NUMERICAL MODELING OF THE LASER SOUNDING OF ATMOSPHERIC TEMPERATURE AND HUMIDITY USING A DIFFERENTIAL ABSORPTION METHOD IN THE NEAR IR SPECTRAL RANGE BY MEANS OF MEL–01 METEOROLOGICAL LIDAR

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Received December 16, 1996

The results are presented of the numerical modeling of laser sounding of atmospheric temperature and humidity using a differential absorption method in the near IR spectral range (water vapor absorption bands 0.72 *and* 0.94 μm, *and oxygen band* 0.76 μm*) by means of the MEL–01 meteorological lidar. The possibilities are shown of performing of both two-frequency and three-frequency methods of sounding meteorological parameters. The absorption lines of water vapor and oxygen suitable for sounding of the temperature and humidity profiles in the lower troposphere have been selected. It is shown that the random errors in reconstructing humidity do not exceed* 10% *in the altitude range up to* 1.8 km, *and the error in reconstructing temperature does not exceed* 0.5 K *at the altitudes up to* 1.2 km.

The MEL–1 meteorological lidar[1,2] is intended for remote sensing of practically all principal meteorological parameters of the atmosphere, namely temperature, humidity, and wind velocity. The wavelength of the laser transmitter radiation of the MEL–01 lidar based on the titanium supphire laser can be tuned in three wavelength ranges (730 ± 6), (766 ± 6) and (940 ± 6) nm which cover known absorption bands of the water vapor 0.72 and 0.94 μm and of the oxygen 0.76 μm. Some principal parameters of the MEL–01 meteorological lidar are given below.

Specification of the MEL–01 Meteorological Lidar

Energy of the laser radiation pulse in the spectral range (730±6) nm	15 mJ
(766±6) nm	30 mJ
(940±6) nm	10 mJ
Laser radiation line width	0.03 cm^{-1}
Pulse repetition rate	30 Hz
Wavelength tuning accuracy	0.2 pm
Efficiency of the receiving-transmitting optics	0.6
Diameter of the receiving telescope	300 mm
PMT quantum efficiency	0.02

There is a possibility in the lidar of performing both two-frequency and three-frequency methods of sounding of meteorological parameters. In the two-frequency method one line of the radiation coincides with the oxygen or water vapor absorption line, and the other one is in the nearest "transmission microwindow".

The H_2O absorption line with minimum temperature dependence is selected for sounding water vapor profiles, and, as known,[3] the humidity profile is determined by the relationship

$$\rho(h) = \frac{\alpha_1(h)}{K_1(h) - K_0(h)}, \tag{1}$$

where

$$\alpha_1(h) = \frac{1}{2\Delta h} \ln \left(\frac{U_1(h)U_0(h + \Delta h)}{U_1(h + \Delta h)U_0(h)}\right), \tag{2}$$

$K_i(h)$ is the absorption coefficient dependence on the altitude on the wavelengths at the center ($i = 1$) and out of the contour ($i = 0$) of a selected absorption line of water vapor. The dependence is calculated using *a priori* information on the distribution of thermodynamic parameters of the atmosphere and spectral composition of the laser radiation, $U_i(h)$ and $U_i(h + \Delta h)$ are the lidar signals received from the volumes of the atmosphere sounded which are at the distances h and $h + \Delta h$ from the lidar.

When sounding temperature by the two-frequency method, the oxygen absorption line with maximum temperature sensitivity is selected.

The temperature profile at sounding by the two-frequency method can be obtained from the following relationship[4,5]:

$$T(h) = T_{\rm m}(h) \left[1 + \left(\frac{1.439E''}{T_{\rm m}(h)} - 3/2\right)^{-1} \times\right.$$

0235-6880/97/02 198-04 $02.00

$$\times \ln\left(\frac{\alpha_1(h)}{q_0(1-q^*)K_1(h)b_m(h)}\right)\Bigg] . \quad (3)$$

where $T_m(h)$ is the model vertical profile of temperature, E'' is the energy of the lower state of the absorbing transition, $q_0 = 0.2095$ is the volume oxygen content in the dry atmosphere, q^* is the volume content of water vapor obtained either from the data of laser measurements or from the atmospheric model, and $b_m(h)$ is the model profile of air density.

