

RESULTS OF INVESTIGATIONS OF THE ATMOSPHERIC WATER VAPOR COLUMN DENSITY USING AN OPTICAL HYGROMETRY METHOD.

PART 1. ANALYSIS OF THE METHOD AND RESULTS OF ITS CALIBRATION

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In this paper we describe the characteristics of the optical hygrometer spectral channels and main features of the spectroscopic method to measure moisture content in the atmosphere in the NIR ($\lambda = 0.94 \mu\text{m}$). Different measurement approaches are analyzed taking into account the influence of the variability of spectral behavior of aerosol optical thickness. We also deal with the error estimates and calibration results of the two- and three-channel techniques based on the aerological sounding data.

1. INTRODUCTION

Studies of the regularities in spatiotemporal variability of the water vapor column density (vapor content) of the atmosphere is of great importance for solving a wide range of atmospheric-optical and climatological problems.

In parallel with the known tendency of the growth of the atmospheric moisture content W from winter to summer and with decreasing latitude, complex variations of this value are observed under the effect of geophysical conditions of specific place and time.¹

The greater part of the data on the variability of W was obtained using balloonborne observations (usually two times per day) at the network of aerological stations.² At the same time, when investigating the dynamics of W in the range of diurnal variation and under field conditions the most promising is the method of optical hygrometry or the spectroscopic one.^{3,4} Spectroscopic measurements of W most widely employ the version of filter solar photometers using a $0.94 \mu\text{m}$ water vapor absorption band.⁵⁻⁹

The basis of the optical hygrometry method is the relation between W and relative depth of the water vapor absorption band normally determined by the following relations^{5,6}:

$$V(W) = 2 I_2 / (I_1 + I_3) \quad \text{or} \quad V(W) = I_2 / I_1, \quad (1)$$

where I_2 is the radiation intensity at the maximum of the absorption band; I_1 and I_3 are the intensities in the adjacent portions of spectrum out of the absorption band.

When determining W by a spectroscopic method different approaches are used either based on direct calculation of the empirical dependence of the signal ratio (1) on moisture content, measured by a radiosonde technique,⁴⁻⁶ or with the use of the results of the laboratory experiments and model representations of the relation between W and the optical thickness of the atmosphere due to absorption by water vapor.^{8,10} The error of spectroscopic measurements depends mainly on the accuracy of absolute calibration and normally it is 10–20% (Refs. 4, 7, and 8).

2. EXPERIMENTAL CONDITIONS

To fulfil the State Program "Global Changes of the Environment and Climate" and the program of SB RAS "Climatic-Ecological Monitoring of Siberia", the authors have conducted the investigations of time variability of W in the region of Tomsk in 1992–1994.

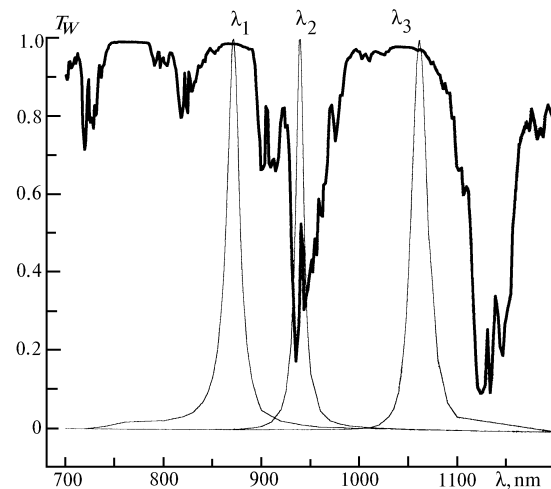


FIG. 1. Characteristics of spectral channels (relative units) and atmospheric transmission within the water vapor absorption bands calculated by the LOWTRAN-7 model (midlatitude summer).

A modified solar photometer (MSP) was used for the measurements of moisture content.¹¹ The characteristics of spectral channels (taking into account the transmissions of interference filters, input window, photodetector sensitivity, and so on) are given in Fig. 1. The peaks in the transmission curves of filters correspond to the wavelengths $\lambda_1 = 870 \text{ nm}$, $\lambda_2 = 940 \text{ nm}$, and $\lambda_3 = 1061 \text{ nm}$. This figure also shows the atmospheric transmission due to absorption by water vapor and calculated using the LOWTRAN-7 model¹² (midlatitude summer).

The total moisture content of the atmosphere W_a (aerological), used for calibration, was determined by integration over the altitude of the absolute humidity profiles. The calculation of absolute humidity was carried out based on the data on the dew point (calibration of 1994) or the temperature and relative humidity (1992) with the use of the Hoff and Grach formula (see, for example, Ref. 1), recommended by the World Meteorological Organization.

