Cloud Bottom Altitude Determination From a Satellite

Alexander A. Kokhanovsky and Vladimir V. Rozanov

***Abstract*—The letter is devoted to the introduction of a new technique to derive the cloud bottom height (CBH) from satellite measurements of the cloud reflectance in the oxygen A-band. The information on the cloud top height needed in the retrieval of the CBH must be obtained from separate measurements to insure small biases in the retrieved CBH. Such measurements can be performed by a space-based lidar.**

***Index Terms*—Cloud remote sensing, O_2 A-band spectrometry, radiative transfer.**

I. Introduction

THE DETERMINATION of cloud geometrical characteristics (e.g., the cloud geometrical thickness l, the cloud top height h, and the cloud bottom height H) is of a great importance for climate issues, dynamical meteorology, and aircraft safety issues. Global determinations of geophysical parameters are possible only using satellite measurements. There are a number of techniques to determine the cloud top height from a satellite. A recent review of these techniques is given by Rozanov and Kokhanovsky [12]. The techniques range from active measurements (e.g., see Winker *et al.* [15] and Poole *et al.* [9]), using lidars and radars on satellite platforms, to passive techniques, based on the processing of information, contained in the thermal infrared radiances [4], Ring effect [2], reflected light polarization [5], [14], stereo photogrammetric technique [8], and oxygen A-band technique [12], [16], to name a few.

Rozanov and Kokhanovsky [12] has extended the O_2 A-band technique to the determination of the cloud geometrical thickness. However, it was found that simultaneous determination of both the cloud top height and the cloud geometrical thickness introduces large biases in the retrieved cloud bottom height in many cases.

To reduce these biases we propose to use the simultaneous measurements of the cloud top height by a lidar system (the accuracy in h is better than 20 m) and the cloud reflectance spectrum by the O_2 A-band spectrometer. These two independent pieces of information can be used to determine the cloud bottom height $H = h - l$ from a satellite or aircraft. The study of the accuracy of such a technique is the main subject of this work.

II. Theory

The cloud reflectance spectrum is almost not sensitive to the cloud geometrical characteristics outside of gaseous absorption bands. The situation is radically changed if we consider the radiative transfer in the molecular absorption line [12], [13], [16]. Indeed, let us assume that we have a gas in a planetary atmosphere, which absorbs almost all incident radiation in a narrow band. Then the depth of this band, measured by a receiver on a satellite will depend on the cloud altitude. Gas concentrations generally decrease with the distance from the ground. Therefore, clouds at a high altitude do not allow most of photons to penetrate to low atmospheric layers and be absorbed there. So the depth of a molecular line in the reflected light will decrease, if high clouds are present in the field of view of a sensor.

The next question to address is the influence of the cloud geometrical thickness on the reflectance spectrum $R(\lambda)$ in the gaseous absorption band. One expects that spectra $R(\lambda)$ in the gaseous absorption band for clouds having the same top heights but different cloud geometrical thicknesses will differ even if the cloud optical thicknesses τ coincide [6]. This is due to the fact that multiple light scattering will lead to larger average photon path lengths in clouds as compared to a cloudless atmosphere, thereby increasing absorption. This must lead to the decrease of the reflectance for geometrically thicker clouds. Radiative transfer calculations (see Fig. 1) confirm this fact.

The spectrum $R(\lambda)$ as shown in Fig. 1 can be used to determine the cloud bottom height from a satellite. The main steps of the inversion technique are given below.

