JOINT INTERPRETATION OF LIDAR AND PHOTOMETRIC DATA IN THE SPACEBORNE MEASUREMENTS OF CLOUD FIELDS

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A possibility of conducting a complex optical experiment using an orbiting lidar and radiometer is discussed in the paper. The lidar and photometric measurements were assumed to be interrelated based on model representations of vertical stratification of stratus clouds .

A closed numerical experiment was conducted which simulated a random cloud field against the underlying surface with different albedo. The results illustrate the efficiency of the combined measurements.

At the 15–th International Laser Radar Conference (Tomsk, USSR, 1990) it became clear that in the nearest future a new class of spaceborne research instrumentation, i.e., orbiting lidars will be able to provide remote sounding of the atmosphere and underlying surface from space. The first experiments might be expected to be most efficient in solving such atmospheric optics problems as the determination of vertical structure and opto–physical parameters of clouds, detection of cloudiness against the underlying surface background, investigation of a statistical structure and optical parameters of the underlying surface, e.g., of the ocean surface, etc., in particular, in studying the objects based on interpreting signals due to elastic scattering of radiation on aerosol and reflection from the underlying surface.

The spaceborne TV instrumentation available now is incapable of measuring cloud heights as well as of distinguishing dense clouds against the underlying surface if their albedos are close in value. Identification of cirrus clouds with a TV instrument is also too problematic. The spaceborne IR instrumentation is demonstrating the capability of determining the height of cloud top (provided that the atmospheric temperature stratification is known) based on measurements of outgoing radiation in the atmospheric transmission windows at 3.5, 4.2, and 8...12 μm. However, such measurements are more than likely of a qualitative nature due to inherently large measurements errors. For these reasons the lidars are expected to be the most useful facilities for solving the above–mentioned problems.

The information efficiency and algorithms for interpreting data of a single–frequency spaceborne lidar operating in an analog mode when sounding clouds and underlying surface are described in detail elsewhere.[1] It is shown in Ref. 1 that the lidar considered in it enables one to obtain more accurate data on the cloud vertical structure and underlying surface reflectivity compared with that provided by passive techniques. At the same time, restrictions on power consumption by a lidar facility on a spaceborne platform make it impossible to obtain observational data at a rate sufficient for studying horizontal structure of cloudiness. From this point of view passive techniques have obvious advantages. Therefore, a lidar can be very useful if used for simultaneous measurements at some reference points.

This paper presents an analysis of a possible technique of combining the lidar photometric measurements in application to studies of cloud field structure from space. A closed numerical experiment conducted for assessing the efficiency of such a combination of the observational techniques is also described in the paper.

DATA PROCESSING TECHNIQUE

In the joint processing of the lidar and photometric data the algorithms described in Ref. 1 are used for interpreting the spaceborne lidar data[1]. These algorithms enable one to make a classification (or to distinguish) of types of the objects sounded and, simultaneously to estimate their optical and geometric parameters. Among the parameters being estimated are the distance to an underlying surface, the reflection coefficient of an underlying surface, the cloud top height and the gradient of the extinction coefficient of a cloud downward from its top.

The interrelation between the lidar and photometric measurements has been done in their joint interpretation based on a model representation of vertical stratification of stratus clouds.[2] For describing a vertical profile of the extinction coefficient in a cloud we used the empirical expression

$$\alpha_{mod}(z) = 2.8\,\frac{t}{H}\left[\left(\frac{z - z_0}{H}\right)^{1/4} - \left(\frac{z - z_0}{H}\right)^{5/4}\right], \qquad (1)$$

where τ and H are the optical and geometric thicknesses of the cloud, respectively, z_0 is the cloud top height. The albedo of a cloud (which is assumed to be determined with a photometer) is determined according to Ref. 2, in terms of the parameter H by the formula[2]

$$A = 1 - \exp[-(4.7 - 3.2H)H]\,. \qquad (2)$$

Therefore, the lidar and photometric measurements prove to be related by a common parameter H in Eqs. (1) and (2) which, for this reason, is convenient to be considered unknown in the joint interpretation.