3. ANALYSIS OF THE METHODS

Let us consider some peculiarities of different two- and three-wavelength methods of measurements.

In accordance with the Bouguer law the solar radiation signal can be written as follows

$$U_i = k_i I_i = k_i I_{0i} \exp(-m \tau_i^a) T_W, \quad (2)$$

where I_{0i} is the extraterrestrial solar radiation constant, k_i is the instrumental constant; τ_i^a is the optical depth of the atmosphere due to Rayleigh and aerosol scattering; T_W is the spectral transmission function due to absorption by water vapor.

Then for a two-channel technique in the absence of absorption in the channel $I_{0.87}$ ($I_{1.06}$) the signal ratio is as follows

$$V_2 = \frac{k_2 I_{0.2}}{k_1 I_{0.1}} \exp[m(\tau_1^a - \tau_2^a)] T_{2W}, \quad (3)$$

in this case the relation of T_W to the moisture content (see, for example, Ref. 8) can be presented by the following formula

$$T_W = \exp(-[a + b\sqrt{mW}]), \quad (4)$$

where a and b are the model constants.

It should be noted that in a more general case the absorption in the channel $\lambda_1(\lambda_3)$ cannot sometimes be neglected, therefore in Eq. (3) T_{2W} denotes a certain equivalent value, allowing for joint action of two adjacent channels:

$$T_{2W} = \exp[(a_1 - a_2) + (b_1 - b_2)\sqrt{mW}]. \quad (5)$$

Similarly in the designation of T_{3W} for the three-channel technique we understand its corresponding value allowing for three spectral channels (with the dominating contribution from the spectral transmission at the wavelength λ_2).

Selectivity of the spectral behavior $\tau_a(\lambda)$ in the IR range is mainly determined by the aerosol component and it can be approximated by the known Angstrom formula:

$$\tau_i^a = \beta \lambda_i^{-\alpha}, \quad (6)$$

where β is the turbidity factor, α is the selectivity index.

Having substituted Eqs. (4), (6) into Eq. (3) we obtain the expression describing the functional dependence $V_2(W)$:

$$V_2(W) = \left(\frac{k_2 I_{0.2}}{k_1 I_{0.1}}\right) \exp(-a) \exp[m\beta(\lambda_1^{-\alpha} - \lambda_2^{-\alpha})] \times$$

$$\times \exp[-b(mW)^{1/2}] = V_{02} \gamma_2 \exp[-b(mW)^{1/2}], \quad (7)$$

where V_{02} is the instrumental constant of the two-channel technique; $\gamma_2 = \exp[m\beta(\lambda_1^{-\alpha} - \lambda_2^{-\alpha})]$ is the correction for selectivity of the spectral behavior of $\tau_a(\lambda)$. It should be noted that if the values of λ_1, λ_2 are close the correction γ_2 tends to unity.

For estimating the γ_2 variations we use the results of investigations of the aerosol optical thickness under different atmospheric conditions. According to Ref. 5 the range of α variations for different regions (ocean, arid zone, and so on) is within 0.2–1.6 with the average value $\bar{\alpha} \approx 1$. The total range of variations of τ in the region of $0.9 \mu\text{m}$ can be evaluated by the value 0.03–0.35 at the average value of $\bar{\tau}_1 \approx 0.13$. According to this assumption, for the maximum range of variability of γ_2 we write:

$$\left(\frac{\Delta\gamma}{\gamma}\right)^{\text{max}} = m \left\{ \left[1 - (\lambda_1/\lambda_2)^{\bar{\alpha}} \right]^2 \Delta\tau^2 + \left[\bar{\tau}_1 (\lambda_1/\lambda_2)^{\bar{\alpha}} \ln(\lambda_2/\lambda_1) \right]^2 \Delta\alpha^2 \right\}^{1/2} \approx 0.0272m (2.72\%). \quad (8)$$

From Eq. (8) it follows that because of a large uncertainty in the value τ the variations of γ_2 exceed the error of signal measurement and they cannot be neglected. Use of additional data on τ in the two-channel technique (i.e., correction for the aerosol optical depth, with $\Delta\tau \approx 0.03$) makes it possible to decrease slightly the variability of the error of γ_2 . The value of $(\Delta\gamma/\gamma)^{\text{max}}$ in this case is 1.32%. The version of the two-channel technique is of considerable interest when using the wide and narrow spectral channels centered at the maximum of the absorption band.⁷ In this case the correction γ_2 in Eq. (7) in the real range of α variations does not practically differ from unity, that is, the influence of spectral behavior $\tau(\lambda)$ variation is excluded. A disadvantage of this version is a slight dependence of V_2 on mW because of smaller values of the constant b as compared to that in the other methods. This version of the two-channel technique was not used by the authors, therefore for brevity of the presentation the calculation of the estimates of γ_2 and b is omitted here.

