Modeling of wind reconstruction from measurements with a space-borne coherent Doppler lidar

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Received April 11, 2001

A method is proposed for reconstruction of altitude profiles of the wind speed and direction from measurement data of a scanning coherent Doppler lidar. The method does not require pre-estimation of the radial wind speed and allows one to retrieve altitude profiles of the wind speed with the error no higher than 2 m/s and wind direction with the error no higher than 20° up to the heights of 18 km from the data of sensing with a space-borne lidar.

Introduction

The increase in reliability of weather forecasts is connected with the possibility of obtaining global-scale information on the wind velocity. A space-borne Doppler wind lidar is an efficient tool for solution of this problem.[1–7] In this connection, it becomes an urgent task to study some methodical aspects of reconstruction of the wind speed and direction from lidar data.

One of the possible approaches here is numerical simulation of operation of a space-borne Doppler lidar with imitation of propagation processes in the atmosphere and recording of a lidar echoes with the subsequent retrieval of the information about the wind from the model data.[5–7]

The principle of operation of a Doppler lidar is the following. As the sensing laser pulse propagates through the atmosphere, the wave is scattered by particles (aerosol, molecules) entrained by the wind flow. The motion of particles causes the Doppler shift in the frequency of scattered wave. After processing the received echo signal, the projection of the wind velocity vector onto the direction of pulse propagation (radial wind velocity) can be determined from this shift. To determine the speed and direction of the wind, one has to have measurements along different directions. When measuring with a satellite-borne lidar, conic scanning of a sensing beam can be used.[1,5]

There are two types of Doppler lidar that differ by the methods of detecting echo signals. A coherent and incoherent lidars. In the case of the coherent Doppler lidar, the source of information on the wind speed are aerosol particles, whereas molecular scattering can be used for incoherent lidar being operated in the UV spectral region.[6]

In this paper, numerical simulation is applied to the study of a possibility of reconstructing the wind field from measurements of a space-based scanning coherent Doppler lidar. If the speed and direction of the wind are calculated based on the array of radial speed values estimated from single-pulse echoes (emitted into the atmosphere at different azimuth angles when scanning), then the accuracy of calculations proves to depend on the number of pulses and the error of single estimation of the number of pulses and the radial wind velocity. The latter, in its turn, depends on the signal-to-noise ratio (the number of coherently detected photons) determined, among other factors, by the energy of sounding pulse and the value of the refractive scattering coefficient.[5,6] The concentration of aerosols rapidly decreases with height (in the cloudless atmosphere), the signal-to-noise ratio decreases, and the accuracy of wind reconstruction decreases as well.

Numerical simulations show that this method reconstructs the altitude profiles of wind velocity with acceptable accuracy only up to the altitudes of 2 to 3 km above the ground. In this paper, we analyze the method for estimating the wind speed and direction directly from lidar data without pre-estimation of the radial speed; this method significantly improves the accuracy of reconstructing the altitude wind profiles.

1. Structure of the program on numerical simulation of operation of the space-borne coherent lidar

To study the capabilities of reconstructing the wind velocity fields from measurements of a space-borne Doppler lidar, the Lidar Group of the German Aerospace Center have developed the ALIENS program[6] that

0235-6880/01/10 848-08 $02.00

imitated the measurement of the radial speed by a space lidar. This program uses the data on the global distribution of atmospheric parameters for the period of January 19–30 of 1998 given by the German Weather Service. The team of the Laboratory of Wave Propagation (Institute of Atmospheric Optics SB RAS, Tomsk) has developed a part simulating turbulent fluctuations of the wind velocity according to data of the German Weather Service. The co-operation among the German Aerospace Agency (DLR), German Weather Service (GWS), and Institute of Atmospheric Optics (IAO) has led to the development of a virtual Doppler instrument for studying the capabilities of wind sensing from space under close-to-real conditions.[7]

Figure 1 demonstrates the structure of the ALIENS program for a coherent Doppler lidar. The program consists of the four main parts: (1) startup module, (2) numerical simulation of a signal, (3) processing of a signal, and (4) exit.

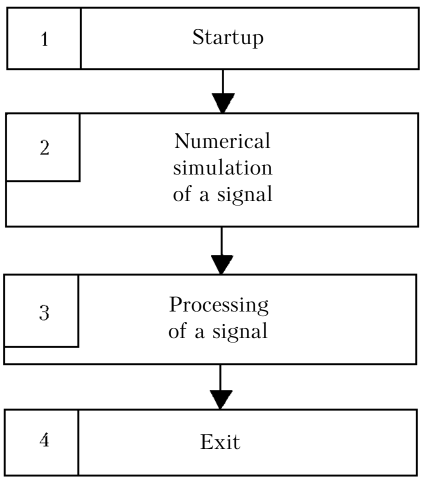

Fig. 1. Structure of the ALIENS program for a coherent Doppler lidar.

