Laser and microwave methods of cloud investigations

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The results of measuring cloud parameters based on laser methods and microwave atmospheric remote sensing are discussed. Laser initiation of lightning from thunderclouds is also considered.

Water vapor content determination (in atmosphere) from microwave radiometric measurements

The columnar water vapor Q determination (or atmospheric water content) is carried out by measuring the atmospheric thermal self-radiation (radiobrightness temperature T_b) in the resonance H_2O absorption line at λ = 1.35 cm.

On the basis of long-term observations in Voeikovo settlement, the correlation equation (relation) between the atmospheric water content in cm of condensed water and the radiobrightness sky temperature, in K, has been derived[1]:

$$Q = 0.56\ T_b - 0.16.$$

In the presence of clouds incapable of precipitating, Q is determined from measurements at two wavelengths, one of them is in the H_2O line near λ = 1.35 cm, and another one is in the atmospheric transparency window near λ = 0.8 cm (Ref. 2). In this case, it is possible to determine simultaneously the liquid water path W in clouds using the following regression relations:

$$Q = a_o + a_1\ T_b(\lambda = 1.4\ \text{cm}) + a_2\ T_b(\lambda = 0.8\ \text{cm});$$
$$W = b_o + b_1\ T_b(\lambda = 1.4\ \text{cm}) + b_2\ T_b(\lambda = 0.8\ \text{cm})\ \ldots\ .$$

Regression coefficients a_1 and b_1 were calculated by the least square method for different models of the cloud atmosphere. *A priori* information about temperature profiles, atmospheric humidity, and liquid water content was used as the initial one obtained from the aircraft and radiosonde sensing.

Relative error in determination of atmospheric water content is about 10%, and liquid water path of stratus clouds is about 30%.

Experimental investigations of atmospheric water content were carried out in different regions: Crimea, Northern Atlantic, and Leningrad Region in the Voeikovo and Turgosh field experimental bases. The radiosensing, meteorological, radar data, and synoptic maps were involved into interpretation of the obtained results. The analysis of synoptic, seasonal, mesoscale variations of atmospheric water content and liquid water path has been carried out for the regions under study (above the ocean and land). A considerable influence of synoptic processes proceeding in the atmosphere on variation of atmospheric water content and the liquid water path has been marked.

Investigations of the atmospheric water content and the liquid water path in Leningrad region, carried out in different seasons of 1988–1997, show that the atmospheric water content varies between 2 and 45 kg/m^2 and the liquid water content of the stratus-cloud atmosphere does not exceed, as a rule, 1 kg/m^2. On a synoptic segment of time scales, the maximal atmospheric water content was recorded in periods of the maximal liquid water content. The maximal values of atmospheric water content were recorded during passing warm and occlusion fronts, which in summer period are about 30–40 kg/m^2 and in winter period about 10–18 kg/m^2. The fact that in warm front conditions precipitations are observed in a definite time interval after the derivative maximum $\partial Q/\partial t$ demonstrates an opportunity of using the microwave radiometric data for the short-term precipitation forecast.

The seasonal behavior of atmospheric water content is reflected in Table 1, where its mean values and root-mean-square deviations (RMSD) for different periods of the year in Leningrad Region are given. Table 1 also presents corresponding estimations obtained by integration of radiosonde values of absolute humidity, which show a satisfactory agreement between thermo-microwave imaging and radiosonde data on the atmospheric water content: the root-mean-square error (radiometer–radiosonde) for different periods was 1.5–2 kg/m^2.

Table 1. Mean values and root-mean-square deviations (kg/m^2) of atmospheric water content for different periods

Period	Q	RMSD (Q)	Q_{rs}	RMSD (Q_{rs})
July, 1993	24.99	5.70	23.61	4.83
October, 1993	12.81	5.98	11.91	5.72
January, 1993	8.20	3.05	7.92	4.20
April, 1990	17.55	8.49	15.59	8.17

Investigations of spatiotemporal variability of atmospheric water content in period of development

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of the heavy convective and thunderclouds were carried out in Leningrad Region at the Turgosh field experimental base as a part of complex experiments with the use of active and passive location methods.[2] The conducted experiments confirm the connection between favorable conditions for development and formation of the high-power convection and the level of atmospheric water content in preceding hours. The maximal atmospheric water content[2] is observed, as a rule, in the region of development of heavy thunderclouds.

Application of lasers to atmospheric studies and initiation of lightnings from thunderclouds

An important laser application is the formation of conducting channels under thunderclouds aiming at initiating the lightnings. First, such experiments on lightning initiation by means of UV and CO_2 lasers were conducted in Japan.[3] The impacts on thunderclouds were carried out in winter, when these clouds were located lower than in summer and the electric field strength near the ground attained 10 kV/m. During the experiments, the laser was switched on after appearance of the first intracloud lightning. To produce the initiating plasma, necessary for the CO_2 laser operation, the UV laser was used. Among numerous experiments, only two can be considered successful: when the rising leader was directed upwards from a tower of 50 m height, and the clouds with lateral dimensions about 2 km and lightning current of 35 kA were discharged via the tower, while the transported charge was 3 C.