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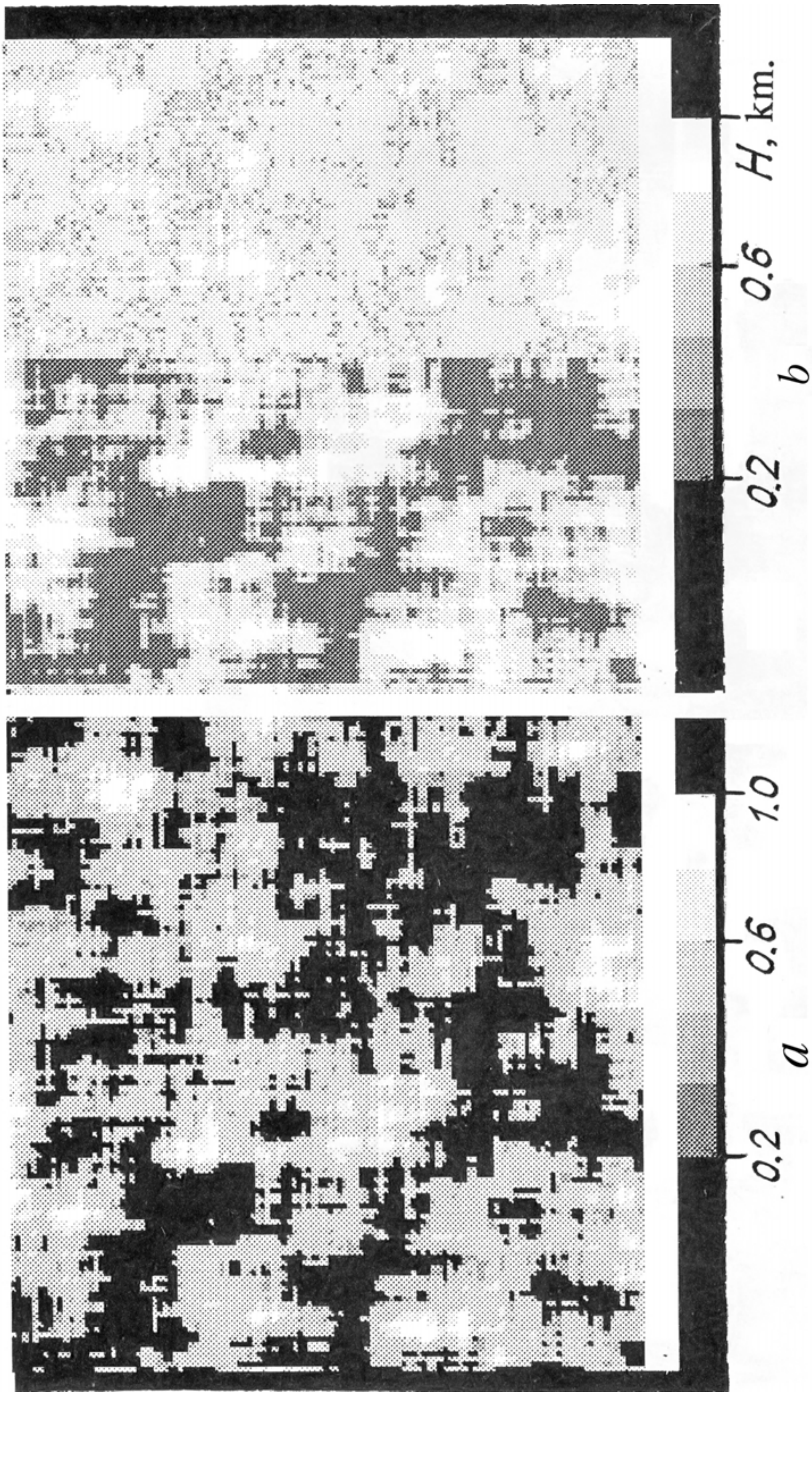

FIG. 1. Model field of a cloud geometric thickness (a) and the field of albedo calculated from it (b).