First of all, the TOA reflectance R is presented in the form of a Taylor expansion around the assumed value of the cloud bottom height equal to H_0

$$R(H) = R(H_0) + \sum_{i=1}^{\infty} a_i (H - H_0)^i \qquad (1)$$

where $a_i = R^{(i)}(H_0)/i!$. Here $R^{(i)}(H_0)$ is the i-derivative of R at the point H_0. The next step is the linearization, which is a standard technique in the inversion procedures [11]. We found that the function $R(H)$ is close to a linear one in a broad interval of the argument change [6]. Therefore, we neglect nonlinear terms in (1). Then it follows that

$$R = R(H_0) + R'(H_0)(H - H_0) \qquad (2)$$

where $R' = (dR)/(dH)$. We assume that R is measured at several wavelengths $(\lambda_1, \lambda_2, \ldots \lambda_n)$ in the oxygen A-band. Then instead of the scalar quantity R we can introduce the vector $\vec{R}_{\text{mes}}$ with components $(R(\lambda_1), R(\lambda_2), \ldots R(\lambda_n))$. The same applies to other scalars in (1).

Therefore, (2) can be written in the following vector form:

$$\vec{y} = \vec{a}x \qquad (3)$$

Manuscript received January 10, 2005; revised March 2, 2005. This work was supported by the DFG Project BU 688/8-1.

The authors are are with the Institute of Environmental Physics, Bremen University, D-28213 Bremen, Germany (e-mail: alexk@iup.physik.uni-bremen.de).

Digital Object Identifier 10.1109/LGRS.2005.846837

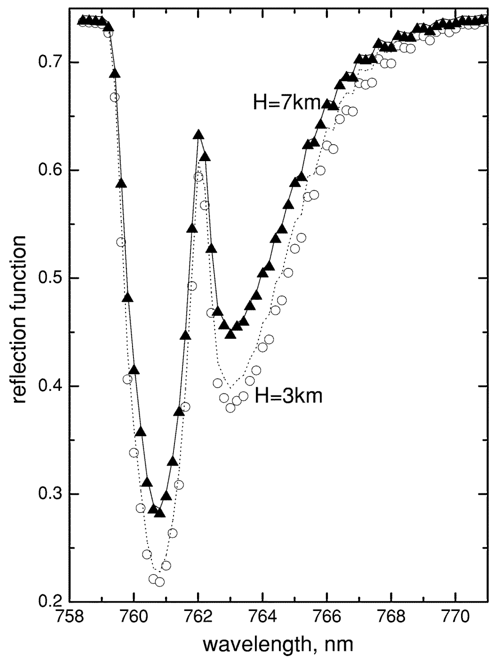

Fig. 1. Cloud reflection function in the oxygen A-band calculated using SCIATRAN (lines) [10] and asymptotic analytical theory (symbols) [6] at the nadir observation, the solar zenith angle equal to 60°, the optical thickness equal to 50, the cloud top height equal to 9 km, and the cloud bottom height equal to 3 km (circles) and 7 km (triangles). All other parameters (e.g., atmospheric vertical profiles) coincide with those described in [6]. The reflectance function is averaged with the step 0.2 nm using a SCIAMACHY [1] response function.

where $\vec{y} = \vec{R}_{\mathrm{mes}} - \vec{R}(H_0)$, $\vec{a} = \vec{R}'(H_0)$, and $x = H - H_0$. Note that both measurement and model errors are contained in (2). The solution $\hat{x}$ of the inverse problem is obtained by minimizing the following cost function:

$$\Phi = \|\vec{y} - \vec{a}x\|^2 \tag{4}$$

where $\| \, \|$ means the norm in the Euclid space of the correspondent dimension.

The value of $\hat{x}$, where the function Φ has a minimum can be presented as

$$\hat{x} = \frac{(\vec{y}, \vec{a})}{(\vec{a}, \vec{a})} = \frac{\sum_{i=1}^{n} a_i y_i}{\sum_{i=1}^{n} a_i^2} \tag{5}$$

where $(,)$ denotes a scalar product in the Euclid space, n is the number of wavelengths, where the reflection function is measured.

