RECONSTRUCTION OF TWO-DIMENSIONAL FIELDS OF ATMOSPHERIC PARAMETERS FROM A LIDAR RETURN FROM THE EARTH'S SURFACE

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Received July 10, 1991

Use of airborne DIAL return signals from the Earth's surface in combination with a tomographic data processing technique enables one to essentially lower the sounding radiation power sufficient for effective sensing of the atmosphere.

An optical arrangement of sounding and an algorithm of lidar data inversion aimed at reconstruction of two–dimensional fields of atmospheric parameters are proposed. Some results of numerical simulations of the technique are presented.

Information about the spatial and temporal structure of the fields of the atmospheric parameters is important for all problems of atmospheric physics. An effective extraction of such an information on the global and mesoscale can be provided by means of the active remote sensing of the atmosphere using airborne and spaceborne instrumentation. Recent advances in the development of laser radar systems show that in the nearest future the lidars could become a part of the spaceborne meteorological systems. However, to provide for a reliable interpretation of lidar data an essential increase of energy potential of a spaceborne lidar system compared to that of the ground–based one, is needed.[1]

It is clear that traditional ways of increasing the lidar energy potential, i.e., the use of bigger receiving antennas and high–power lasers, are inapplicable due to limitations on onboard power supplies. Therefore, the method of obtaining spatially resolved data on the fields of humidity, temperature and concentration of atmospheric components from lidar returns reflected by the Earth's surface seems to be very promising. Corresponding optical arrangement of sounding is shown in Fig. 1. Considerable lowering of sounding radiation power can be reached[2] owing to essentially higher reflectivity of the underlying surface ρ compared to the backscattering coefficient of the atmosphere.[3]

The energy of radiation reflected by the underlying surface, in the Lambertian scattering approach,[4] is described by the equation

$$E(z, x) = \frac{P_0}{\pi} \rho \tau_p S_0 k \frac{\cos\Theta}{L^2} \times$$
$$\times \exp\left\{-2 \int\limits_0^L \sigma_t(x + \xi\sin\Theta, z + \xi\cos\Theta)d\xi\right\}, \tag{1}$$

where P_0 is the power of the laser transmitter, τ_p is the pulse duration, S_0 is the area of the receiving aperture, k is the instrumental constant that includes the efficiencies of the receiving and transmitting optics, etc., the meaning of symbols H and L is clear from Fig. 1, σ_t is the volume coefficient atmospheric extinction due to scattering and absorption by aerosols and air molecules. In the case of the DIAL technique[2,5] of sounding the atmosphere at two wavelengths λ_1 and λ_2 one obtains from Eq. (1)

$$\frac{1}{2} \ln \frac{E(z, x, \lambda_1)}{E(z, x, \lambda_2)} = \exp\int\limits_0^L \sigma_t\,(\lambda_1, x + \xi\sin\Theta, z + \xi\cos\Theta)d\xi, \tag{2}$$

where $\sigma_t(\lambda_1, \mathbf{r}\,(\xi, \Theta))$ is the volume extinction coefficient of the atmosphere due to the resonance absorption by the atmospheric component under study.

The set of lidar data (2) acquired at different positions of the lidar and along different directions of sounding is composed of integral characteristics (projections) $\sigma_t(\lambda_1, \mathbf{r})$ and serves as the initial data set for solving the inverse problem of topographic reconstruction of the field of the extinction coefficient $\sigma_t(\lambda_1, \mathbf{r})$. Finally, if the absorption coefficient is known, this data set can be inverted onto the field of the specie concentration.

Let the soundings yield N values of the optical depth

$$\tau_i = \frac{1}{2} \ln \frac{E_i(z, x, \lambda_1)}{E_i(z, x, \lambda_2)}, \quad i = 1, 2, ..., N$$

measured at different positions of the lidar and a reflector. In accordance with Eq. (2) one can write

$$\tau_i = \int\limits_0^{L_i} \sigma_t(\lambda_1, x + \xi\sin\Theta_i, z + \xi\cos\Theta_i)d\xi\ , \tag{3}$$

where $L_i = h\cos\Theta_i$ and h is the height of the lidar over the Earth's surface.