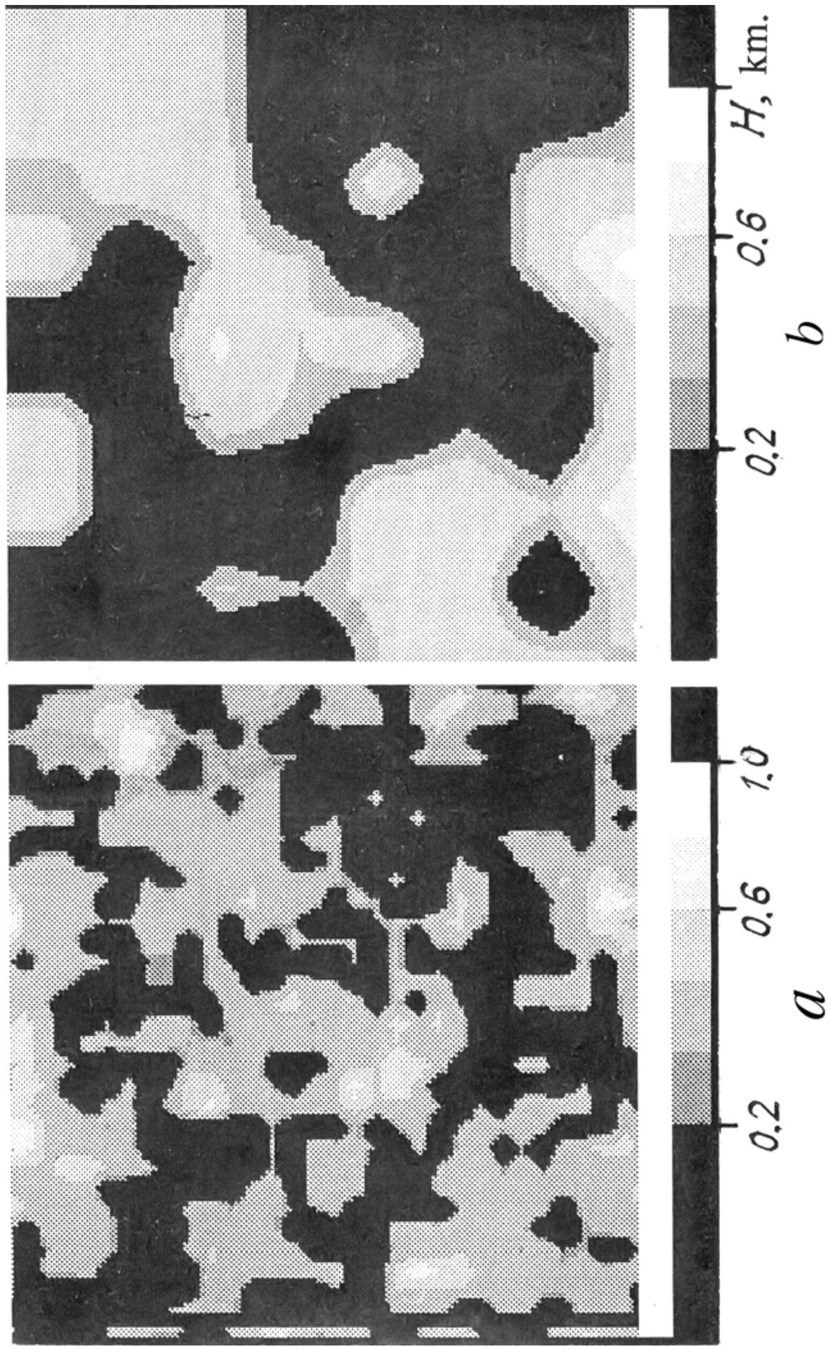

FIG. 2. Reconstruction of the cloud geometric thickness field from lidar measurements: a) measurements at 32×32 reference points and b) measurements at 8×8 reference points.