The functions $\vec{R}(H_0)$ and $\vec{R}'(H_0)$ in (5) must be calculated using the radiative transfer theory with input parameters characteristic for a given atmospheric state. We use the approximate analytical theory for such a calculation. The details of this theory are given by Kokhanovsky and Rozanov [6]. Basically, the approximation has an accuracy better than 5% as compared to line-by-line calculations in the O_2 A-band [6] for typical cloudiness with $\tau \geqslant 5$. The use of the exact radiative transfer theory is also possible but it leads to huge calculation time and does not provide a better approach to the problem at hand due to all uncertainties involved (e.g., possible multilayered cloudiness).

Therefore, knowing values of the measured spectral reflection function R_{mes} and also values of the calculated reflection function R and its derivative R' at $H = H_0$ and several wavelengths, the value of the cloud bottom height can be found from (5) and equality: $H = \hat{x} + H_0$. The value of H_0 can be taken equal to 0.5 km, which is a typical value for low level clouds at middle latitudes [3]. The main assumption in our derivation is that the dependence of R on H can be presented by a linear function on the interval x [6].

The retrieved value of H is compared with H_0. If the difference is smaller than 100 m, the value of H is taken as a retrieved value and the inversion procedure is finished. Otherwise, the retrieved value of H is substituted in (2) instead of H_0 and iterations are performed until the convergence is reached. We need three to five iterations to reach a convergence, if the initial guess is far away from the true value of the cloud bottom height.

Several additional parameters are needed in the retrieval procedure. They are the cloud optical thickness, the cloud liquid water profile, the cloud thermodynamic state, the cloud droplet radii, etc. They must be simultaneously derived or assumed using climatological values. We have found that the cloud optical thickness τ is the most important parameter, which influences the retrieval. So we find the value of τ from measurements outside the gaseous absorption band as described by Kokhanovsky and von Hoyningen-Huene [7].

Clearly, if the forward and inverse models use the same system of equations, the inverse problem solution reproduces accurately the input parameters for the forward model in the absence of the measurement noise. We have checked this using the forward and inverse models based on the same set of analytical equations as described by Rozanov and Kokhanovsky [12]. Indeed, the cloud bottom height used as input in the retrieval scheme coincided with the cloud bottom height retrieved by the solution of the inverse problem as specified above in this case.

The next possible step is to introduce measurement errors and see the influence of these errors on the retrieval of H. However, we have chosen a different strategy in this work. Namely, we calculate the cloud reflectance spectrum $R(\lambda)$ in the O_2 A-band using the exact radiative transfer calculations with the latest version of the radiative transfer solver SCIATRAN [10] and use this exact spectrum in the analytical retrieval procedure described above. Because possible measurement errors are well below the accuracy of analytical equations (see Fig. 1), such an approach can be considered as a simulation of noise in the inversion procedure having as an input SCIATRAN-generated synthetic spectra.

Results of the inversion procedure described above are shown in Fig. 2. It follows that with exclusion of clouds having large top altitude and small cloud bottom height (very thick clouds), which are rare cases in terrestrial atmosphere, there is one-to-one correspondence between retrieved H_r and exact H_e cloud bottom heights. Biases $\Delta H = H_r - H_e$ are given in Fig. 3. It follows that biases only weakly influenced by values of τ and generally they are below 0.5 km for clouds having the geometrical thickness below 4.5 km. Most of clouds in the terrestrial atmosphere have geometrical thicknesses below 1 km [3]. Then biases are just 0.25 km as shown in Fig. 3. Therefore, we conclude that the technique presented here can be used for

