ON VISIBILITY THROUGH THE CLOUDS

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The contrast of the objects observed through the clouds is calculated on the basis of the values of transmission and albedo of the plane cloud layer obtained by the Monte Carlo method. It is shown that the large (several kilometers) high–contrast objects can be seen through the continuous cloud layer of optical depths $\tau \le 10$ *while the small (less than* 100 m*) objects can be seen only through the thin upper clouds. The possibility of the observation through the clouds is evaluated by means of an active pulsed vision system. It is possible to observe the large objects from an altitude of* 100 km *through the clouds at* $\tau \approx 30$ *given that the power of radiation is about* 5 MW.

The theory of radiation transfer through the cloud layers with their microstructure, inhomogeneities, and the fluctuations of the optical characteristics taken into account was presented in detail in Ref. 1. However, the exact calculation of the visibility of the real objects through the real clouds is difficult due to the limited amount of experimental data on the cloud microstructure and its variations. Here we consider a simpler problem of evaluating "from above" what can be seen from onboard an aircraft or spacecraft through the continuous cloud layer. In addition, we keep in mind that the optical depth of the clouds τ has been most extensively studied.[2–5] According to the data obtained in Refs. 2 and 3 the value of τ of the one–layer lower and middle clouds lies within the limits 5 ... 70 with the mean value $\bar{\tau} = 20$. For the multilayer clouds τ can reach several hundreds, while for the upper clouds τ does not exceed several units.[4] The measurements of the optical depth of the clouds over the ocean performed in Refs. 5 and 6 over a period of many years showed that the clouds over the ocean have, on the average, much more better transparency than the clouds over the dry land. For example, according to the measurements performed over the Atlantic ocean, $\tau \le 6$ with the probability $P = 20\%$, $\tau \le 15$ with $P = 50\%$, and $\tau \le 25$ with $P = 80\%$, whereas over the dry land the optical depths corresponding to the same probabilities are 30, 50, and 90.

Let us write down the well–known relation for the visible contrast in the observation of the infinite plane with the spatial frequency of the elements ν through the layer of the scattering medium[7]

$$K = K_0\, k(\nu)/(1 + B_h/\bar{B}), \tag{1}$$

where $K_0 = (R_{ob} - R_{bg})/(R_{ob} + R_{bg})$ is the real contrast between the object and the background with the reflection coefficients R_{ob} and R_{bg}, respectively; $k(\nu)$ is the frequency–contrast characteristic (FCC) of the scattering layer, B_h is the haze brightness (backscatter interference), $\bar{B} = 0.5\,(B_{ob} + B_{bg})$ is the mean brightness of the image disregarding the haze. With natural illumination at the solar zenith angle θ for the observation through the clouds in the nadir direction $B_h = RE/\pi$ and $\bar{B} = \bar{R}T(\mu)T(1)E/\pi$, where R is the cloud albedo; E is the irradiance on the upper boundary of the cloudiness; $T(1)$ and $T(\mu)$ are the transmissions of the cloud layer for $\cos\theta = 1$ and $\cos\theta = \mu$, respectively; and, $\bar{R} = 0.5\,(R_{ob} + R_{bg})$. Then Eq. (1) assumes the form

$$K = K_0 k(\nu)/[1 + R/(\bar{R}T(\mu)T(1))]\ . \tag{2}$$

The formulas for calculating the transmission and albedo of the weakly absorbing layers[8] can be used to find R and T of the optically dense layers (τ 5)

$$T(\mu) = g(\mu)\ \mathrm{sh}\,y/[\mathrm{sh}(x + y)]\ , \tag{3}$$

$$y = 4q\sqrt{\frac{1 - \mathrm{L}}{q\mathrm{L}}}\ ,\ x = \sqrt{\frac{1 - \mathrm{L}}{q\mathrm{L}}}\ \tau\ ,\ g(\mu) = \frac{1}{3} + \mu\ ,$$

$$q = 1/(3 - x_1)\ ,\ R(\mu) = \mathrm{e}^{-y} - T(\mu)\mathrm{e}^{-x-y}\ , \tag{4}$$

where x_1 is the first term in the expansion of the scattering phase function in the system of the Legendre polynomials and Λ is the single–scattering albedo.