To solve Eq. (3) let us make use of the representation of $\sigma_t(\lambda_1, \mathbf{r})$ in the form of a series of the piece–constant basis functions

$$\sigma_t(\lambda, \mathbf{r}) = \sum_{j=1}^{M} b_j\, \sigma_j\,(\mathbf{r})\ . \tag{4}$$

Let the area under study be divided into the rectangular elements, where the value σ_t is constant. Taking Eq. (4) into account one can rewrite Eq. (3)

$$\tau_i = \sum_{j=1}^{M} b_j \int\limits_0^{L_i} \sigma_j\,(x + \xi\sin\Theta_i, z + \xi\cos\Theta_i))\, d\xi = \sum_{j=1}^{M} b_j\, G_{ij}\ , \tag{5}$$

0235-6880/91/10 740-03 $02.00

where

$$G_{ij} = \int_0^{L_i} \sigma_j(\mathbf{r})\mathrm{d}\xi\ .$$

Let us solve the system of equations (5) for the unknown coefficient b_j by the iteration technique. In doing so, let us first set the initial distribution of $\sigma_t(\lambda_1, \mathbf{r})$ and then find an estimation of the initial input data set

$$\tilde{\tau}_i = \sum_{j=1}^{M} G_{ij} b_j^q\ . \tag{6}$$

The superscript q denotes the number of an iteration. Then we determine the array of corrections which makes the ith equation to be exact

$$\tau_i = \sum_{j=1}^{M} (b_{ij}^q + \Delta b_{ij}^q) G_{ij}\ . \tag{7}$$

From Eqs. (6) and (7) it follows that

$$\Delta\tau_i = \tau_i - \tilde{\tau}_i = \sum_{j=1}^{M} \Delta b_{ij}^q G_{ij}\ . \tag{8}$$

By minimizing the discrepancies $\Delta\tau_i$ using the least–squares method one obtains the following expression for the corrections:

$$b\Delta_{ij}^q = \frac{G_{ij}\,\Delta\tau_i}{\sum\limits_{j=1}^{M} G_{ij}}\ . \tag{9}$$

Thus determined Δb_{ij} values yield

$$\Delta b_{ij}^{q+1} = b_{ij}^q + \Delta b_{ij}^q\ . \tag{10}$$

Finally, the system of corrections for the qth iteration is formed from all of the K–rays crossing the jth element

$$\Delta b_j^q = \frac{1}{K} \sum_{i=1}^{K} \Delta b_{ij}^q\ . \tag{11}$$

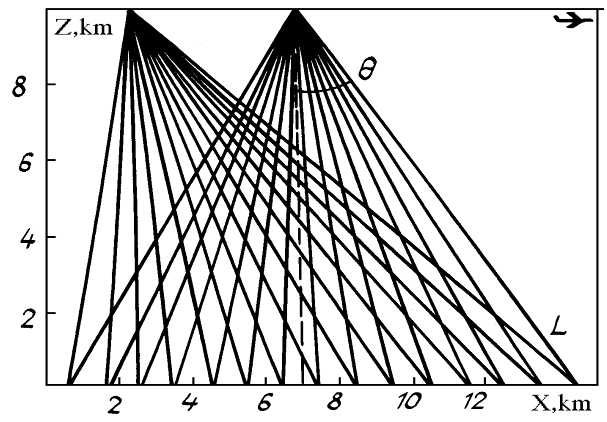

FIG. 1. Optical arrangement of sounding.

The above–described iteration algorithms are used quite widely. They are often used in problems of image processing and physical and medical tomography.[6] Note that the optical scheme of sounding shown in Fig. 1 is very similar to the scheme of inter–borehole transmission[7] used in geophysics for studying the rock massifs. Therefore, in our study we used a modified algorithm for the seismic tomography data processing described in Ref. 8.