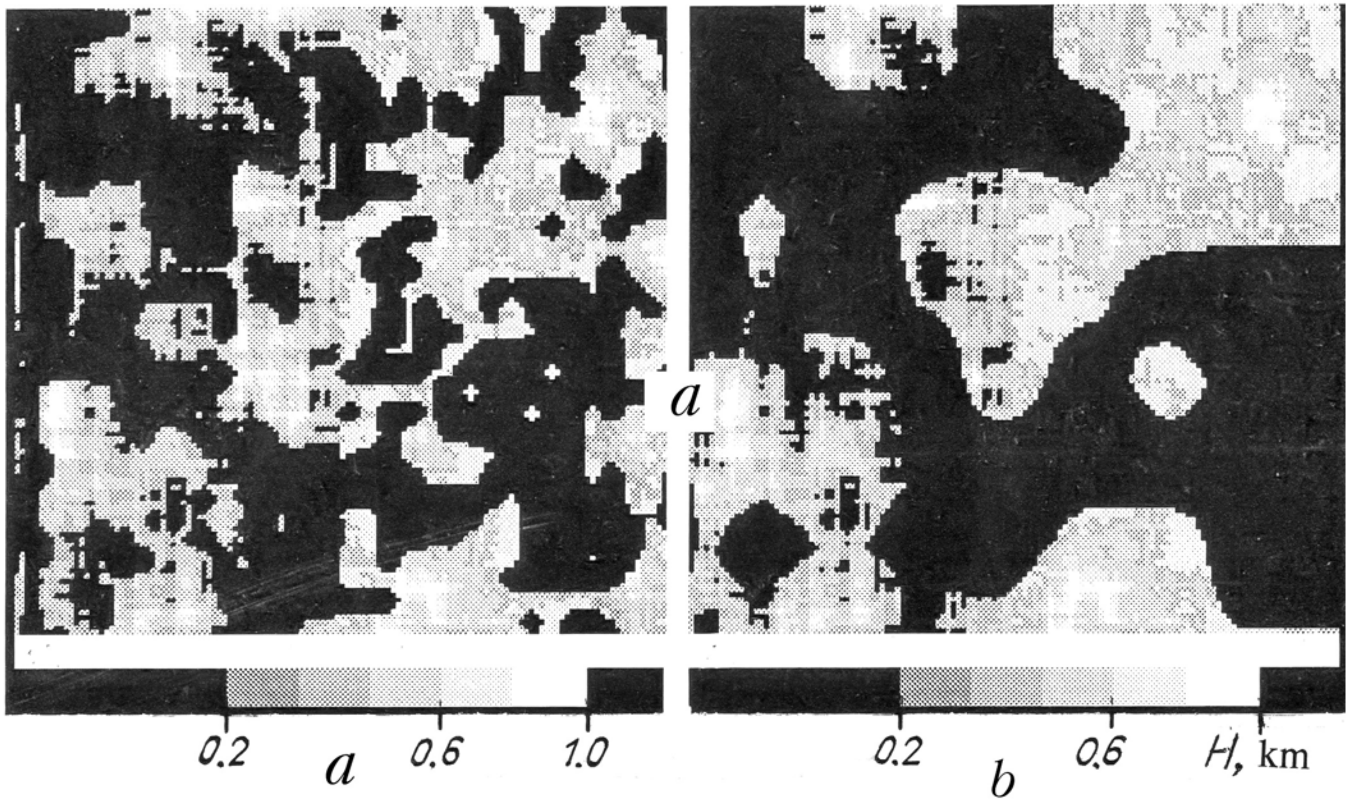

FIG. 3. Reconstruction of the H field from the combined lidar and photometric measurements. a) the case of the 32×32 field of reference lidar measurement points and b) the case of the 8×8 field of reference lidar measurement points.

For photometric measurements it is not a complicated task to determine a geometric thickness of a cloud from Eq. (2). On the other hand, its determination from lidar data can only be done when using specially constructed stable techniques, because a solution of the lidar equation is unstable at large values of the optical thickness[3] and, also due to errors of extrapolation the lidar data obtained for a cloud top onto the whole cloud thickness. The final expression for H derived from a statistically regularized solution of the lidar equation in combination with Eq. (1) has the form

$$H = \left\{ \sum_{i=1}^{N-1} D(\bar{H}, z_i)[F(\bar{H}, z_i) + D(\bar{H}, z_i)\bar{H}] + \alpha \right\} \times$$

$$\times \left\{ \sum_{i=1}^{N-1} D^2(\bar{H}, z_i) + \alpha \right\}^{-1}, \qquad (3)$$

where

$$D(\bar{H}, z_i) = \left. \frac{\partial f(\bar{H}, z_i)}{\partial H} \right|_{H=\bar{H}},$$

$$f(H, z_i) = \ln\left[\frac{P(z_i)\, z_i^2}{P(z*) z*^2}\right] = \ln\left[\frac{\alpha_{mod}(z_i)}{\alpha_{mod}(z*)}\right] - 2\int_{z*}^{z_i} \alpha_{mod}(z')dz',$$

$$F(\bar{H}, z_i) = f(H, z_i) - f(\bar{H}, z_i) - D(\bar{H}, z_i)\bar{H}, \quad \alpha = \frac{\sigma_\varepsilon^2}{\sigma_H^2},$$

where $P(z)$ is the lidar return power.

