MODELING OF THE DISTRIBUTION OF THE NEAR-IR ATMOSPHERIC TRANSMISSION

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Received April 2, 1990

An algorithm for constructing a model of the distribution function of the transmission of the , layer of the atmosphere near the ground for radiation at the wavelength λ = 1.064 μm *is studied. A model of atmospheric transmission as a function of the meteorological visibility range is developed. It is suggested that Johnson's distribution be used for the meteorological visibility range.*

In solving a wide range of applied problems, connected with laser remote sensing in the layer of the atmosphere near the ground,[1] the effect of the atmosphere on the passage of radiation must be taken into account. The spectral transmission of the atmosphere is a quantitative characteristic of the radiation losses. Modern requirements make it necessary to have climatic data on this geophysical parameter, in particular, its probability distribution. However *in situ* measurements of the IR spectral transmission of the atmosphere, performed in a number of scientific centers in the USSR, are sporadic and cannot be used as a basis for obtaining the corresponding climatic characteristics.

One way to solve this problem is to develop a probability model. The algorithm of such a model is based on two basic assumptions:

– the IR transmission of the atmosphere is estimated using an empirical model, developed based on the results of sporadic experiments, where data from standard meteorological observations are used as the input parameters;

– the climatic data for the meteorological parameters employed are incorporated in the model.

In this paper I examine an algorithm for constructing an analytical model of the probability distribution of the near-IR transmission of the layer of the atmosphere at the ground (AT), for radiation with the wavelength λ = 1.064 μm. The radiation with wavelengths near λ = 1.064 μm is generated by YAG lasers, which are widely employed in infrared laser ranging systems.[1]

According to the investigations of Mitsel' et al.,[2] the extinction of radiation from a YAG laser with the wavelength λ = 1.06415 μm owing to molecular absorption in the region of its luminescence band varies in the range 0–20% over a 10 km horizontal path and reaches a maximum at the frequency 9391.96 cm^{-1}. The main absorbing component of the atmosphere is water vapor. The contribution of CO_2 and O_2 can be neglected. At the same time, for this region the contribution of molecular scattering is $8.458 \cdot 10^{-4}$ km^{-1} and is negligible. Therefore, in the transmission microwindows, for example, at λ = 1.0641 μm, extinction is determined primarily by atmospheric aerosol, and the importance of the aerosol increases as the atmospheric turbidity increases.

An empirical relation between the variations of the aerosol extinction coefficient in the near-IR (1.06 μm) and visible (0.55 μm) ranges of the spectrum was established based on experimental data which I obtained in the region of central Povolzh'ye.[3] The relationship, studied graphically, for weather conditions characterized by the absence of hydrometeors or 1ithometeors, is shown in Fig. 1.

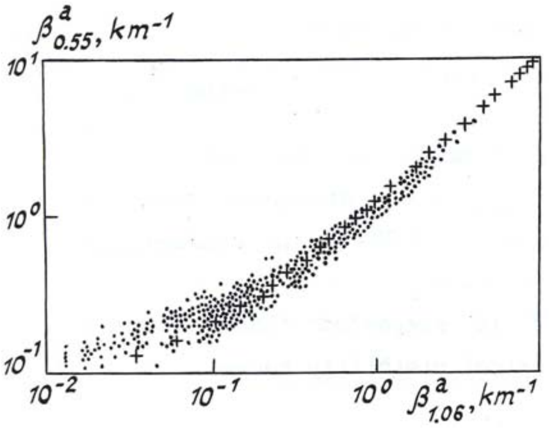

*FIG. 1. Empirical relation between variations of the aerosol extinction coefficient in the near-IR (*λ = 1.06 μm*) and visible (*λ = 0.55 μm*) ranges of the spectrum.*

Under the indicated conditions the dynamics of the optical weather is determined primarily by the condensation process. For this reason, we shall refer to such weather conditions as of the "condensation" type. The experimental data presented in Fig. 1 were used to develop an analytical model. relating the near-IR atmospheric transmission with the meteorological visibility range(MVR):

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$$T_{1.06} = \exp\left(-\beta_{1.06} \cdot L\right) =$$

$$= \exp\left[-\left(\frac{3.689}{S_M} - 0.075\right)^{1.035} \cdot L\right], \qquad (1)$$

where S_M is the MVR (in km) and L is the path length (in km).

The meteorological visibility range is in turn related with the aerosol extinction coefficient $\beta_{0.55}$ by the well-known relation

$$S_M \simeq 3.912/\beta_{0.55}.$$

The computational results obtained using the analytical model (1) are marked in Fig. 1 by the cross marks. They show that the proposed model agrees well with the data obtained in *in situ* experiments.

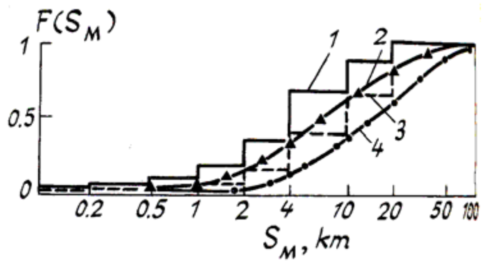

FIG. 2. The integral distributions of MVR under weather conditions of the "condensation" type: 1) empirical (winter); 2) approximation (winter); 3) empirical (summer); and, 4) approximation (summer).

Figure 2 shows the empirical integral distributions of MVR $F(S_M)$ for the region of central Povolzh'ye (the representative station is Gor'kiĭ) for weather conditions of the "condensation" type during winter and summer. The statistical sample of MVR was obtained over a period of ten years of observations.