We calculated the functions $T(\tau)$ and $R(\tau)$ by the Monte Carlo method at $\tau = 0$ ... 40 for $\Lambda = 0.995$, 0.998, and 1.0 (Λ of the real clouds varies within these limits according to the data of Ref. 3) and Deirmendjian's C1 scattering phase function ($x_1 = 2.565$) at several solar zenith angles ($\mu = 1$, 0.9, 0.7, and 0.5). The calculation was made by the direct simulation method. The algorithm was improved with the help of different procedures (in particular, by means of the special preparation of the scattering phase function) in such a way that the efficiency of calculation substantially increased. The error in the simulation did not exceed 3%. Some results are presented in Table I.

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TABLE I. Transmission (T) and albedo (R) of the plane cloud layer (calculation by the Monte Carlo method).

τ	Λ = 1		Λ = 0.995			
	μ = 1	μ = 0.5	μ = 1		μ = 0.5	
	T	*T*	*T*	*R*	*T*	*R*
1	0.959	0.842	0.955	0.040	0.843	0.154
2	0.909	0.730	0.899	0.089	0.714	0.262
3	0.858	0.649	0.842	0.137	0.628	0.337
4	0.809	0.591	0.788	0.182	0.565	0.390
5	0.769	0.544	0.743	0.219	0.514	0.432
7	0.687	0.472	0.650	0.292	0.435	0.494
10	0.596	0.400	0.545	0.366	0.354	0.552
12	0.547	0.364	0.486	0.405	0.313	0.579
14	0.502	0.333	0.434	0.438	0.277	0.602
16	0.465	0.306	0.388	0.463	0.246	0.619
18	0.437	0.284	0.351	0.482	0.220	0.633
20	0.408	0.265	0.317	0.498	0.198	0.644
30	0.309	0.198	0.195	0.545	0.120	0.674
40	0.244	0.158	0.122	0.564	0.074	0.685

Note: For Λ = 1 the sum $R + T = 1$ at each τ.

The comparison of the results of calculations by the Monte Carlo method and from Eqs. (3) and (4) shows that they have sufficiently high accuracy at large τ. The error in the calculation of the transmission from Eq. (3) is $\delta \le 12\%$ at $\tau \ge 5$ and $\delta \le 5\%$ at $\tau \ge 15$ and it decreases at larger τ with growth of the incidence angle θ. The error in calculation of the albedo from Eq. (4) is $\delta \le 20\%$ at $\tau \ge 5$. Formulas (3) and (4) are found to be unsuitable for calculating T and R at small $\tau \le 3$ since they can yield $T > 1$ and negative R. Let us calculate the visibility of the objects through the continuous cloud layer using the values of T and R from Table I and Eq. (2). As far as we evaluate "from above", let us take the most favourable conditions of observation: the highest real contrast K_0 and the largest objects ($k(\nu) \equiv 1$). Let us consider two cases: light sand ($R_{ob} = 0.3$) and green ($R_{ob} = 0.1$) against the background of water ($R_{bg} = 0.05$). In the first case $\overline{R} = 0.175$ and $K_0 = 0.71$ while in the second case $\overline{R} = 0.075$ and $K_0 = 0.33$.

The results of calculation of the contrast from Eq. (2) are shown in Fig. 1. We must know the threshold contrast sensitivity (K_{th}) of the photodetector (or the eye) in order to estimate the visibility range. It is obvious that for the objects observed through such an inhomogeneous and fluctuating background as cloud layer, K_{th} is greater than $K_{th}^{(0)} \cong 0.01$, which is used in the observation without fluctuations.