In solving these equations we have employed an empirical relation between the optical and geometric thicknesses of a stratus cloud $\tau = 40\,H$ (Ref. 2) as well as *a priori* information about the mean geometric thickness H, its variance σ_H^2, and the noise power σ_ε^2 contributing to the measured power of a lidar return.

Stability of algorithm (3) with respect to the lidar–return measurement error was studied using the Monte Carlo method. For a single–layer stratus cloud a superposition of a lidar return and an additive uniformly distributed noise with the variance σ_ε^2 was calculated. A relative threshold of recording the lidar return was set with the parameter δ. The table lists relative errors of the reconstruction of the parameter H at $\varepsilon = 0.01$, 0.1, and 0.3 ($\delta = 0.2$) and at $\delta = 0.1$, 0.2, and 0.5 ($\varepsilon = 0.1$). The exact values of H are given in the left column.

The lidar and photometric data are jointly interpreted in the following manner. At a point where the lidar identifies a cloud the value of H was determined using Eq. (3), its values at intermediate points are linearly interpolated. Then the results were corrected using Eq. (2) to provide higher spatial resolution.

NUMERICAL EXPERIMENT

To study the quality of joint interpretation we have conducted a closed numerical experiment in which for a simulated random cloud the field corresponding fields of H, τ, and z_0 were calculated. The albedo of the underlying surface was taken to be 0.2 (in the left side of Fig. 1*b*) and 0.7 (in the right). Figure 1*b* presents the model albedo field model represented in a discrete form of a 128×128 matrix of point values for a 5–point cloudiness with the inhomogeneities scale of mean size of 25 km along both coordinates (the dimensions of the field described are 250×250 km). It is clear that if the values of albedo for the cloudiness and underlying surface are close the cloud field structure can hardly be revealed. Figure 1*a* presents the model field of H, and Fig. 2 depicts the results of its reconstruction from the lidar data (neglecting the photometric results) for two cases, i.e., when the lidar measurements are conducted over the fields of 32×32 (Fig. 2*a*) and 8×8 (Fig. 2*b*) reference points, the values at intermediate points being linearly interpolated between the adjacent ones. The H field reconstructed based on the joint interpretation of the lidar and photometric measurements is shown in Fig. 3. Figure 3*a* presents the case in which the lidar measurements were made at 32×32 reference points, as in the case of data presented in Fig. 2*a*. Figure 3*b* presents the same field for the case of 8×8 field of reference lidar measurements.

TABLE I. The errors in reconstructing the cloud thickness from lidar data.

H	δ=0.2			ε=0.1		
	ε=0.01	ε=0.1	ε=0.3	δ=0.1	δ=0.2	δ=0.5
0.11	0.03	0.03	0.05	0.01	0.03	0.09
0.6	0.02	0.26	0.87	0.26	0.26	0.31
1.1	0.02	0.22	0.81	0.16	0.21	0.26
1.6	0.02	0.29	0.65	0.18	0.29	0.32
2.1	0.01	0.18	0.29	0.11	0.18	0.24
2.6	0.03	0.26	0.87	0.11	0.26	0.28
3.1	0.02	0.13	0.42	0.11	0.13	0.32
3.6	0.03	0.17	0.19	0.15	0.17	0.23
4.1	0.02	0.1	0.16	0.09	0.1	0.15
4.6	0.02	0.03	0.03	0.002	0.03	0.05

The analysis of the results of numerical simulation allows us to arrive at the following conclusions:

1) the photometric measurements do not always provide reliable data on cloud fields (Fig. 1);

2) the use of simultaneous lidar measurements can essentially increase the interpretation reliability but only if the spatial density of lidar measurements is fairly high (Fig. 2);

3) the combined lidar and photometric measurements provide an admissible compromise between the required interpretation reliability and the actual capabilities of lidar systems.

REFERENCES

1. Yu.S.Balin, S.I.Kavkyanov, G.M.Krekov, I.V.Samokhvalov, and S.V. Strepetova, Opt. Atm. **1**, No. 1, 93–99 (1988).

2. E.M. Feigel'son, ed., *Radiation in a Cloudy Atmosphere* (Gidrometeoizdat, Leningrad, 1981), 280 pp.

3. V.E. Zuev, S.I. Kavkyanov and G.M. Krekov, Izv. Akad. Nauk SSSR, Ser. Fiz. Atmos. i Okeana **19**, No. 3, 255 (1983).