouds are given in Figs. 5–7. Figs. 5a and 6a show a spec-

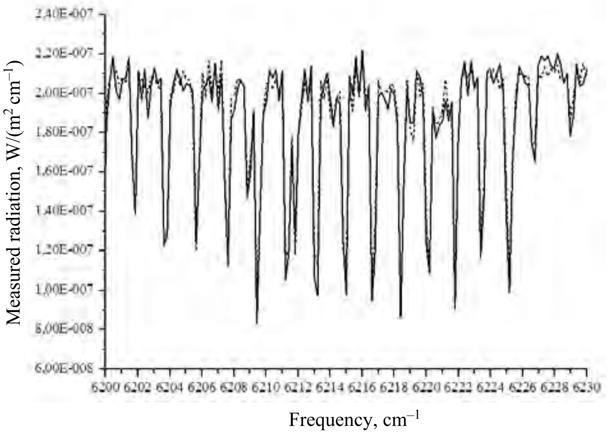
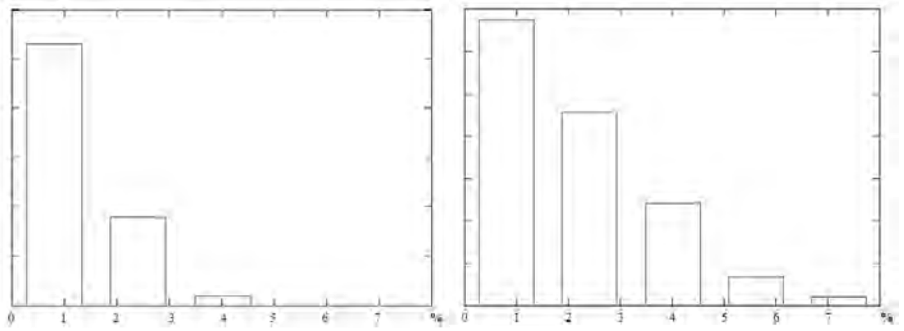


Fig. 6. Comparison of real (solid line) and *GOSAT* computed (dashed line) of *GOSAT* signals (co-ordinate of a point are 64.054 ^{0} N and 69.141° E – a northern tundra region)



a) b)

Fig. 7. A histogram of deviation of the signal computed according to the model from the real signal with the Sun declination angles of 10^{o} (a) and 60^{o} (b)

tral radiation process in the second spectrometer channel within 1.6 µm, and Figs. 5b and 6b show a part of the spectrum within carbon dioxide absorption band, which is used to solve a reverse problem: to determine CO_2 general concentration.

One can see from the pictures that a difference of the model (computed) and of the real spectra takes place, and the main deviation reason is an unknown atmosphere state (meteorological parameters, gas and aerosol composition), as well as change of the surface reflective ability in the measurement point at a given atmosphere state. It should be noticed that for uniform surfaces, such as sand, the deviation is less, and for non-uniform, when surfaces of several types are in the device visual field, this error is just over.

As a whole, if also to take into consideration the Sun illumination angles relative to the surface, the main deviation values are within interval from (4–5)% to (10–15)% (Fig. 7).

The results given in Fig. 7 show that at big angles of the Sun declination, the calculation model of the radiation received by the satellite spectrometer gives a relatively big error when comparing with real signals, which is a consequence of a simple scattering model use. However, if to take into account that the proposed program system allows computing for a single-pass many data over Earth surface with a deviation from reality not worse than (5–10)%, then it is enough to carry out numerical experiments in order to exercise the reverse problem solution techniques, to develop devices and applications.

6. CONCLUSION

Use of space measuring equipment when solving practical problems makes new requirements to models of transforming solar radiation in the “earth surface- atmosphere” system taking into account a specific character of an instrument measurement base. Determination accuracy of the atmosphere optical characteristics depends on the mathematical model of radiation transfer and on the relevant priori information. To account factors influencing formation of the measured radiation when solving equation of radiation transfer in three-dimensional version, one should as much as possible completely take into consideration both: space-time environment fluctuations and features of the reflecting surface. The results of the presented work allow expanding possibilities of simulation programs of radiation transmission and transformation in atmosphere for a more precise solution of the optical remote sensing problems. Taking into account the multidimensional structure of space and time changing in the atmosphere parameters is a new element of the received by satellites signals calculating. Use of the atmosphere parameter model presentation limits accuracy of the calculated signals because of a considerable time and space averaging, which does not allow obtaining detailed information on signal variation. The proposed program makes it possible to compute the signals received by satellites for any spot of the globe and for any season. The obtained results give evidence of acceptability of the calculation quality of the received *GOSAT* signal ((5–10)% in comparison with the real measurement results). It should be notice that obtaining more precise results requires construction of a new model of aerosol scattering and reflection from the surface.

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