In the case of a three-channel technique the dependence on $\tau^a(\lambda)$ may be essentially decreased. Thus, in the version used, for example, by the authors⁶, the initial ratio (1) can be presented as

$$V'_3 = \frac{2 I_{02} k_2 T_{3W}}{k_1 I_{01} \exp[m(\tau_2 - \tau_1)] + k_3 I_{03} \exp[m(\tau_2 - \tau_3)]}. \quad (9)$$

The exponents in Eq. (9) can be expanded in the series over relatively small variable $(\tau_2 - \tau_i)$ and after simple transformations we can obtain

$$V'_3 \approx \frac{1}{k_1 I_{01} + k_3 I_{03}} \times \frac{2 k_2 I_{02} \exp(a - b\sqrt{mW})}{1 + m \tau_1 [(\lambda_1/\lambda_2)^{\alpha} - (\lambda_1/\lambda_3)^{\alpha} + n (\lambda_1/\lambda_3)^{\alpha} - n]} = V'_{03} \exp(-b\sqrt{mW}) \gamma'_3, \quad (10)$$

where V'_{03} is the instrumental constant;

$$\gamma'_3 = \left\{ 1 + m \tau_1 [(\lambda_1/\lambda_2)^\alpha - (\lambda_1/\lambda_3)^\alpha + n (\lambda_1/\lambda_3)^\alpha - n] \right\}^{-1};$$

$n = k_1 I_{01} / (k_1 I_{01} + k_3 I_{03})$ is the coefficient from the signal ratio (signals U_{01} and U_{03}).

For determining the value of $(\Delta\gamma/\gamma)$ we use the same values of $\Delta\alpha$ and $\Delta\tau$. Then for a special case of $n = 0.5$ (signals in the first and the third channels are identical) we obtain

$$\begin{aligned} \left(\frac{\Delta\gamma}{\gamma} \right)^{\max} &\approx \frac{m}{2} \left\{ [2(\lambda_1/\lambda_2)^\alpha - 1 - (\lambda_1/\lambda_3)^\alpha]^2 \Delta\tau^2 + \right. \\ &+ \left. [2(\lambda_1/\lambda_2)^\alpha \ln(\lambda_1/\lambda_2) + (\lambda_1/\lambda_3)^\alpha \ln(\lambda_3/\lambda_1)]^2 \tau_1^2 \Delta\alpha^2 \right\}^{1/2} \approx \\ &\approx 0.52 m \%, \end{aligned} \quad (11)$$

that is much better than in the case of the two-channel technique. At the same time, when we have the improperly chosen signal ratio (n), the range of γ'_3 variations increases and its influence on the error becomes comparable with that of the two-channel technique.

Similarly one can follow the increase in the error because of the improper selection of the wavelengths λ_1 and λ_3 relative to λ_2 . When summing, one can conclude that the three-channel technique⁶ is less sensitive to the variation of τ^a , but at large differences of the signals U_{03} , U_{01} and $(\lambda_3 - \lambda_2)$, $(\lambda_1 - \lambda_2)$ differences the technique reduces to the two-channel one.

From the point of view of influence of the variability in $\tau^a(\lambda)$ preferable is another version of three-channel technique

$$\begin{aligned} V''_3 &= \frac{U_2^2}{U_1 U_3} = \frac{(k_2 I_{02})^2}{k_1 I_{01} k_3 I_{03}} K''_3 W \exp [m(\tau_1 + \tau_3 - 2\tau_2)] \approx \\ &\approx V''_{03} \exp(-2b\sqrt{mW}) \gamma''_3, \end{aligned} \quad (12)$$

where $\gamma''_3 = \exp \left\{ m \tau_1 [1 + (\lambda_1/\lambda_3)^\alpha - 2(\lambda_1/\lambda_2)^\alpha] \right\}$.

Having repeated the procedure of estimating the maximum variability of γ we obtain

$$\begin{aligned} \left(\frac{\Delta\gamma}{\gamma} \right)^{\max} &\approx m \left\{ [1 + (\lambda_1/\lambda_3)^\alpha - 2(\lambda_1/\lambda_2)^\alpha]^2 \Delta\tau^2 + \right. \\ &+ \left. [(\lambda_1/\lambda_3)^\alpha \ln(\lambda_1/\lambda_3) + 2(\lambda_1/\lambda_2)^\alpha \ln(\lambda_2/\lambda_1)]^2 \tau_1^2 \Delta\alpha^2 \right\}^{1/2} \approx \\ &\approx 1.03 m \%, \end{aligned} \quad (13)$$

That is, in the use of the three-channel technique the influence of the variability of γ is even less than corresponding value for the two-channel technique with a correction for aerosol being equal to 1.32 m %.

