PHOTOMETRIC DETECTION OF CLOUDS ALONG THE INSTRUMENT SIGHTING LINE

V.K. Oshlakov

Institute of Atmospheric Optics, Siberian Branch of the Academy of Sciences of the USSR, Tomsk
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This paper analyzes observational data on zenith sky brightness within three spectral ranges around $\lambda_1 = 0.42$ μm, $\lambda_2 = 0.53$ μm, $\lambda_3 = 0.69$ μm. A possibility of detecting a cloud of any type at zenith from the position of its chromaticity point in the tricolor diagram is demonstrated.

When interacting with the earth's atmosphere, optical radiation alters its own parameters: amplitude, frequency, direction of propagation, and degree of polarization. Suffering these various changes, the radiation accumulates information on the optical characteristics of the medium it propagates through, in particular, on the characteristics of aerosol and cloud fields. Rapid identification of clouds in the sensing beam paths, and retrieval of their parameters from the results of optical observations are one of the crucial problems of atmospheric optics.[1] The possibility of solving this problem employing means and techniques of passive sensing in the visible spectrum constitutes the subject matter of the present article.

By analyzing spectral luminance distributions from cloudy and cloudless skies (e.g.. Refs. 2 and 3), one concludes that the differences in such distributions can be considered a source of information for solving this and other related problems. In the present paper we analyze results from luminance observations of cloudy and cloudless skies in the Southern Balkhash Lake region. Measurements were conducted using the spectrophotometer described in Ref. 4 ($\lambda_1 = 0.42$, $\lambda_2 = 0.53$, $\lambda_3 = 0.69$ μm, field of view of about 5 arcmin). This is a spectrozonal instrument recording the incoming radiation spectra in several spectral zones. All in all, 40 realizations, each 3.5 hour long, were analyzed at a temporal resolution of about 15–20 seconds.

The results from processing these data are presented in the tricomponent diagram (TCD) as chromaticity point coordinates m, n, l, defined in terms of the color-separated signals

$$m = U_1/T; \; n = U_2/T; \; l = U_3/T; \; T = U_1 + U_2 + U_3, \quad (1)$$

where U_i (i = 1, 2, 3) is the output signal of the integrating photoelectric converter; T is the total signal. For narrow spectral ranges U_1 can be written as

$$U_1 = k \cdot G(\lambda_1)\tau_f(\lambda_1)\tau(\lambda_1)W(\lambda_1), \quad (2)$$

where k is the recording device sensitivity; λ_1 is the wavelength; $G(\lambda_1)$, $\tau_f(\lambda_1)$, $\tau(\lambda_1)$, and $W(\lambda_1)$ are the spectral parameters of the photoconverter, the spectrozonal filter, the target under study, and the incident radiation, respectively. Each element in the TCD was demonstrated[5] to affect all the variations in spectral characteristics, provided they do not displace that element in the system chosen for assessing spectrozonal distribution of radiation energy. If the spectral characteristics of the converter and filters remain unchanged, then, following (1) and (2), variations in chromaticity coordinates would result from changes in spectral characteristics of the target under study; indeed, relationship (1) does not depend on the detector sensitivity.

Variations in spectral characteristics of the atmosphere as a scattering medium are known to relate to changes in the type of radiation scattering particles, their number density and size. Scattering properties -of air molecules and other, larger particles, such as aerosols, cloud particulate matter, ice crystals, differ from each other. That is why clouds in the atmosphere generally seem white against the background of the blue sky. When clouds are present, white light scattered by clouds contaminates blue radiation coming from cloudless skies and the latter becomes different from the 'base of pure Rayleigh scattering.[6] Using tabulated values of the spectral solar constant, e. g. Ref. 7, one can compute the chromaticity coordinates for a given set of wavelengths, and then use them as a TCD reference point to characterize aerosol scattering. The second such reference point might be the chromaticity coordinates for pure Rayleigh scattering.

By a preliminary classification of situations relating to various cloud types, we applied a conditional scale and employed in it the optical characteristics from the cloud classification presented in Ref. 8 (by color and transparency): a is a clear sky, haze; b is a veil; c are white or bluish homogeneous thin clouds (no greyish shades); d refers to grey veil,

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grey cloud bottoms, the Sun shines through as through a milky glass; *e* refers to grey dense clouds, the Sun does not shine through.