We will set the coefficient of signal variation α to be equal to 0.1, which is quite arbitrary and can be significantly greater under the unfavourable conditions of observations. In this case (for $\alpha \gg K_{th}^{(0)}$) the threshold contrast sensitivity $K_{th} \approx \alpha \approx 0.1$ (see Ref. 7). Thus, as can be seen from Fig. 1, under favourable conditions of observation (small solar zenith angle and not very great (< 10%) fluctuations of the cloud albedo) the lightest large objects with high initial contrast (sand against the background of water) can be seen through the relatively thick clouds ($\tau < 10$) while darker objects (green) can be seen only through the upper clouds ($\tau < 3$).

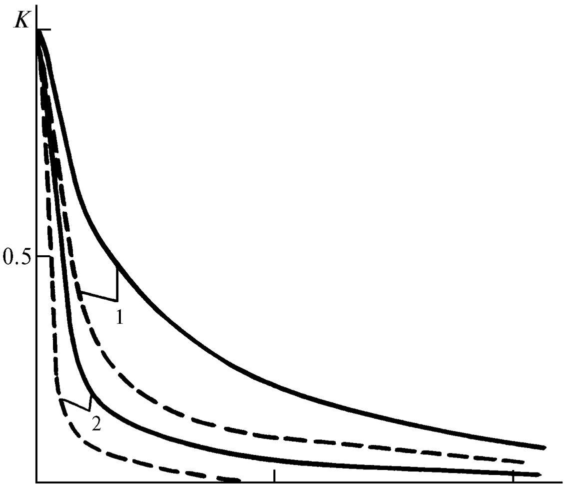

FIG. 1. The contrast of the large objects observed through the continuous cloud layer as a function of its optical depth τ for μ = 1 and Λ = 1 (solid lines) and μ = 0.5 and Λ = 0.995 (dashed lines): 1) sand and 2) green against the background of water.

The natural question arises: what objects can be considered large, i.e., at which spatial frequencies ν can one assume $k(\nu) \equiv 1$? Figure 2 represents the FCC calculated from the following relations[1,7]:

$$k(\nu) = k_{hg}(\nu, z_0 + H)/k_{hg}(\nu, H)\,, \tag{5}$$

$$k_{hg}(\nu, z) = \exp\left[-\sigma z\left(1 - \frac{1}{\tilde{\nu}}\ln\left(\tilde{\nu} + \sqrt{1 + \tilde{\nu}^2}\right)\right)\right] \tag{6}$$

as a function of the element size $d_{el} = 1/2\nu$, where z_0 is the depth of the cloud layer, H is the height of its lower boundary, σ is the scattering coefficient of the cloudy medium, $\tilde{\nu} = 2\pi z\nu a^{-1} = 2\pi z(d_{el}\, a)^{-1}$ is the normalized spatial frequency (a is the parameter of fitting the scattering phase function by the function $\exp(-a\theta)/\theta$).

Formula (5) describes the FCC of the layer–gap system, i.e., of the scattering layer at a distance H from the observed object, and formula (6) describes the FCC of the homogeneous layer of the scattering medium (at $H = 0$). In calculation from Eqs. (5) and (6) we set $\sigma = 16\ \text{km}^{-1}$ that corresponds to Deirmendjian's $C1$ cloud.[9] The parameter a of this model was calculated directly from the scattering phase function and appeared to be equal to 4.7. Calculations were made at several $\tau = \sigma z_0$ for two ratios between H and z_0: $H/z_0 = 0.25$ and 1.0.

It can be seen from the figure that the objects whose characteristic size is 0.1 – 0.5 km can be assumed large for optically thin layers (τ = 1–2), and those whose size is 1–5 km – for thicker clouds (τ = 5–10). Thus, the objects whose characteristic size is several kilometers can be seen through the continuous cloud layer at τ up to 10 (Fig. 1). The oral report of cosmonaut O.G. Makarov, in which he said that he distinctly saw the Volga when the cloud cover index was equal to 10, is in agreement with this statement.