Comparing Eqs. (7), (10), and (12) it should be concluded that the expressions $V_i(mW)$ of the techniques considered have the same functional dependence, and the differences are in the influence of variations of τ^a and in the values of the constant b , depending on the spectral channels selected.

4. RESULTS OF CALIBRATION

Calibration of spectroscopic measurements was performed on the basis of the results of aerological sounding carried out at the observation point. Spectroscopic results obtained in the 1992–1993 period were calibrated using five radiosonde profiles obtained in Tomsk (July 6 – July 15, 1992). In 1994 the calibration was performed during the sea expedition to Canary Islands (17 radiosondes in the period from May 2 to May 22, 1994).

Let us analyze the calibration results using more complete and reliable data of 1994 as an example.

The procedure of obtaining the calibration dependence involved two stages. At the first stage the data were used that were obtained in the period of $t = \pm 1$ h with respect to the starting time of a radiosonde launch.

Then, on the basis of a comparison of the values of V_2 with the aerological data ($W_a m$) we determined the approximate calibration and calculated the values of the moisture content W_s from the spectroscopic method.

The values of W thus obtained were analyzed for stability ($\delta W/W < 10$ per cent) and for every day the period of t_i was finally found, during which the results of joint measurements could be used for calibration.

The final calibration of the optical hygrometer was performed for the three versions of the determination of the value of W : $V'_2 = U_{0.94}/U_{0.87}$ (with correction for τ^a , $/^*/$ and without it); $V''_2 = U_{0.94}/U_{1.06}$ and $V'''_2 = U_{0.94}^2/(U_{0.87}U_{1.06})$.

The results of a comparison of the optical data on V_i and aerological ones on (mW_a) indicate that they are well described by the dependence of the type (7). As an example, Fig. 2 shows an approximation dependence for the values of $(V_{0.2}\gamma_2) = 2.275$ and $b = 0.618$ for the first version of the two-channel technique (V'_2).

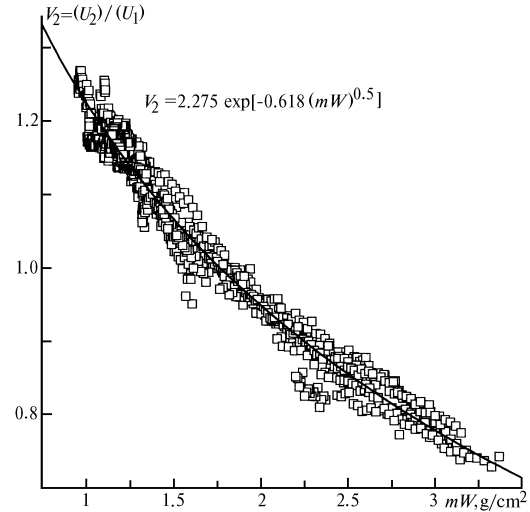


FIG. 2. Results of comparison of the relation of photometric signals of V_2 with aerological data of mW_a and the approximation curve.

For analytical description of calibration diagrams and the estimate of errors we can turn to the logarithmic form of expressions (7), (10), and (12)

$$\ln(V_i) = \ln \gamma V_{0i} - b\sqrt{mW}; \quad (14)$$

$$W_s = (\ln V_i - \ln \gamma V_{0i})^2 / m b^2. \tag{15}$$

The results of linear approximation of $\ln V_i$ as a function of \sqrt{mW} for different versions are given in Fig. 3, and the table gives the parameters of approximation relations of $\ln V_{0i}$ and b , their rms deviations σ and the coefficients of cross-correlation $r[\ln(V), (mW)^{0.5}]$.

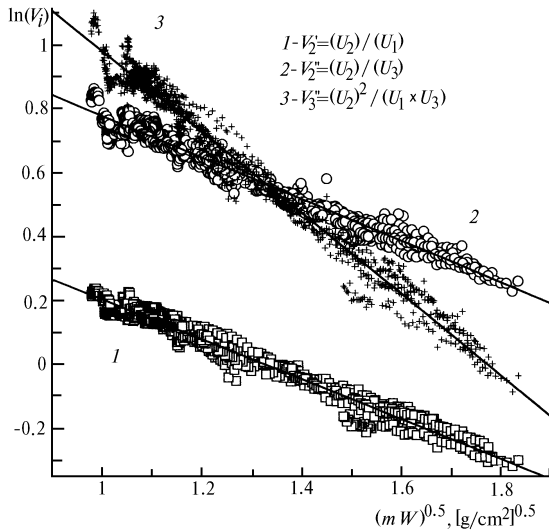


FIG. 3. Calibration dependences of $\ln V_i$ as a function of \sqrt{mW} for three versions of estimating W using the spectroscopic method.