The first part includes lidar parameters (wavelength, energy and duration of a sensing pulse, pulse repetition frequency, diameter of a tranceiving telescope, parameters of an analog-to-digital detector, receiver's pass band, etc.), geometric parameters of sensing and position of the satellite platform (nadir, angular scanning rate, satellite altitude), and atmospheric parameters (altitude profiles of the backscattering and extinction coefficients, the GWS data on the global distribution of the altitude profiles of meridional and zonal wind velocities, temperature, cloudiness, and turbulent exchange coefficients).

The second part consecutively simulates the following process: backscattering of the sensing pulse by aerosol particles – optical mixing of the scattered and reference waves – detection – digitization of the data. This part describes the time dependence of photocurrent arising in the lidar receiving system. Numerical simulation is based on the algorithm described in Refs. 8–10.

In the third part, the modeled data are processed to obtain the altitude profiles of the radial components of the wind velocity with the given altitude resolution. The radial speed can be estimated by different methods, for example, from the argument of the correlation function, from maximum likelihood, using the spectral method, etc.[9,10] Then, if conic scanning by a sensing beam is used, the altitude profiles of the wind speed and direction in the sounding area (for example, with the altitude resolution ~ 1 km and the horizontal resolution of 100×100 km) can be reconstructed along the satellite trajectory from the arrays of the radial wind speed.

The obtained altitude profiles of the wind speed and direction are accumulated in the exit part and can be compared with the initial GWS data for the wind. From the results of this comparison, we can judge on the efficiency of lidar measurements of the wind fields.

Figure 2 depicts the scheme of sensing, using a scanning Doppler lidar. The arrow indicates the direction of motion of the satellite, at which the lidar is mounted. The dots show the distribution of single sensing pulses in the horizontal plane. The size of grid cells corresponds to the resolution of the GWS data (1.125° longitude and 1.121° latitude, i.e., about 100×100 km near the equator). The information on the altitude behavior of the wind speed and direction is retrieved from sensing pulses falling within one computational cell. The connection between the radial speed, directions of propagation (nadir, azimuth angle of scanning), and the wind velocity vector (two horizontal components; the vertical component is assumed zero) is used on the assumption that the wind is constant inside every altitude cell chosen.

In making numerical simulations, we have specified the following parameters: satellite altitude – 400 km, nadir – 35°, one complete scanning for 10 s, repetition rate of sensing pulses – 10 s^{-1}, pulse duration – 1 μs, pulse energy – 0.5 J, wavelength – 2.02184 μm, telescope diameter – 70 cm, data reading frequency – 200 MHz, pass band for processed data – 50 MHz, vertical resolution – 1258 m, horizontal resolution – 1.125° longitude and 1.121° latitude.

Figure 3 depicts some examples of altitude profiles of the wind speed and direction reconstructed from modeled lidar data when allowing for the noise and when ignoring it. The values of the wind speed and direction were calculated from estimates of the radial wind speed for sensing pulses falling within the selected cell of the GWS data. The radial speeds, in their turn, were estimated made using the positions of peaks in the power spectra of modeled signals. The dashed curves are for the GWS data. It can be seen that in the absence of noise the wind is reconstructed with a good accuracy. However, in the presence of noise, the useful component of the signal is lost in the noise peaks and the error of reconstruction becomes very high for the parameters listed above (in this example even at the altitude ~ 3 km).