In the three-frequency sounding scheme, two lines of laser radiation exactly coincide with two quite close absorption lines of the water vapor with different temperature dependence, and the third radiation line is in the nearest "transmission microwindow".

The temperature profile can be obtained from the following relationship[6]

$$T(h) = T_0 \{A/[\ln C - \ln E(h)]\}, \quad (4)$$

where

$$A = \frac{E''_1 - E''_2}{kT_0} , \quad C = \frac{S_{01}\,\gamma_{02}}{S_{02}\,\gamma_{01}} \exp(A), \quad E(h) = \frac{\alpha_1(h)}{\alpha_2(h)} , \quad (5)$$

E''_1, S_{0j}, and γ_{0j} are the energy of the lower vibrational-rotational level, intensity, and half-width, respectively, at temperature T_0 and pressure P_0 for the first and second absorption lines of the water vapor, $j = 1,2$. The extinction coefficient $\alpha_2(h)$ is determined similarly to $\alpha_1(h)$ (see Eq. (2)).

Then the temperature values obtained are used for calculation of the profiles of the extinction coefficient when determining the profiles of the water vapor by Eq. (1).

The absorption lines of water vapor and oxygen suitable for sounding temperature and humidity profiles in the lower troposphere in the radiation ranges of the laser transmitter of the MEL–01 lidar (730 ± 6); (766 ± 6) and (940 ± 6) nm were selected using the criteria derived in Refs. 1 and 6–8. Spectral parameters of the absorption lines of water vapor and oxygen taken from the atlas of the spectral lines[9] are given in Table I. Calculations of the laser radiation absorption spectra in these spectral ranges showed that the absorption lines of oxygen selected are isolated and quite strong.

As was shown earlier,[1,7] the absorption lines of water vapor with the energy of the lower state of about 200–225 cm^{-1} and the intensity of 0.1–0.7 are optimum for sounding of the humidity profiles in the lower troposphere, depending on different climatic zones. It is seen from Table I, that the line 6 well satisfies these requirements.

TABLE I. Spectral parameters of the absorption lines of oxygen and water vapor and the wavelengths of the laser radiation on and off the absorption lines.

N	Gas	λ, nm	ν, cm^{-1}	S_0, cm/g	γ_0, cm^{-1}	E'', cm^{-1}
1	O_2	768.3802	13014.3905	0.00365	0.042	1085.206
2	O_2	768.2760	13016.1504	0.00365	0.042	1085.206
3	O_2	768.3200	13015.4102	–	–	–
4	H_2O	725.7947	13778.0009	0.26100	0.116	95.176
5	H_2O	725.7378	13779.0811	0.16300	0.097	610.341
6	H_2O	727.9392	13737.4102	0.72700	0.111	224.838
7	H_2O	725.7600	13778.6596	–	–	–
8	H_2O	940.0080	10638.2073	1.22000	0.092	142.279
9	H_2O	940.2617	10635.3369	0.77700	0.086	552.912
10	H_2O	940.1000	10637.1663	–	–	–

When sounding temperature by the two-frequency method, one needs for quite an intense absorption line of oxygen with the high value of the lower state energy. The line 1 meets these requirements.

The pairs of lines 4–5 and 8–9 presented in Table I are appropriate for the three-frequency method, because, according to Ref. 6, the pairs of the water vapor absorption lines with the greatest difference in the values of the lower state energy are necessary.

The systematic errors appearing due to the errors in preliminary calculations of the profile of the effective extinction coefficient depend on many factors, such as the variations of meteorological parameters and gas concentrations along the sounding path, the shift of the absorption line centers of the atmospheric gases under the effect of air pressure, Doppler broadening of the backscattered signal from the randomly moving molecules. The effect of these factors on the results of sounding and the ways of its minimization, including the spectral ranges we consider, were analyzed in Refs. 7 and 8.