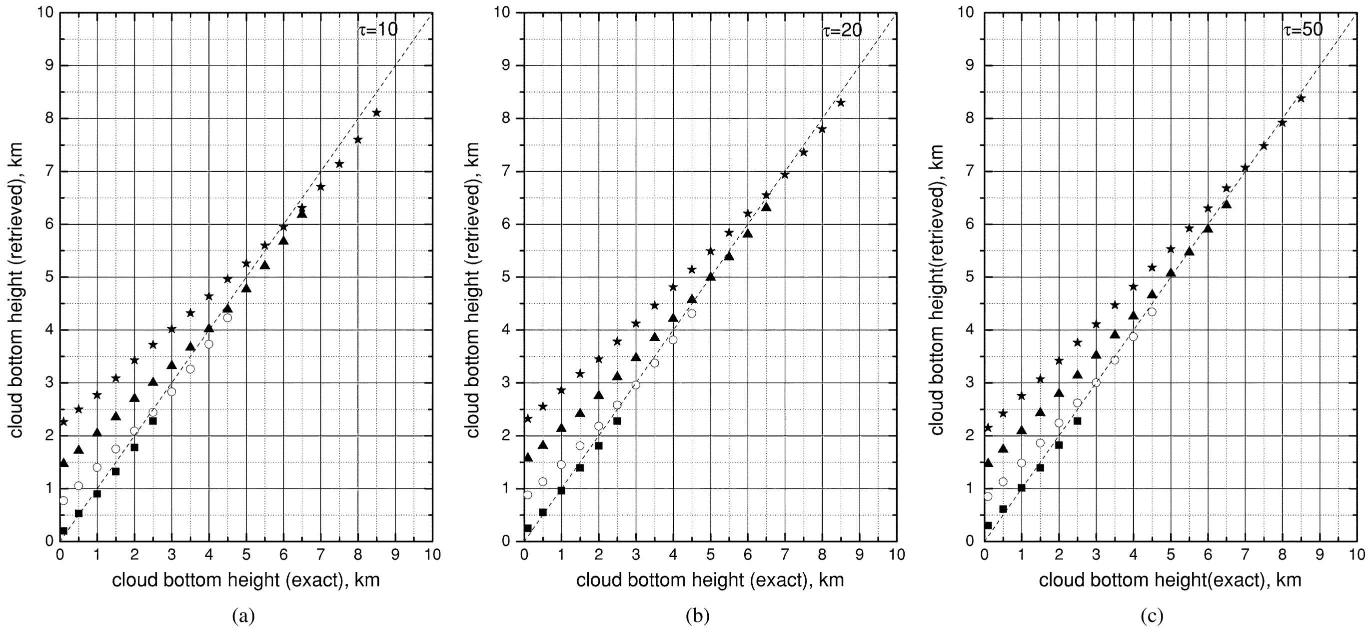

Fig. 2. Dependence of the retrieved cloud bottom height on the exact cloud bottom height at $\tau = 10(a)$, $\tau = 20(b)$, $\tau = 50(c)$ for cloud top height 9 km (stars), 7 km (triangles), 5 km (circles), 3 km (squares).