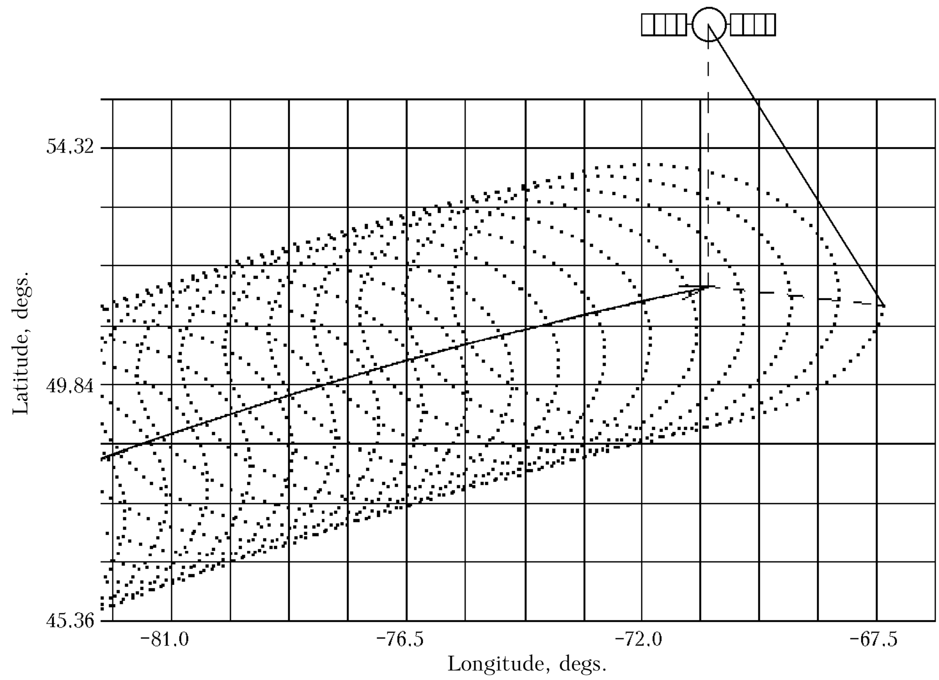

Fig. 2. Geometry of sensing with a satellite-borne scanning Doppler lidar.

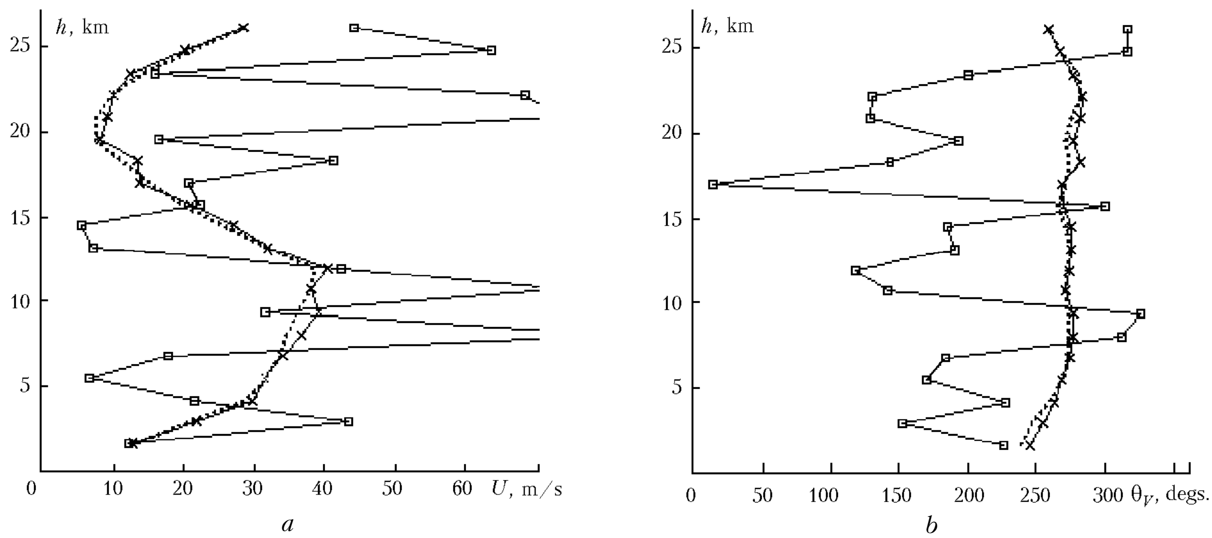

Fig. 3. Example of altitude profiles of the wind speed (*a*) and direction (*b*) reconstructed from modeled lidar data allowing for (squares) and ignoring (crosses) the noise. The dashed curves are for the GWS data.

At the low signal-to-noise ratio, it is quite probable that a noise peak is higher than the return signal and, consequently, the frequency assigned to the radial wind speed is estimated incorrectly. These "false" estimates of the Doppler frequency are distributed uniformly in the 50-MHz frequency band or, taking into account the Doppler equation $V = (\lambda/2)f$, in the speed range $\sim \pm 50$ m/s.

The only reliable method to obtain the correct estimate of the radial wind speed at the low signal-to-noise ratio is likely the accumulation of spectra measured from a series of sensing pulses. In this case, noise peaks are averaged and the signal distinguishes against their background. The method proposed below is based just on this approach.