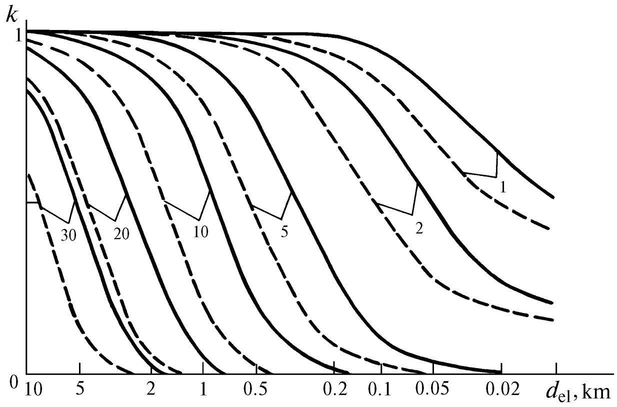

FIG. 2. The frequency–contrast characteristics of the cloud layer for σ = 16 km^{-1} *and* H/z_0 = 0.25 *(solid lines) and* 1.0 *(dashed lines). The numbers adjacent to the curves indicate the optical depth of the cloud* $\tau = \sigma z_0$.

Figure 3 illustrates the visibility range of the small objects through the cloud layer. The dashed curves are for the elements with the spatial frequency ν_a corresponding to the asymptotic value $k_{hg} = \exp(-\tau)$. It is easily to verify that such values of ν correspond to the characteristic size of the elements of the order of 1 m in our case. We note that for $k_{hg} = \exp(-\tau)$ the FCC $k(\nu) = k_{hg}(\nu)$ and it is independent of the cloud height H. It can be seen from Fig. 3 that small (< 100 m) objects can be seen only through thin upper clouds.

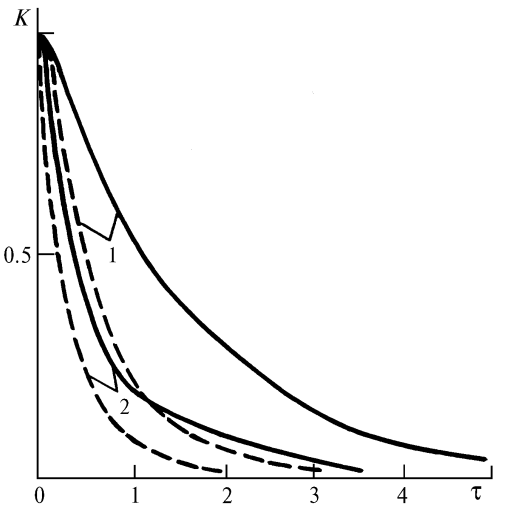

FIG. 3. The contrast of the small objects observed through the continuous cloud layer as a function of its optical depth τ *for* $\mu = 1$, $\Lambda = 1$, *and* d_{el} = 0.1 km *(solid lines) and* $d_{el} \to 0$ *(dashed lines): 1) sand and 2) green against the background of water.*

In conclusion we evaluate the possibility of observation through the clouds with the help of the active vision system with pulsed illumination. The well–known method of pulse gating[7] (the receiver is turned off until the short light pulse propagates from the transmitter to the object and backward, and is turned on at the instant of arrival of the reflected pulse at the receiver) makes it possible to get rid of the backscatter interference almost completely. In this case we may set $B_h = 0$ in Eq. (1), i.e.,

$$K = K_0 k(\nu) . \tag{7}$$

It can be seen from Fig. 2 that sufficiently high contrast is achieved in observation of the large objects (1 km < d_{el} < 10 km) with the help of the pulsed system not only at $\tau = 10$ but also at $\tau = 20$ and even at $\tau = 30$ (for d_{el} > 5 km). However, in this case the maximum visibility range is determined by the energy sensitivity of the system, i.e., by the signal–to–noise ratio. This ratio is given by the formulas[7]

$$\delta = \delta_0 / \sqrt{1 + \alpha^2 \delta_0^2 / 4K^2} , \tag{8}$$

$$\delta_0 = K \sqrt{2W\eta_{ph}/e_e} ; \tag{9}$$

$$W = \frac{W_0 T^2 \bar{R}\, \Sigma_r\, \beta^2}{\pi [L\beta + (z_0 + H)\bar{\theta}]^2} . \tag{10}$$