In this paper we consider the random errors in reconstructing the temperature and humidity profiles.

The random errors in reconstructing temperature and humidity by the two-frequency method at the limitation of the lidar signal by the shot noise, that corresponds to the use of PMT operating in the analog mode in the MEL–01 lidar, are determined as follows:

$$\delta_i(\rho) = \frac{1}{2\Delta h\ \alpha_i(h)\sqrt{n}} \left\{ \frac{cF(\lambda)}{2\Delta h} \sum_{j=1}^{2} \left(\frac{1}{U_{ij}} + \frac{1}{U_{0j}} \right) \right\}^{0.5}, \quad (6)$$

$$\delta(T) = \frac{T_m(h)\ D_m(h)}{\sqrt{n}\ \Delta h\ \alpha_i(h)} \left\{ \frac{cF(\lambda)}{2\Delta h} \sum_{j=1}^{2} \left(\frac{1}{U_{ij}} + \frac{1}{U_{0j}} \right) \right\}^{0.5}, \quad (7)$$

where

$$D_m(h) = \left(\frac{1.439E''}{T_m(h)} - 3/2 \right)^{-1}, \quad F(\lambda) = \frac{\hbar}{\chi\lambda}. \quad (8)$$

Here U_{ij} are the lidar returns at the center ($i = 1$) and out of the absorption line contour ($i = 0$) of water vapor or oxygen at the distance h ($j = 1$) and $h + \Delta h$ ($j = 2$) from the lidar, c is the light speed, $\hbar$ is the Plank constant, χ is the efficiency of the receiving-transmitting system, and n is the number of laser shots.

The random errors in reconstructing the temperature and humidity profiles by the three-frequency method at the limitation by the shot noise are determined as

$$\delta(T) = \frac{T_m^2(h)}{\sqrt{n}\ AT_0} \{\delta_1^2(\rho) + \delta_2^2(\rho)\}^{0.5}. \quad (9)$$

The calculations were carried out for the conditions of the night-time atmosphere and clear sky. The spatial resolution was taken to be equal to 200 m, time of measurement was 5 min. The absorption coefficient profiles were calculated for the Voigt contour taking into account the absorption by wings of the neighbor lines for three atmospheric models: tropics, midlatitude summer and Arctic winter.[10] The aerosol and molecular scattering coefficients and aerosol absorption coefficients were taken from the model,[10] and the profiles of the scattering phase function were taken from the model[11] too.

The results of numerical estimation for the selected sounding wavelengths in the spectral ranges of 0.72, 0.76 and 0.94 μm are presented in the Tables II*a* (errors of humidity, δ(ρ), %) and 2*b* (errors of temperature δ(*T*), *K*).

The calculations show that, as is seen from Table II*a*, when using the absorption lines from the band 0.72 μm for sounding the water vapor profiles, the errors in reconstructing humidity do not exceed 10% at the altitudes up to 1.8 km in all climatic zones. Sounding of humidity in the absorption band 0.94 μm is less effective, even under the Arctic winter conditions.

Numerical modeling of the sounding of temperature profiles (see Table II*b*) have revealed the advantage of using the two-frequency method in the spectral range of 0.76 μm, where the random errors do not practically exceed 0.5 K for all climatic zones in the altitude range up to 1.2 K.

TABLE IIa. Errors in reconstructing humidity, %

h, km	Wavelength, nm								
	725.79			727.93			940.26		
	Tropics	Midlatitude summer	Arctic winter	Tropics	Midlatitude summer	Arctic winter	Tropics	Midlatitude summer	Arctic winter
0.2	0.19	0.25	2.06	0.15	0.15	0.80	0.26	0.20	0.94
0.4	0.49	0.57	4.00	0.59	0.46	1.59	1.29	0.77	1.93
0.6	0.97	1.09	6.31	1.83	1.22	2.54	5.13	2.38	3.07
0.8	1.77	1.88	8.99	5.10	2.86	3.69	17.90	6.50	4.46
1.2	3.00	3.03	11.85	12.73	6.09	4.97	55.11	15.85	5.98
1.4	4.65	4.50	15.24	28.46	11.77	6.51	>100	34.73	7.91
1.6	6.97	6.48	18.96	60.91	21.74	8.34	–”–	72.24	10.15
1.8	10.34	9.25	23.40	>100	39.12	10.56	–”–	>100	12.95