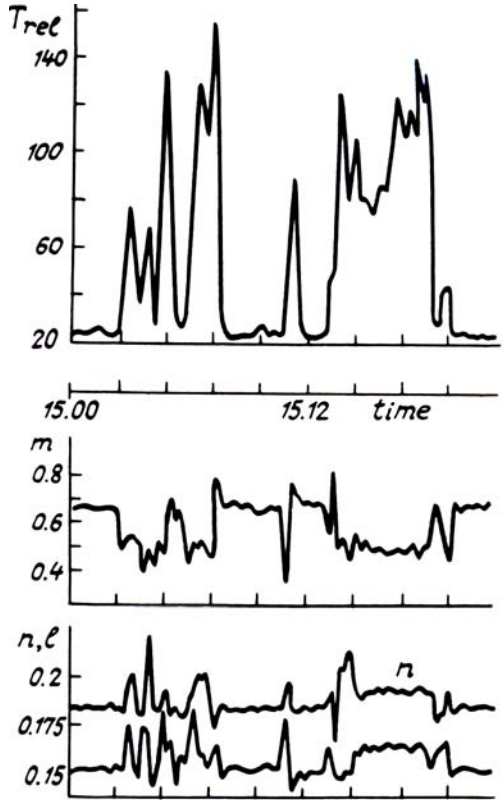

FIG. 1. Temporal variability of chromaticity coordinates and of the total luminance signal from Cu clouds passing through zenith (partial realization)

Figure 1 illustrates the character of changes in chromaticity coordinates and in the total signal during passage of Cu clouds across the zenith. Figure 2 gives the averaged values of chromaticity coordinates (more than 120 points all in all); preliminary classification zones are shown in the ml plane.

Averages were calculated for sets corresponding to the situations described above. The averaging interval varied from 15 minutes to three hours, depending on the stability of the situation. The diagram gives the coordinates of the reference points: squares refer to Rayleigh scattering; circles-to energy distribution in the solar spectrum; triangles-to the most probable values of chromaticity coordinates for cloud cover and breaks in cloud cover; a local distribution was processed taking a realization of May 23, 1989 (Fig. 3, Cu clouds). According to a visual estimate they were white clouds with bluish- grey bottoms, observed against the background of a blue sky; the Sun was able to shine through cloud edges. This example refers to a single-layer cloud realization. When several layers of clouds are present, and the upper layer clouds can be seen through breaks in the lower and/or middle cloud canopy, a multi-modal distribution is observed. with its separate modes occupying adjacent areas as demonstrated in Fig. 2.

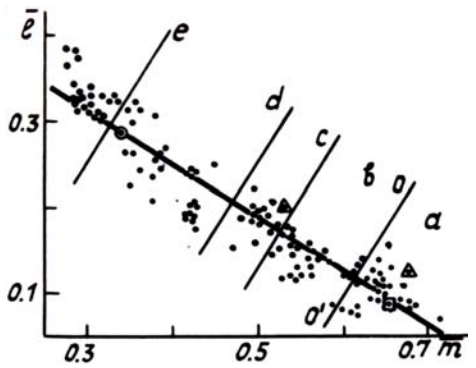

FIG. 2. Average values of the zenith chromaticity coordinates for various situations: a) clear sky; b) veil; c) white or bluish homogeneous thin veil, white clouds (no greyish shades); d) grey veil, grey cloud bottoms, the Sun shines through as through milky glass; e) grey dense clouds, the Sun does not shine through.

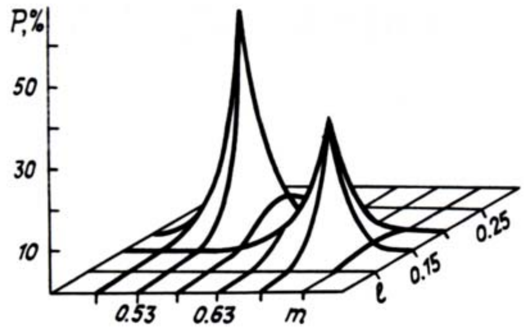

FIG. 3. The zenith chromaticity coordinates probability distribution in the presence of Cu clouds.

The possibility of distinguishing between objects leaving close color characteristics is determined by the color threshold of the system. When analyzing the actual target TCD distributions, the notion of the color contrast ρ_c is employed. This contrast is defined with respect to the target background. Geometrically it means the distance between the areas of different types, e.g., in the (*ml*) plane

$$\rho_c(\bar{m}\ \bar{l}) = [(\bar{m} - \bar{m}_f)^2 + (\bar{l} - \bar{l}_f)^2]^{0.5}. \quad (3)$$

Tables I, II, and III present the color contrasts for adjacent areas on an arbitrary scale (Fig. 2) for various combinations of average chromaticity coordinates $\bar{m}$, $\bar{n}$, $\bar{l}$.