The optical state of the atmosphere depends on a large number of random processes occurring in the atmosphere. It is natural to conjecture that the resulting effect will be manifested in the form of a normally distributed value of MVR or a modification of the normal distribution.

The MVR distributions presented in Fig. 2 are asymmetric, they are unimodal, they are limited on the left by zero, and in the general case they are unbounded on the right. Operating in correspondence with the method presented in Ref. 4 I find that Johnson's distribution is suitable for our problem. An earlier attempt to describe analytically the MVR distribution with the help of Johnson's distribution was made in Ref. 5. The characteristic of the four-parameter Johnson's distribution (the parameters ε, λ, γ, and η in the standard notation) is presented in Ref. 4.

In its general form Johnson's distribution for MVR, taking into account the fact that in our case we assume that $\varepsilon = 0$ and $\lambda = 100$ km, has the following form:

$$f\left(S_M\right) = \frac{39.89\eta}{100S_M - S_M^2} \times$$

$$\times \exp\left\{-0.5\left[\gamma + \eta \ln\left(\frac{S_M}{100 - S_M}\right)\right]^2\right\}. \qquad (2)$$

Estimates of the parameters η and γ for the empirical MVR distributions studied are as follows:[4]

winter $-\eta = 0.79$, $\gamma = 2.04$;

summer $-\eta = 0.77$, $\gamma = 1.38$.

The integral characteristics of MVR obtained after the approximation are shown in Fig. 2.

Finally we have an analytical model of near-IR AT ($\lambda = 1.06$ μm), in which the MVR is the argument. If the distribution of the random quantity (MVR) is known, then the distribution of the AT $f(T_{1.06})$ 1 can be obtained by the method of transformation of a random variable.

The meteorological visibility range can be assumed to be a continuous random quantity, varying from 0 to 100 km, with a probability distribution $f(S_M)$. In its turn, the AT ($\lambda = 1.06$ μm) from 0 to 1.0 is a strictly increasing function of the random quantity S_M. Then the distribution of the random quantity $T_{1.06}$ can be written in the following form:

$$f\left(T_{1.06}\right) = f\left[S_M\left(T_{1.06}\right)\right] \cdot \left|\frac{dS_M}{dT_{1.06}}\right|. \qquad (3)$$

An expression for S_M as a function of $T_{1.06}$ can be obtained from the relation (1):

$$S_M = \frac{3.689}{0.075 + y^{0.966}}, \qquad (4)$$

where $y = \dfrac{\ln T_{1.06}}{L}$ and $T_{1.06}$ is the atmospheric transmission on a path of length L (in km).

Taking the derivative of the expression (4) with respect to $T_{1.06}$, we obtain the Jacobian of the transformation:

$$\frac{dS_M}{dT_{1.06}} = \frac{3.564}{L\left(y^{0.966} + 0.075\right)^2 y^{0.034} \exp\left(-yL\right)}. \qquad (5)$$

Substituting in the formula (2) the expression (4) for the argument S_M, we obtain the function $f[S_M[T_{1.06})]$ which according to (3) must be multiplied by the Jacobian (5) of the transformation in order to obtain, in the final form, the distribution of the AT in the region of the spectrum $\lambda = 1.06$ μm. After the corresponding transformations we obtain the following expression:

$$f(T_{1.06}) = \frac{10.447\eta}{L\left[27.11y^{0.966} + 1.033\right]y^{0.034}\exp(-yL)} \times$$

$$\times \exp\left\{-0.5\left[\gamma - \eta\ \ln\left(27.11y^{0.966} + 1.033\right)\right]^2\right\}. \quad (6)$$

The formula (6) is the analytical expression of the probability distribution of the AT ($\lambda = 1.06$ μm) under weather conditions of the "condensation" type.

After the values of the parameters η and γ, indicated above, were substituted into the expression (6), the histograms of the repetition of the AT ($\lambda = 1.06$ μm) were calculated for the region of central Povolzh'ye during winter and summer. The results of the calculations for the case $L = 1$ km are presented graphically in Fig. 3. The distribution of the winter AT is gently sloping and has a maximum (~ 20%) in the interval $T_{1.06} \in 0.8$–0.9. During summer the AT distribution has a strong left-sided asymmetry and a narrow (occurring with a gradation of 0.9–1.0) maximum, whose level is equal to 36%.

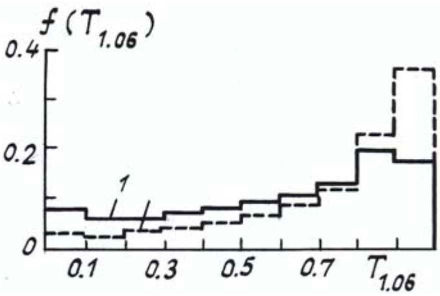

FIG. 3. Histograms of the repetition of the AT ($\lambda = 1.06$ μm) under weather conditions of the "condensation" type: 1) winter and 2) summer.

The proposed algorithm for modeling the AT is constructed taking into account only one extinction factor — the aerosol extinction. The principles on which the model of the distribution of the IR AT is constructed, taking into account both the aerosol and gaseous components of radiation extinction, are examined in Refs. 6 and 7.

In conclusion, it should be noted that if the AT distribution is known, then probabilistic estimates of the effect of the atmosphere in an analysis of systems employing optical radiation for information transmission can be made.

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