TABLE IIb. Errors in reconstructing temperature, δ(*T*), K.

h, km	Wavelength, μm								
	0.72			0.76			0.94		
	Tropics	Midlatitude summer	Arctic winter	Tropics	Midlatitude summer	Arctic winter	Tropics	Midlatitude summer	Arctic winter
0.2	0.05	0.06	0.55	0.13	0.11	0.09	0.11	0.07	0.17
0.4	0.12	0.15	1.05	0.13	0.11	0.09	0.74	0.32	0.34
0.6	0.23	0.27	1.66	0.20	0.17	0.15	4.23	1.29	0.55
0.8	0.42	0.45	2.36	0.28	0.24	0.20	9.98	4.61	1.09
1.0	0.68	0.71	3.10	0.40	0.33	0.30	>10	>10	1.46
1.2	1.02	1.09	3.97	0.55	0.45	0.42	–”–	–”–	1.89

Use of a three-frequency method in the range of 0.72 μm in tropics and midlatitude summer allows one to reconstruct the temperature profile with the accuracy better than 1 K at altitudes up to 1.2 km. The three-frequency method is practically useless for the Arctic winter.

Thus, the results of numerical modeling of sounding of the atmospheric temperature and humidity profiles by differential absorption method in the near IR spectral range by means of the MEL–01 meteorological lidar show that the three-frequency method using the absorption lines from the band 0.72 μm in tropics and midlatitude summer can compete with the two-frequency method of separate sounding of temperature and humidity. Only the two-frequency method is practical in the Arctic winter conditions. The absorption band of 0.94 μm is only weakly suitable for sounding in the atmospheric boundary layer.

REFERENCES

1. G.G. Matvienko, Yu.F. Arshinov, A.I. Grishin et al., *Proceedings of the XI Symposium on Laser and Acoustic Sounding of the Atmosphere*, Tomsk (1993), pp. 130–136.

2. A.I. Grishin, G.G. Matvienko, O.V. Kharchenko et al., Atmos. Oceanic Optics **7**, No. 11, 854–856 (1994).

3. R.M. Schotland, *Proceedings of third Symposium on Remote Sensing of the Environment*, Michigan, Ann Arbor (1964), pp. 215–224.

4. J. Mason, Appl. Opt. **14**, No. 14, 76–78 (1975).

5. J.E. Kalshoven, C.L. Korb, G.K. Schwemmer, and M. Dombrovsky, Appl. Opt. **21**, No. 11, 921–930 (1981).

6. M. Endeman and R.L. Byer, Opt. Lett. **5**, No. 10, 452–454 (1980).

7. V.V. Zuev and O.A. Romanovskii, *Taking into Account the Systematic Errors in the Lidar Differential Absorption Method*, Dep. v VINITI, Reg. No. 46756–B87, June 25, 1987.

8. C.L. Korb, G.K. Schwemmer, J. Famigletti et al., *Differential Absorption Lidars for Remote Sensing of Atmosphere Pressure and Temperature Profiles: Final Report,* NASA Technical Memorandum 104618, Goddard Space Flight Center, Greenbelt, Maryland (1995), 249 pp.

9. N. Husson, A. Chedin, N.E. Scott et al., Annal. Geophys. Fasc. **2**, Serias A, 185–190 (1986).

10. R.A. McClatchey, R.W. Fenn, J.E.A. Selby et al., *Optical Properties of the Atmosphere,* Report AFCRL–71–0297, AFCRL, Bedford, Mass (1971), 86 pp.

11. G.M. Krekov and R.F. Rakhimov, *Optical-Radar Model of Continental Aerosol* (Nauka, Novosibirsk, 1982), 199 pp.