Here δ_0 is the signal–to–noise ratio determined solely by the shot photocurrent fluctuations, i.e., without external noise ($\alpha = 0$), W is the mean energy at the photocathode of the receiver, η_{ph} is the photocathode sensitivity, $e_e = 1.6\cdot10^{-19}$ C is the charge of electron, W_0 is the initial energy of the light pulse, Σ_r is the area of the input pupil of the receiver objective multiplied by its transmission, 2β is the angle of radiation equal to the angle of the field of view of the receiver, $\theta = 52°$ is the mean angle of photon exit from the cloud,[10] L is the distance from the observational system to the upper boundary of the cloudiness. As can be seen from Eqs. (8)–(10), the higher is the energy of the initial pulse, the greater is the value of δ_0. However, for W_0 and δ_0 as great as is wished when the contrast $K \approx \alpha/2$ the signal–to–noise ratio is less than unity. Therefore, the observation with the help of the pulsed system is possible only for sufficiently high contrasts. In order to evaluate the possibility of the observation through the cloud with the pulsed illumination we may set the threshold value of the signal–to–noise ratio δ_{th} and, by replacing δ by δ_{th} in Eq. (8), to solve it for the energy W_0 on account of Eqs. (7), (9), and (10). The results of this calculation for the following conditions: η_{ph} = 0.04 A/W ($\approx$ 100 μA/lm); the input pupil is 200 mm in diameter; the same observed objects (sand and green); the height L = 1, 100, and 300 km; $z_0 + H$ = 1–5 km; the angle β = 0.01,...,0.1; and, δ_{th} = 2 are presented in Table II.

The values of T were taken from Table I. The values of the power of the initial pulse P_0 (in MW) of duration Δt = 10 ns ($P_0 = W/\Delta t$) are written down in the last column of the table. The lower values of W_0 and P_0 are for the light objects (sand), and the upper ones – for the dark objects (green).

TABLE II. The pulse energy and power needed for observation through the cloud layer

L, km (d_{el}, km; α)	τ	$z_0 + H$, km	W_0, J	P_0, MW ($\Delta t = 10$ ns)
300 (5; 0.03)	20	< 2	0.01 … 0.05	1 … 5
		5	0.02 … 0.1	2 … 10
	30	< 2	0.03 … 0.15	3 … 15
		5	0.07 … 0.35	7 … 35
100 (5; 0.1)	20	< 2	0.0015 … 0.0075	0.15 … 0.75
		5	0.002 … 0.01	0.2 … 1
	30	< 2	0.004 … 0.02	0.4 … 2
		5	0.007 … 0.035	0.7 … 3.5
1 (0.5; 0.01)	20	< 2	0.002 … 0.01	0.2 … 1
		5	0.01 … 0.05	1 … 5
	30	< 2	0.01 … 0.05	1 … 5
		5	0.07 … 0.35	7 … 35

It can be seen from Table II that the high pulse power is necessary for observation through the clouds. If the maximum power of the pulsed system is assumed to be $W_0 = 5$ MW, the observation of the objects whose characteristic size is about 5 km through the clouds with the help of such a system for $L = 300$ km is possible only at $\tau \le 20$ for $z_0 + H < 2$ km and for $L = 100$ km – at $\tau \le 30$. The observation of the objects whose size is about 0.5 km from onboard the low–flying aircrafts is possible at $\tau = 5$–10 for $z_0 + H < 2$ km.

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