2. Method for reconstruction of altitude profiles of the wind speed and direction

Let we operate a scanning space-borne coherent lidar and record a noisy echo signal $z(\theta_i, mT_s)$. Then these values are processed to obtain the information on the wind. Here θ_i is the azimuth scanning angle, i is the number of scanning pulse, T_s^{-1} is the data reading (discretization) frequency, $m = 0, 1, 2, \ldots$. The pass band $B = 50$ MHz, $T_s = 1/(2B) = 10$ ns. To estimate the radial speed at some fixed altitude, let us separate M values of the recorded signal (vertical resolution).

Using FFT, we find the power spectra:

$$W\left(\theta_i, \frac{k}{MT_s}\right) = \frac{T_s}{M}\left|\sum_{m=0}^{M-1} z(\theta_i, mT_s)\, e^{-2\pi j(km/M)}\right|^2, \quad (1)$$

where $k = 0, 1, \ldots, M-1$. The frequency resolution here is determined by the parameter $\Delta f = 1/(MT_s)$. With the allowance for the Doppler equation, the speed resolution $\Delta V = (\lambda/2)\,\Delta f$ for $M = 1024$, $\lambda = 2$ μm, and $T_s = 10$ ns is roughly equal to 0.1 m/s.

We assume that n sensing pulses ($i = 1, 2, \ldots, n$) fall within a cell of the GWS horizontal grid. If there is no scanning, then the procedure of data accumulation consists in simple summation of the values in the corresponding channels (spectral channels are numbered as $k = 0, 1, \ldots, M-1$). As a result of averaging with the use of moving smoothing, we can estimate the radial wind velocity from the resulting spectrum with the acceptable accuracy.

In the case of a scanning lidar, the radial wind speed V_r is a function of the angle θ_i. On the assumption of the horizontal homogeneity of the wind, $V_r(\theta_i)$ is determined as

$$V_r(\theta_i) = U \cos\alpha \cos(\theta_i - \theta_V), \quad (2)$$

where U and θ_V are the wind speed and the wind direction angle, α is the elevation angle (angle between the axis of the sensing beam and the Earth's surface).

The parameters U and θ_V are sought in the chosen sensing volume. They can be found without estimation of radial speeds from the data of single-pulse sensing. The proposed approach is based on the variational principle. A 2D array of $F(U, \theta_V)$ at the arbitrary U and θ_V is calculated with the allowance for Eq. (2)

$$F(U, \theta_V) = \sum_{i=1}^{n} \sum_{k''=k'-\Delta k}^{k'+\Delta k} W\left(\theta_i, \frac{k''}{MT_s}\right), \quad (3)$$

where

$$k' = \left[\frac{U}{\Delta V}\cos\alpha \cos(\theta_i - \theta_V)\right], \quad (4)$$

$U = \Delta U\, l$; $\theta_V = \Delta\theta_V\, m$, $l = 1, 2, \ldots$, $m = 1, 2, \ldots$, ΔU and $\Delta\theta_V$ are the speed and angular resolutions; square brackets in Eq. (4) denote the integer part of a value. Then the wind speed U and direction θ_V are determined from the position of the maximum of the function $F(U, \theta_V)$.

Thus, using Eq. (3), the wind speed is estimated from measurements averaged over n sensing pulses and the spectral window with the width $(2\Delta k + 1)/(MT_s)$. Numerical experiments showed that $\Delta k = 4$ is the optimal value in Eq. (3) at the speed resolution $\Delta V \approx 0.1$ m/s. If the radial speed $\hat{V}_r(\theta_i)$ is first estimated from measured spectra and then used to determine the wind speed and direction by, for example, the least squares method under conditions of low signal-to-noise ratio, the presence of even small fraction of false estimates of the radial speed may lead to a large error in the determination of U and θ_V (see Fig. 3).

According to data from Fig. 2, the maximum number of pulses within one cell is 53 (on the average $n \sim 26$). It follows from the results of numerical simulation that this number of pulses is sufficient for reconstruction of the wind profile up to the altitude ~ 7–8 km. The analysis of the GWS data for the wind at high altitudes showed that for better averaging in Eq. (3) we can use lidar data obtained as sensing pulses fall in 9 cells without additional averaging of the wind over a large area ~ 300 × 300 km.

3. Results of numerical simulation

Figure 4 depicts examples of the functions $F(U, \theta_V)$ at different altitudes h. To determine these functions, we used the data simulated in a cell with the horizontal size ~ 100 × 100 km in a cloudless area according to the GWS data for January 20 of 1998. The intersection of solid curves indicates the position of the maximum of $F(U, \theta_V)$, and the intersection of the dashed curves corresponds to the wind velocity and direction according to the GWS data. The distance between the intersection points gives an idea of the accuracy of lidar reconstruction of the wind speed and direction at a given altitude. It can be seen that the pattern of $F(U, \theta_V)$ distribution becomes less contrast with the altitude, i.e., the value of the signal approaches the value of the noise background. As shown in Fig. 4, at $h = 21.9$ km one of the numerous noise peaks may exceed the peak of signal thus leading to a large error in estimation of the wind speed and direction.