If the system color threshold is known, one can find from tables, similar to Tables I, II, and III, which-of the actually observed situations can be differentiated by the system. Figure 2 also demonstrates the regression line computed from the total ensemble of color coordinates. With a 95 % probability the linear correlation coefficients fall into the ranges: $R_m = (-0.82...-0.9)$, $R_{ml} = (-0.9...-0.98)$,

$R_{nl} = (-0.18...+0.2)$. One should recall that the data presented here refer to projections of chromaticity points from three-dimensional space m, n, l. Retrieval of the type and character of the distribution for the multitude of points reflecting both color and spectral characteristics of daytime sky in this space presents an interesting separate problem. Meanwhile, let us only point out the linear character of the mutual positions of the projections of chromaticity points upon the ml plane.

TABLE I

Color contrast $\rho_c(\bar{m}, \bar{n})$

	$\bar{a}$	$\bar{b}$	$\bar{c}$	$\bar{d}$	$\bar{e}$
$\bar{a}$	0				
$\bar{b}$	0.08	0			
$\bar{c}$	0.14	0.06	0		
$\bar{d}$	0.3	0.2	0.14	0	
$\bar{e}$	0.35	0.27	0.21	0.08	0

TABLE II

Color contrast $\rho_c(\bar{m}, \bar{l})$

	$\bar{a}$	$\bar{b}$	$\bar{c}$	$\bar{d}$	$\bar{e}$
$\bar{a}$	0				
$\bar{b}$	0.09	0			
$\bar{c}$	0.17	0.08	0		
$\bar{d}$	0.29	0.27	0.13	0	
$\bar{e}$	0.41	0.32	0.24	0.12	0

TABLE III

Color contrast $\rho_c(\bar{n}, \bar{l})$

	$\bar{a}$	$\bar{b}$	$\bar{c}$	$\bar{d}$	$\bar{e}$
$\bar{a}$	0				
$\bar{b}$	0.05	0			
$\bar{c}$	0.10	0.05	0		
$\bar{d}$	0.18	0.13	0.08	0	
$\bar{e}$	0.25	0.20	0.15	0.09	0

Let us also note the possibility of applying the dichotomy principle to our analysis. It consists of dividing the TCD into two half-planes, corresponding to "cloudy" and "cloudless" situations, regardless of the form and type of clouds.

Division of the color space into two subspaces is done by means of color filters,[5] their principal parameters being the shape and size of their spectral windows. These filters are described by two-valued predicates [Pr]. For a window of simple shape in the (ml) plane the [Pr] is written as

$$Y_j(ml) = \bigwedge_{1=1}^{k}\left[a_{1j}^{1}\, U_1 + a_{2j}^{1}\, U_3 + a_{3j}^{1}\, T > 0\right] = 1. \quad (4)$$

Here $k = 3$ is for a triangular window, $k = 4$ is for a quadrangular window; $k = 1$ is for the separating line; $a_{1j}^1, a_{2j}^1, a_{3j}^1$ are coefficients to describe position of the lines forming the window in the plane; $U_{1,2,3}$ is the color-separated signal and T is the total signal; [Pr] is the representation relating a certain function to the predicates, such that $Y(ml) = 1$ for true, $Y(ml) = 0$ for false ones. In our situation, the separation into "cloudless" and "cloudy" sky classes can be written in the form

$$Y(ml) = \left[0.25m - 0.14l + 0.17 > 0\right] = 1, \quad (5)$$

Here $Y(ml) = \begin{cases} 1 - \text{cloudy} \\ 0 - \text{cloudless} \end{cases}$.

The position of the line in Fig. 2 is presented by points 00′.

Note that the position of the TCD dividing line and the formulation of the decision rule depend on the needs of the information user.

In the course of analyzing the technique capabilities and measurement results, linear decision rules using triangular and rectangular window contours with various orientations of their TCD plane were also tested. No basic difficulties were encountered. However, statistically significant amounts of information on each chromaticity class are needed for valid conclusions.

To assess rapidly the functioning conditions for an optical system, the decision-making rule (5) and a qualitative estimate of the optical situation (Fig. 2) were employed. In particular, we determined the probability for the sighting line to be obscured. For that purpose we performed the ratio calculation of the number of cases $Y(m, l) = 1$ from temporal series of chromaticity coordinates from a given direction to the total number of observations to obtain the probability of clouds of any type along the sighting line. For example, for the situation shown in Fig. 3 the probability of zenith coverage by clouds is about 0.7, and, conversely, that of a cloudless situation – 0.3.

Thus, the application of algorithms and techniques from coloristics for target classification in terms of their color characteristics has produced a decision rule to identify the presence of clouds along the sighting line from the position of its chromaticity point in the TCD. The possibility of retrieving the probability of coverage/openness of separate sighting lines from photometric results with the help of this rule has been demonstrated

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