A TECHNIQUE FOR RETRIEVING THE ATMOSPHERIC TRANSMITTANCE FROM DATA ON THE SEA HORIZON BRIGHTNESS

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A technique is discussed for interpreting data on the sea horizon brightness, to operationally retrieve the extinction coefficient of air. Estimates of the accuracy of the technique are presented as well as the results of field experiments, and are compared with the results of photometric measurements of the atmospheric transmittance.

The necessity of obtaining the most complete data on the optical parameters of the marine aerosol and of developing a technique by which to operationally determine the level of atmospheric pollution (from the transmittance of the atmosphere and the visibility) have contributed to the development of remote sensing techniques suitable for application at sea. As has been indicated by previous studies,[1] the method for determining the horizontal transmittance from the degree of blurring of the horizon is fairly effective at sea. The method is technically realized in a special measuring device with a built-in microprocessor which makes it possible to realize a more effective technique in comparison with the one described in Ref. 1 of interpretation of the measurement data for the purpose of retrieving the sought-after parameter from the angular distribution of the sea horizon background brightness. The present paper briefly describes this technique and also the estimates of the effectiveness of its application as a function of measurement conditions.

The basic equation for solving our problem is the equation of passive remote sensing, which describes the background brightness at the horizon and below it, which may, with the Earth's sphericity and refraction taken into account, be written as[1]

$$B(\varphi) = B_m(\varphi)\exp\left[-\alpha l(\varphi)\right] + B_0\left[1 - \exp\left[-\alpha l(\varphi)\right]\right]; \quad (1)$$

$$l(\varphi) = R\varphi + (2Rh)^{1/2} - \left[(R\varphi)^2 + 2Rh\sqrt{2Rh}\right]^{1/2}. \quad (2)$$

Here $l(\varphi)$ is the distance from the sea surface at the sighting angle φ; d is the average atmospheric light attenuation coefficient along the beam path above the sea; h is the height of the observation point; $R = R_0(1 - k)$; R_0 is the average radius of the Earth; k is the average refraction coefficient; B_0 is the sky brightness immediately above the horizon; $B_m(\varphi)$ is the sea surface brightness, as yet unknown.

To retrieve the attenuation coefficient a from measurements of the background brightness $B(\varphi)$ (1), the problem has to be additionally determined (with the φ-dependence of $B_m(\varphi)$ represented parametrically). It was shown in Ref. 2 that in the range of sounding angles $\varphi \le 3°$ the sea brightness can be described by the empirical relation

$$B_m(\varphi) = \gamma B_0\left[1 - \exp(-\beta\varphi)\right] \quad (3)$$

with the as-yet undefined parameters j and β. This relation offers the possibility of estimating both the atmospheric transmittance and the intrinsic sea brightness undistorted by the atmosphere. Such a representation is also of interest for studies of the sea roughness and the surface wind velocity, which affect the sea brightness at glancing observation angles. The least squares technique and the optimal parametrization technique developed in Ref. 3 can both serve as the theoretical basis for interpreting the measurement data (1).

As applied to our problem, the mean points of the latter technique[3] consist in the following.

The sea horizon background brightness is taken to be a function of the known parameters $\{\alpha, \beta, \gamma\}$ which belong to the space P, such that the set of these functions forms a parametric family U with domain of definition P. The interpretation of the series of angular measurements $B_j^* = B^*(\varphi_j)$, $j = 1, 2, \ldots, n$, can then be thought of as the determination of the point $p^* \in P$ whose coordinates satisfy the system of nonlinear equations $B(\varphi_j, \rho) = B_j^*$; the point p^* can then be thought of as the approximate solution of the problem that provides the best approximation of the data set $\{B_j^*\}$ from among the functions of the family U. This result is achieved by minimizing the quadratic functional

$$\Phi(p) = \sum_{j=1}^{n} q_j\left[B(\varphi_j, p) - B_j^*\right]^2 \quad (4)$$

over the domain P. The weight factors q_j in Eq. (4) are connected with σ_j^2, the variance of the error of the j-th measurement. The quantity $\Phi^* = \Phi(p^*)$ defines the distance of the vector B^* from the family U, and can be thought of as the error in approximating the function $B^*(\varphi)$ by the functions from the family U and is a measure of the agreement between the initial parametric model and the given experiment.

Let us now consider the question of the information content of such an experiment with respect to the sought-after parameters $\{\alpha, \beta, \gamma\}$ taking into account the errors ξ_j in the measurements of $B^*(\varphi_j)$. It can be shown that the error of estimating one of the parameters, e.g., α, from the condition that $\Phi(\tilde{p})$ be a minimum is estimated by:

$$\varepsilon_\alpha L(B,\alpha) \le \sigma_0, \tag{5}$$

where

$$\varepsilon_\alpha = (\overline{\Delta\alpha^2})^{1/2}/\alpha; \quad \sigma_0 = \max(\overline{\xi_j^2})^{1/2};$$

$$L^2(B,\alpha) = \sum_{j=1}^{n} (\partial B_j/\partial(\ln\alpha))^2.$$

It follows from Eq. (5) that in the presence of measurement errors the retrieval error for the attenuation coefficient ε_α is determined both by the value of σ_0, i.e., the level of measurement error and by the choice of the parametric model, characterized by the functional $L(B, \alpha)$. The value of this functional determines the sensitivity of the model (1) to variations of the parameter α at the point p and serves as an estimate of the information content of the experiment with respect to the parameter α.