Figure 5 depicts the altitude profile of the signal-to-noise ratio (SNR) for the lidar parameters given above in the case of a cloudless atmosphere. At the altitudes $h = 20$ km, the SNR becomes smaller than 10^{-3}. It follows from the results presented below that at such a value of the SNR it becomes impossible to reconstruct the wind field with the needed accuracy.

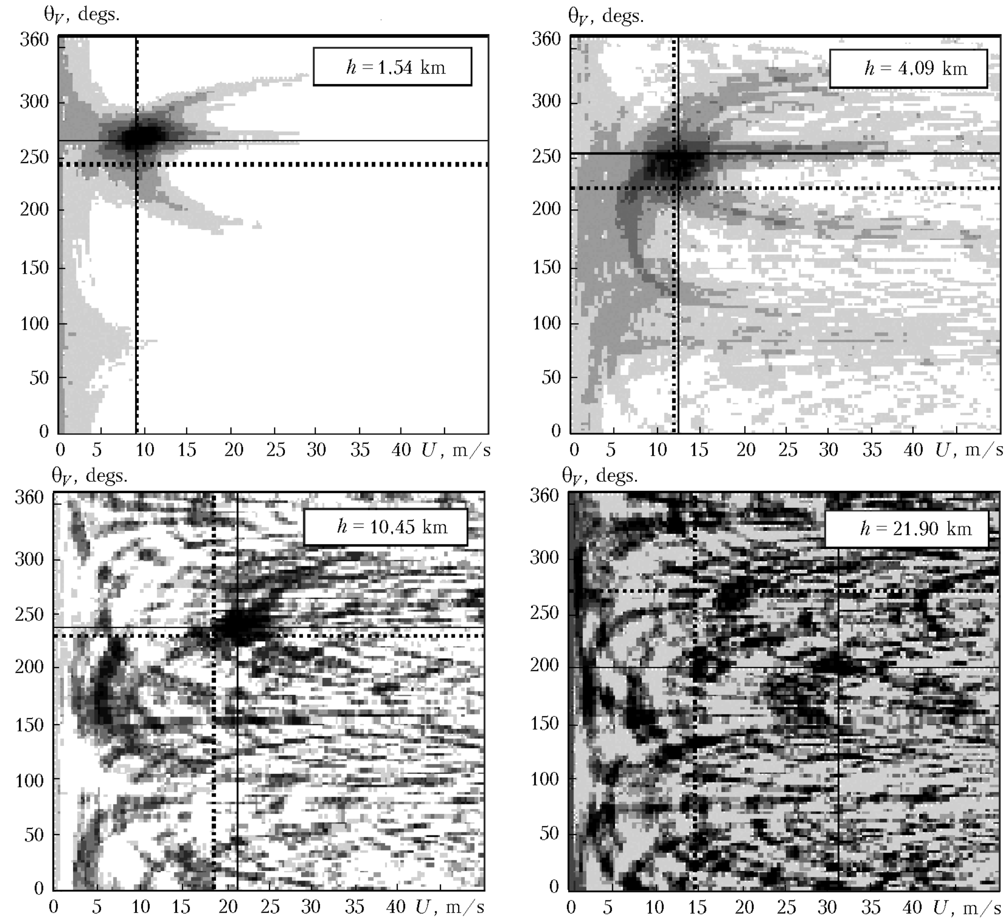

Fig. 4. Examples of functions $F(U, \theta_V)$ at different altitudes.

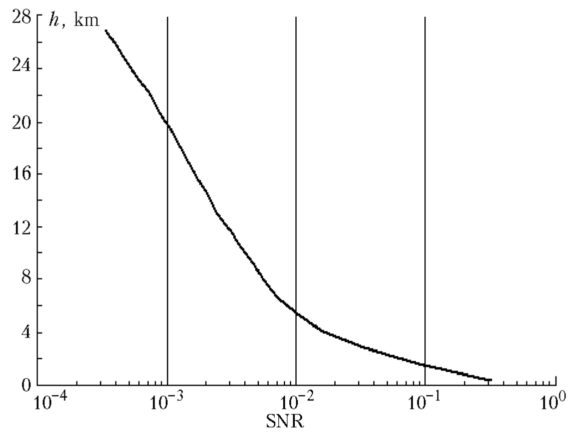

Fig. 5. Altitude profile of the signal-to-noise ratio.