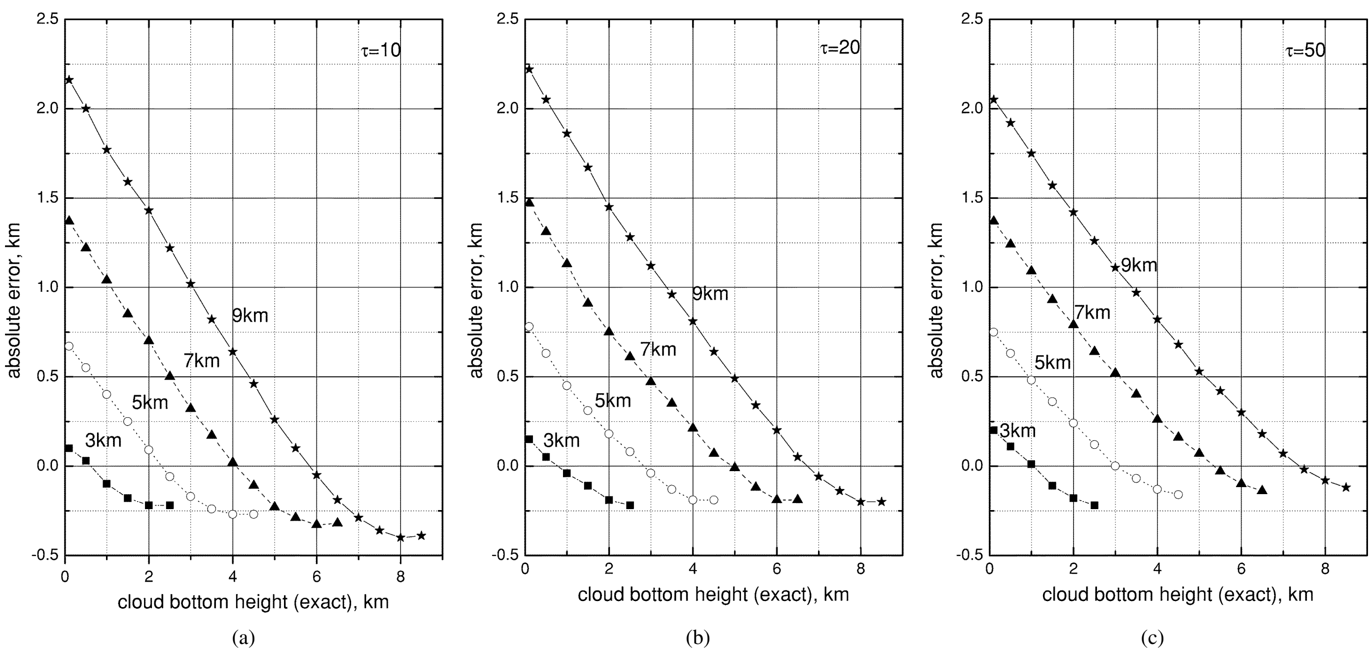

Fig. 3. Dependence of the absolute error of the retrieved cloud bottom height on the exact cloud bottom height at $\tau = 10(a)$, $\tau = 20(b)$, $\tau = 50(c)$ for cloud top height 9 km (stars), 7 km (triangles), 5 km (circles), 3 km (squares). Data are obtained from Fig. 2.

an accurate estimation of a cloud bottom height from a satellite. This is contrary to the general wisdom that satellite techniques measure mostly cloud top height properties.

It follows from Fig. 3 that the accuracy of the retrieval decreases for smaller values of H at the cloud top height equal to 9 km. This is related to the fact that analytical equations have larger errors for smaller H (see Fig. 1). Note that the probability of single clouds having small values of H and large values of the cloud top height is low. So values with large biases of the retrieved cloud bottom altitude as shown in Fig. 3 do not produce significant biases as far as the operational cloud retrievals are concerned.

It is of importance that the dependence of ΔH on τ is weak. We believe that our results are valid for all $\tau \geqslant 5$, where errors of our analytical formulation are small. For smaller thicknesses, the approach given here is not needed because then lidar can penetrate a cloud layer and give information on the cloud bottom altitude.

The results given in Figs. 2 and 3 are obtained allowing for the cloud top height measurements uncertainty $\Delta h = \pm 10$ m. They are not changed appreciably even increasing this uncertainty in ten times (e.g., to 100 m). The changes of biases as shown in Fig. 3 are generally below 30 m then. It means that the technique is not very dependent on the vertical resolution of the lidar system, which is usually better than 20 m.

III. Conclusion

We have presented here a new pathway for the determination of a cloud bottom height from aircraft or a satellite using simultaneous lidar measurements of the cloud top altitude and the cloud reflectance spectrum in the oxygen A-band. Therefore, it is of interest to have such a system on a satellite in the future to address the climatology of cloud bottom altitudes. Such information on a global scale is needed for climate studies. However, it is virtually absent at the moment.

Most of terrestrial cloudiness is characterized by several cloud layers. Our additional numerical experiments (not shown here) suggest that the retrieved cloud bottom height is close to that of a lowest layer of a multilayered cloud system.

References

[1] H. Bovensmann, J. P. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. V. Rozanov, K. V. Chance, and A. P. H. Goede, "SCIAMACHY: Mission objectives and measurement modes," *J. Atmos. Sci.*, vol. 56, pp. 127–150, 1999.