Table I presents examples calculations of the values of $L^{-1}(B, \alpha) \times 10^2$ (numerator) and $L^{-1}(B, \beta) \times 10^2$ (denominator) for various values of α and β corresponding to typical situations observed in the experiments.

TABLE I

β	α									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	1.91/3.97	1.53/4.82	1.42/5.80	•1.41/6.92	1.44/8.22	1.50/9.71	1.59/11.4	1.69/13.4	1.80/15.7	1.94/18.3
2	2.05/4.83	1.68/6.22	1.57/7.84	1.56/9.74	1.60/12.0	1.67/14.6	1.76/17.6	1.87/21.5	2.01/25.3	2.16/30.2
3	2.14/6.26	1.77/8.60	1.65/11.5	1.65/15.0	1.69/19.3	1.75/24.4	1.84/30.6	1.96/38.0	2.09/46.8	2.24/57.3
4	2.20/7.75	1.83/11.3	1.71/16.0	1.69/22.0	1.73/29.6	1.79/39.0	1.88/50.9	1.99/65.4	2.12/83.3	2.28/105

The height of the observation point h was 37 m, and the average refraction coefficient was 0. 15. It can be seen from the table that the experiment is mainly informative with respect to the attenuation coefficient α, independent of the chosen point (α, β). On the other hand, $L^{-1}(B, \beta)$ and, consequently, the information content with respect to parameter β substantially depend on the position of the point (α, β) and are comparable to the value of $L^{-1}(B, \alpha)$. With increasing atmospheric turbidity the information content of the measurements with respect to the parameter β, which characterizes the sea brightness, decreases significantly (by an order of magnitude or more).

The considered technique was used to develop operational estimation algorithms for the air attenuation coefficients and the sea brightness, based on the minimization of the functional (4) over the sought-after parameters. The choice of the concrete numerical minimization algorithms was determined by the possibilities of their effective use in the instrumental realization of the measurement setups. Several direct-search algorithms (the Nelder-Meed and Hook-Jeaves approaches) were compared with the gradient algorithms (Fletcher-Reaves and Davidon-Fletcher-Powell).[4] All of these were used to search for the minimum of the functional (4) over both the measured and the modeled sea horizon background brightnesses. As a result, a coordinate-by- coordinate minimization algorithm combining the methods of the variable-step direct search and the quadratic interpolation approach (Powell) was chosen. It is faster than the Nelder-Meed and Hook-Jeaves methods by about an order of magnitude. The gradient methods require larger computer memory and display a higher sensitivity to the choice of the initial point during the search for the solution.

The above-developed technique was applied to the processing of a set of sea horizon brightness measurements. The measurement were carried out in the Crimea with the observation point located 37 m above sea level. The sea roughness varied from 0 to 3 balls, and the attenuation coefficient, obtained using the base method, varied from 0.08 to 0.4 km.$^{-1}$

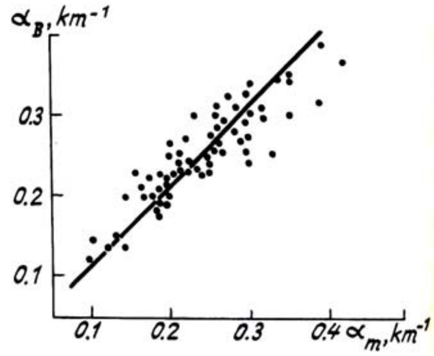

FIG. 1. Regression of the attenuation coefficients α_m *obtained by minimizing the discrepancy functional (4), to the attenuation coefficients* α_B *determined by the base method.*

Figure 1 compares the attenuation coefficients α_B retrieved by the base method and α_M obtained by the proposed technique. The mean level of discrepancy of the retrieved values of the attenuation coefficient α_M was 3%. As for the results shown in Fig. 1, the correlation between α_B and α_M is equal to 0.85, and the corresponding regression equation has the form: $\alpha_M = (1.055\ \alpha_B - 0.3) \pm 0.038$.

REFERENCES

1. M.V. Kabanov and S.M. Sakerin, Izv. Vyssh. Uchebn. Zaved., Ser. FAO **19**, No. 2, 147 (1983).
2. M.V. Kabanov and S.M. Sakerin, *Abstracts of Reports of the Third All-Union Conference on Atmospheric Optics and Actinometry*, Part 1, Tomsk Affiliate, Siberian Branch, USSR Acad. Sci., 147 (1983).
3. V.V. Veretennikov and I.E. Naats in: *Lidar Sounding of the Atmosphere*, ed. V.E. Zuev (Nauka, Moskow, 1976).
4. B. Bandi, *Optimization Methods*: *Introductory Course* (Radio i Svyaz', Moscow, 1988).