Using the method described in Section 2, we have conducted numerous numerical experiments on lidar reconstruction of the wind field in different regions of the globe. Figure 6 gives some examples of reconstruction of the wind speed and direction in the cloudless atmosphere and in the presence of clouds along with the GWS data. It is seen that in the cloudless atmosphere the wind profiles can be reconstructed with the acceptable accuracy up to the altitudes ~ 18–20 km. In the presence of clouds, the error becomes large enough in the layer below ~ 8 km because of the strong extinction of the sensing and backscattered radiation in clouds.

The absolute errors for the wind speed $\varepsilon_U = [\langle(U_L - U_W)^2\rangle]^{1/2}$ and direction $\varepsilon_\theta = [\langle(\theta_L - \theta_W)^2\rangle]^{1/2}$, where U_L and θ_L are the lidar estimates and U_W and θ_W are the GWS data were calculated based on the data of reconstruction of the altitude wind profiles by two methods: (1) the method involving pre-estimation of radial wind speed and then fitting of the estimates to the dependence described by Eq. (2) to calculate the wind speed and direction (this method will be called fitting of radial speed (FRS)) and (2) the method described in Section 2 (this method will be called variational accumulation of the spectra (VAS)).

Figure 7 shows the area of the globe along the satellite track, for which the GWS data were used in numerical simulation. To calculate ε_U and ε_θ, we took 746 reconstructed altitude profiles of the wind speed and direction falling within separate 1.125° (longitude) × 1.121° (latitude) cells of the computational grid. The wind profiles were reconstructed on the assumption that clouds are absent in the area sensed, as well as with the allowance for the GWS data on the distribution of cloudiness in the atmosphere on the January 20, 1998. First, we calculated the errors ε_U and ε_θ for individual wind profiles, and then they were averaged over the area of sensing shown in Fig. 7. In the cross section of the satellite track, the size of the sensed area was ~ 600 km.

Figure 8 depicts the calculated altitude dependences of the errors ε_U and ε_θ for the cases of using the FRS and VAS methods. These results were obtained assuming the absence of clouds along the satellite track and with the allowance for the distribution of clouds (according to the GWS data) in the area sensed. Comparing Figs. 8*a* and *b* with Figs. 8*c* and *d*, one can see that in the cloudless atmosphere the FRS method allows reconstruction of the wind speed and direction profiles with the acceptable accuracy only up to the altitudes of 2–3 km, whereas the VAS method proposed here allows reconstruction of the wind speed with the error of 2 m/s and the wind direction with the error of 20° up to the altitudes ~ 18 km. If there are clouds in the sensed area, then, as follows from Figs. 8*e* and *f*, the lidar reconstruction of the wind is possible only in the layer roughly from 10 to 16 km.