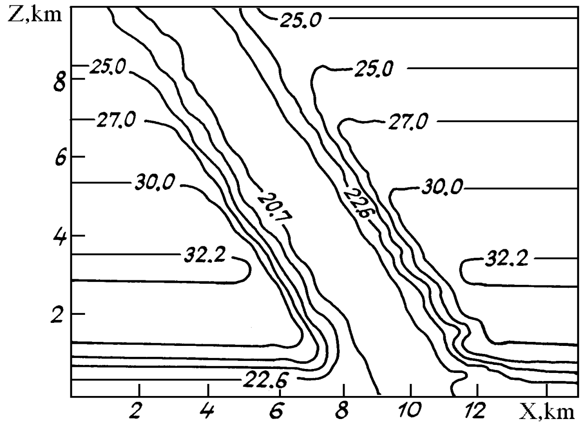

FIG. 2. Model field of O_3 partial pressure.

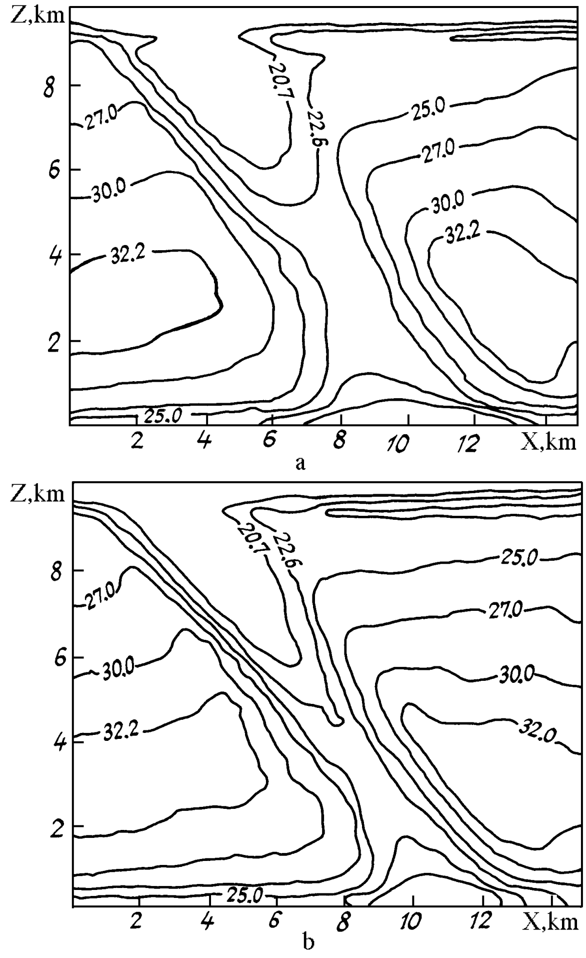

FIG. 3. Reconstructed field of O_3 partial pressure a) 4 iterations and b) 9 iterations.

The simulation of the tomographic sensing of the atmospheric ozone was carried out on the Elbrus computer. The height distribution of the ratio of the ozone partial pressure to temperature chosen as a model function was taken from Ref. 9. On that initial stratified background the area of diminished concentration of O_3 in the form of a plume (Fig. 2) was superposed. In our simulations we have modeled a portion of the atmospheric layer 15 km wide and 10 km high. This volume was divided by a rectangular grid into 40 elements. The reconstruction was carried out using 600 rays arranged as a fan originating from 30 nodes along the flight line. The reconstructed field of the ozone partial pressure after 4 and 9 iterations is shown in Figs. 3*a* and 3*b*. The initial field of the ozone concentration was taken as a stratified field coinciding with the initial background.[9] Calculations of the reconstruction error gave a value from 0.1% to 7% for different elements of the area under study.

Thus, the simulations made have shown the possibility of applying the tomographic technique to the reconstruction of the field of the atmospheric parameters from the lidar return from the underlying surface, though the results presented in this paper are only preliminary.

It is obvious that creation of the mentioned–above lidar systems requires the development of more effective algorithms stable to noise in the input data (in this paper this aspect has not been touched upon). In addition, one should take into consideration inevitable errors in the determination of coordinates of an airspace lidar station and the errors caused by scanning. It is also necessary to search for the most efficient wavelengths from the point of view of information content of sounding and providing maximum reflectivity of the underlying surface. Certain peculiarities of light scattering process also have to be studied.

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