[2] R. de Beek, M. Vountas, V. V. Rozanov, A. Richter, and J. P. Burrows, "The Ring effect in the cloudy atmosphere," *Geophys. Res. Lett.*, vol. 28, pp. 721–724, 2001.

[3] E. M. Feigelson, Ed., *Radiation in Cloudy Atmosphere*. Leningrad, Russia: Gidrometeoizdat, 1981.

[4] M. D. King, Y. J. Kaufman, W. P. Menzel, and D. Tanre, "Remote sensing of cloud, aerosol, and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS)," *IEEE Trans. Geosci. Remote Sens.*, vol. 30, no. 1, pp. 2–27, Jan. 1992.

[5] W. J. J. Knibbe, J. F. de Haan, J. W. Hovenier, D. M. Stam, R. B. A. Koelemeijer, and P. Stammes, "Deriving terrestrial cloud top pressure from photopolarimetry of reflected light," *J. Quant. Spectr. Radiat. Transf.*, vol. 64, pp. 173–199, 2000.

[6] A. A. Kokhanovsky and V. V. Rozanov, "The physical parameterization of the top-of-atmosphere reflection function for a cloudy atmosphere—Underlying surface system: The oxygen A-band case study," *J. Quant. Spectr. Radiat. Transf.*, vol. 85, pp. 35–55, 2004.

[7] A. A. Kokhanovsky and W. von Hoyningen-Huene, "Optical properties of a hurricane," *Atmos. Res.*, vol. 69, pp. 165–183, 2004.

[8] C. Moroney, R. Davies, and J.-P. Muller, "Operational retrieval of cloud-top heights using MISR data," *IEEE Trans. Geosci. Remote Sens.*, vol. 40, no. 7, pp. 1532–1546, Jul. 2002.

[9] L. R. Poole, D. M. Winker, J. R. Pelon, and M. P. McCormick, "CALIPSO: Global aerosol and cloud observations from lidar and passive instruments," *Proc. SPIE*, vol. 4881, pp. 419–426, 2003.

[10] A. A. Rozanov, V. V. Rozanov, M. Buchwitz, A. A. Kokhanovsky, and J. P. Burrows, "SCIATRAN 2.0: A new radiative transfer model for geophysical applications in the 175–2400 nm spectral region," *Adv. Space Res.*, 2005, to be published.

[11] V. V. Rozanov, T. Kurosu, and J. P. Burrows, "Retrieval of atmospheric constituents in the UV-visible: A new quasianalytical approach for the calculation of weighting functions," *J. Quant. Spectr. Radiat. Transf.*, vol. 60, pp. 277–299, 1998.

[12] V. V. Rozanov and A. A. Kokhanovsky, "Semianalytical cloud retrieval algorithm as applied to the cloud top altitude and the cloud geometrical thickness determination from top-of-atmosphere reflectance measurements in the oxygen A band," *J. Geophys. Res.*, vol. 109, 2004. DOI:10.1029/2003JD004104.

[13] V. V. Rozanov, A. A. Kokhanovsky, and J. P. Burrows, "The determination of cloud top altitudes using GOME reflectance spectra: Multilayered cloud systems," *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 5, pp. 1009–1017, May 2004.

[14] C. Vanbauce, R. Cadet, and R. T. Marchand, "Comparison of POLDER apparent and corrected oxygen pressure to ARM/MMCR cloud boundary pressure," *Geophys. Res. Let.*, vol. 30, 2003. DOI: 2002GL016449.

[15] D. M. Winker, "Global observations of aerosols and clouds from combined lidar and passive instruments to improve radiation budget and climate studies," in *Proc. AMS 10th Conf. Atmospheric Radiation*, 1999, pp. 290–293.

[16] G. Yamomoto and D. Q. Wark, "Discussion of letter by A. Hanel: Determination of cloud altitude from a satellite," *J. Geophys. Res.*, vol. 66, p. 3596, 1961.