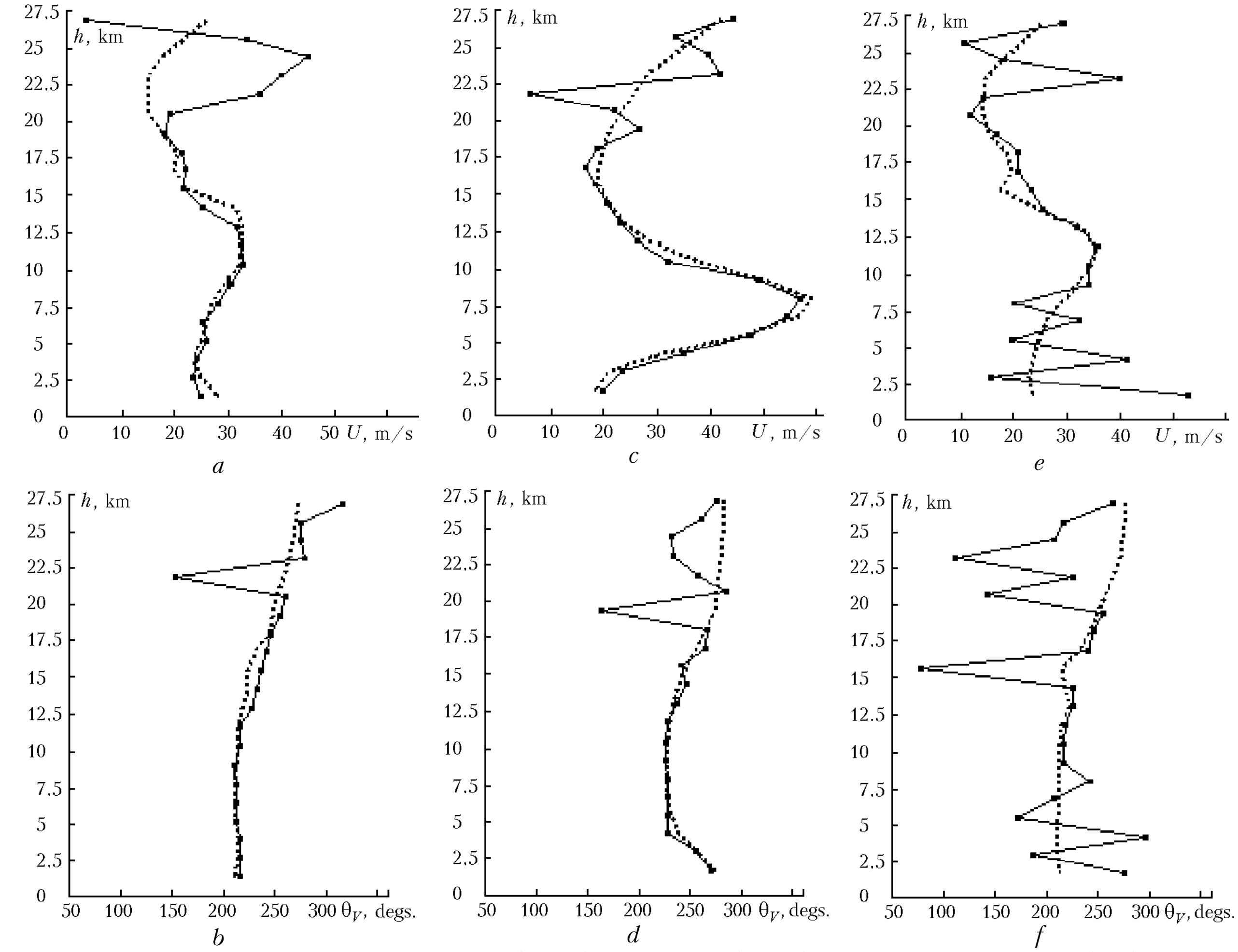

Fig. 6. Examples of reconstruction of the wind speed (*a*, *c*, *e*) and direction (*b*, *d*, *f*) in the cloudless atmosphere (*a*–*d*) and in the presence of clouds (*e*, *f*); lidar data (solid curves) and GWS data (dashed curves).

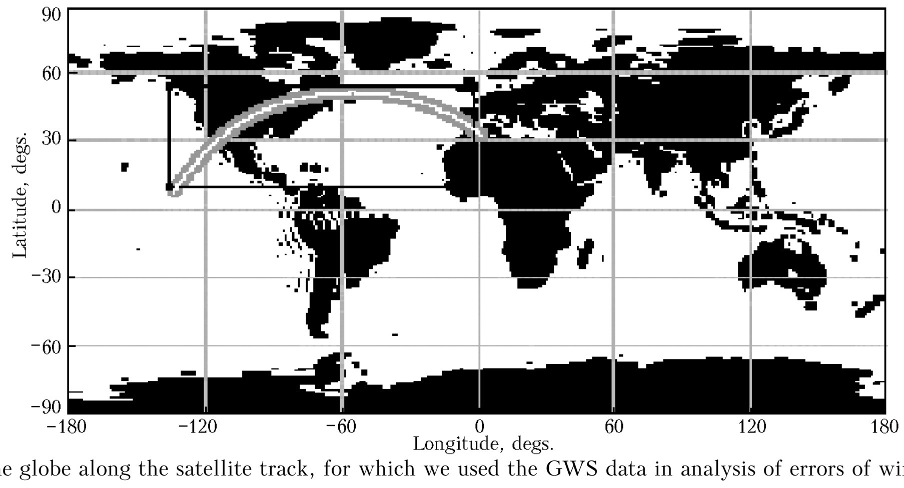

Fig. 7. Area of the globe along the satellite track, for which we used the GWS data in analysis of errors of wind reconstruction.