TABLE I.

Type of technique	$\ln V_0$	$\sigma \ln V_0$	b	σ_b	r	σ_W	N
V'_2	0.822	0.004	0.618	0.003	-0.986	0.066	959
V^*_2	0.818	0.004	0.616	0.003	-0.986	0.068	959
V''_2	1.425	0.005	0.646	0.004	-0.984	0.073	959
V'''_3	2.247	0.008	0.632	0.004	-0.988	0.064	959
$V'_2(1992)$	0.734	0.010	0.473	0.005	-0.996	0.054	65

Similar calculations of calibration dependences were also carried out for other representations of the dependence T_W in the form⁹:

$$T_W = \exp [- b(mW)^{0.57}]. \tag{16}$$

In this case the characteristics of the approximation relation turned out to be similar, and the difference is only in the values of $\ln V_{0i}$ and b .

To estimate the influence of geometrical conditions of observations on the error of determination of the moisture content, the values of difference $(W_a - W_s)$ for various values of mW were calculated (Fig. 4). Based on the data shown in the figure, one can follow the tendency to the increase of the error in the range of small values of mW . The most probable explanation of this fact is the decrease in the technique sensitivity at small optical depths τ_W and the increase of the error of the Sun guide at large observation angles (design features of the guide system).

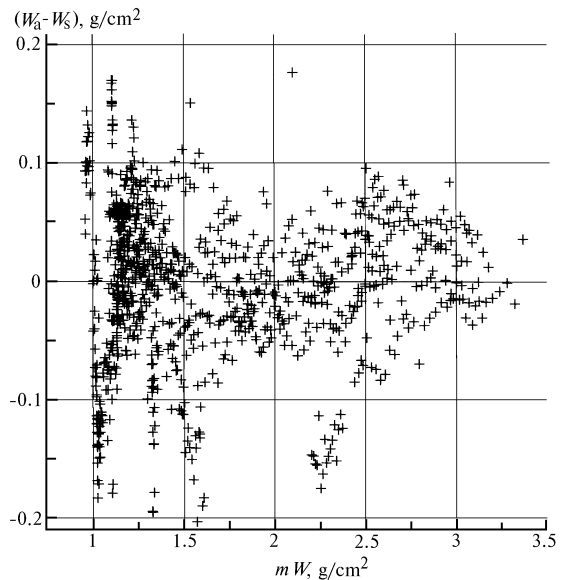


FIG. 4. Dependence of the difference of the values of W_a and W_s , calculated using the three-channel technique, on the value of mW_a .

The upper boundary of the random error of spectroscopic measurements can be estimated from the rms deviation of σ_W for the values of $(W_a - W_s)$, which for different techniques is within 0.064–0.073 (see the table). Maximum range of discrepancies between W_a and W_s does not exceed 0.2 g/cm^2 (Fig. 4). In this case it should be noted that the differences shown in the figure include random errors of both spectroscopic and radiosonde techniques. The error of radiosonde measurements is estimated at 0.14 g/cm^2 (Ref. 13) or 13 percent.⁹

A particular shortcoming of the calibration in 1994 is the small range of the atmospheric moisture content during the period of radiosonde measurements ($W_a = 0.94$ to 1.46 g/cm^2). Therefore when measuring large moisture content a certain increase of the error is possible.

In 1992 the calibration was performed under conditions of higher moisture contents ($W_a = 1.65$ –3.00 g/cm^2). Characteristics of calibration are given in the lower row of the table.

5. CONCLUSION

Thus, the analysis of methods and calibration results make it possible to draw the following conclusions.

1. The dependence of the ratio of photometric signals V_i , measured at two or three wavelengths in the region of an H_2O absorption band, at 0.94 μm , is well approximated by the exponential function with the exponent of $(mW)^{0.5}$ or $(mW)^{0.57}$.

2. Sensitivity of the techniques considered (the degree of correlation of V_i to W) is approximately the same, but, from the standpoint of potentially weaker influence of $\tau^a(\lambda)$ on them, the most effective is the three-channel one in the form of Eq. (12).

3. The upper limit of the error of determination of the moisture content, as can be found from the results of calibration made, can be estimated at the level of 0.07 g/cm^2 .

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