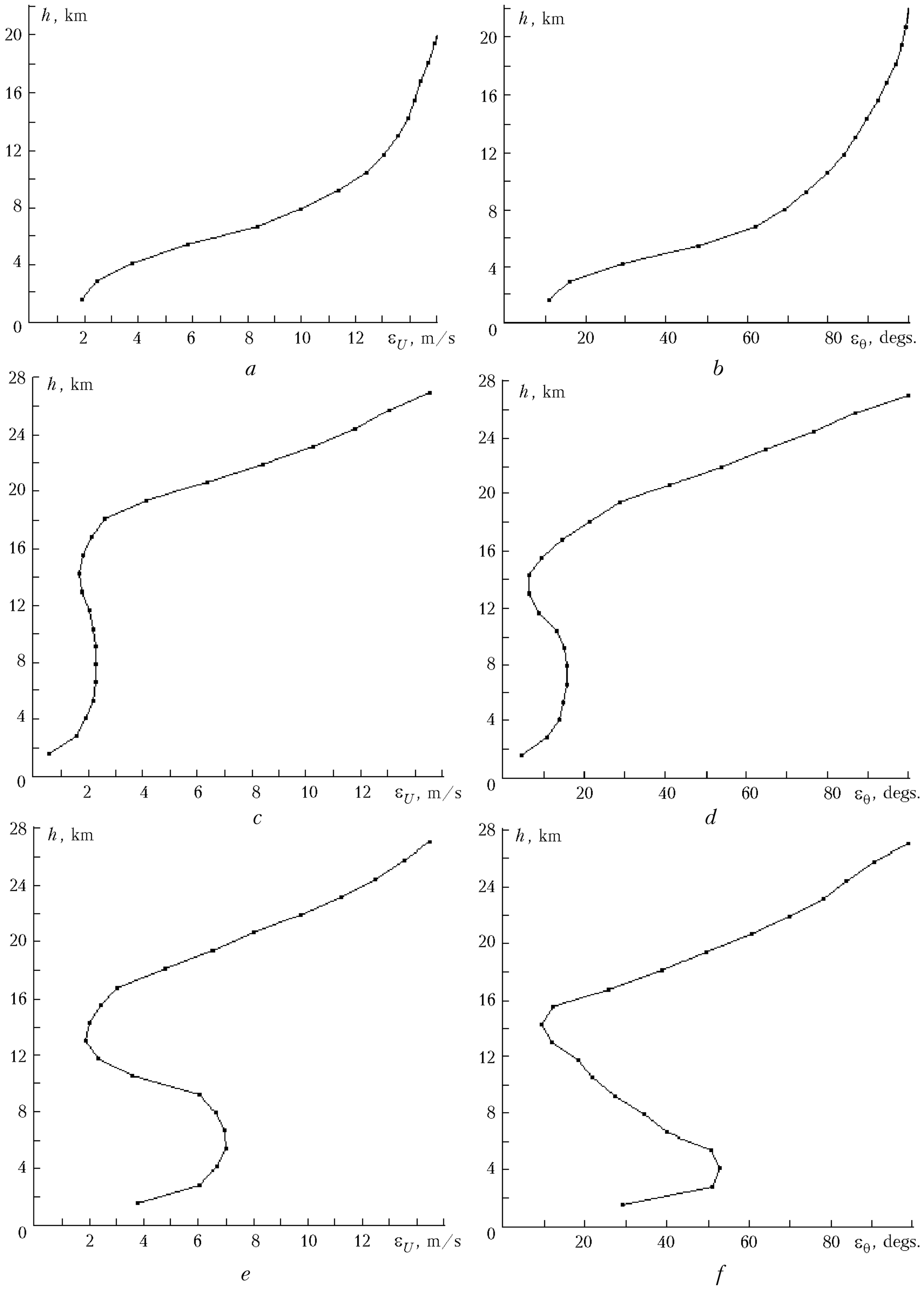

Fig. 8. Altitude dependences of the errors of reconstruction of the wind speed ε_U and direction ε_θ for the FRS (*a*, *b*) and VAS (*c–f*) methods: calculation assuming cloudless atmosphere (*a–d*) and with the allowance for the distribution of clouds according to the GWS data for January 20 of 1998 (*e*, *f*).

Conclusion

The method has been proposed for reconstruction of the altitude profiles of the wind speed and direction directly from the data of a scanning coherent Doppler lidar without pre-estimation of the radial wind speed. Numerical simulation shows that the proposed method allows reconstruction of the wind speed and direction from satellite lidar measurements with sufficiently high accuracy. Thus, for the case of a scanning lidar operated in 2-μm region with the pulse energy of 0.5 J, pulse repetition frequency of 10 Hz, and the telescope diameter of 70 cm under conditions of the cloudless atmosphere, it is possible to reconstruct the altitude profiles of the wind speed with the error of 2 m/s and the wind direction with the error of 20° in the 18-km thick atmospheric layer adjacent to the Earth. This accuracy meets the demands of meteorological services made on the data of wind sensing to be used in prognostic weather models.

Acknowledgments

This work was partly supported by the Russian Foundation for Basic Research (Grants No. 98–05–03131 and No. 00–05–64033).

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