When studying the initiation of lightnings from thunderclouds, the following problems appear, which solution determines the success of the experiments: the passage of the high-power laser radiation through the air and the formation of the ionized plasma channels in atmosphere. A more general problem is a deeper insight into the processes of the discharge initiation by means of the plasma channels generating by laser.

Setting the moment of the laser activation is a technical problem.[4] It was shown, based on solution of the thundercloud electrization problem, that intracloud discharges precede, as a rule, the cloud–earth discharges. This is also confirmed experimentally[5] and justifies the procedure, applied in the experiment, of laser activation just after appearance of the first intracloud discharge.

Physically, the initiation of lightning from the thundercloud by means of the laser is based on the fact that laser radiation produces a conducting plasma channel of the limited extent in the atmosphere due to ionization. This channel being in the thundercloud external electric field leads to generation of the lightning. As it was assumed in Ref. 6, this is analogous to physics of generating the discharge, when a conductor of a final length is in the external electric field (for example, lightning-arrester). It is important to find out to what extent the analogy with the conductor corresponds to the plasma channel generated by laser.

The conductor in the external electric field is polarized due to motion of free electrons in it in such a way that the field at the conductor ends amplifies, which then results in generating a discharge. In the laser channel, in parallel with ionization of air molecules followed by producing electrons, the opposite process of generating heavier negative ions proceeds, which deteriorates properties of the laser channel as a conductor. As a whole, the problem of formation of the plasma-conducting channel generated by a laser, is far from being solved. Some preliminary estimations and results are presented in Refs. 6 and 7.

As it was mentioned above, the problem of high-power laser radiation propagation through the atmosphere accounting for its actual absorption, scattering, and ionization of air molecules is of importance for the lightning initiation by a laser. Let actual absorption and scattering be characterized by the absorption coefficient α_λ, and radiation attenuation due to ionization by the absorption coefficient μ_λ. Then, the transfer equation for laser radiation of I_λ intensity in one-dimensional stationary case for the CO_2 laser has the form

$$\frac{dI_\lambda}{dz} = -(\alpha_\lambda + \mu_\lambda)I_\lambda. \quad (1)$$

We use for μ_λ the representation given in Ref. 8:

$$\mu_\lambda = \frac{4\pi e n_e}{m_e c}\frac{\nu_m}{\omega^2 + \nu_m^2} = 0.106 n_e \frac{\nu_m}{\omega^2 + \nu_m^2}, \quad (2)$$

where n_e is the electron concentration in the laser channel; m_e is the electron mass; e is the electron charge; ν_m is the frequency of electron collisions with neutral air molecules; ω is the frequency of laser radiation related to λ by the relation $\lambda = (2\pi/\omega)c$ (c is the light velocity).

The photon energy for the CO_2 laser makes 0.12 eV. The energy of electrons moving in the electromagnetic laser radiation field increases in the intervals between the electron collisions with neutral molecules up to the energy of the molecular ionization. Variation of the electron concentration with the time in the channel generated by the CO_2 laser can be calculated by the equation[7,8]:

$$n_e = \frac{n_e^0}{1 + \left(\frac{n_e^0}{n_e^1} - 1\right)e^{-\alpha n_e^0 t}}, \quad n_e^0 = \frac{\nu_i}{\alpha};$$
$$\nu_i = \frac{1}{w_i}\left(\frac{\partial \varepsilon}{\partial t}\right)_E = \frac{1}{w_i}\frac{e^2E^2}{m_e(\omega^2 + \nu_m^2)}\nu_m, \quad (3)$$

where n_e^1 is the initial electron concentration; w_i is the potential of the molecular ionization; $E = 19\sqrt{I_\lambda}$ is the electric field strength in electromagnetic laser radiation, V/cm; I_λ is the radiation intensity,

W/cm^2; α is the recombination coefficient with positively ionized air molecules.

As follows from Eq. (3), to generate the CO_2 laser plasma channel, the initial electron concentration n_e^1 is required, i.e., the electron pre-ionization is necessary, which can occur due to heating and evaporating aerosol particles causing generation of seed electrons. It is possible to apply the UV laser to generate the initial plasma channel.[3]

As follows from Eq. (3), at $t \gg (\alpha n_e^0)^{-1}$, the electron concentration tends to $n_e^0 = \nu_i/\alpha$. At $I_\lambda = 10^{10}$ W/cm^2, $E = 1.9\cdot 10^6$ V/cm, $\nu_m = 10^9$ s^{-1}, $\omega = 10^{13}$ s^{-1}, $w_i = 2.4\cdot 10^{-11}$ erg, $\nu_i = 2.9\cdot 10^9$ s^{-1}, $\alpha = 10^{-7}$ cm$^3\cdot$s^{-1}, we obtain $n_e^0 = 2.9\cdot 10^{15}$ cm^{-3}. If the CO_2 laser pulse duration τ is $5\cdot 10^{-8}$ s, then $n_e \cong n_e^0$ and further, after the pulse passage, the concentration decreases with the characteristic time $\tau_p = (\alpha n_e^0)^{-1} = -3.4\cdot 10^{-9}$ s.

When substituting the stationary value $n_e = n_e^0$ into Eq. (2), we obtain

$$\mu_\lambda = \gamma_\lambda I_\lambda;$$
$$\gamma_\lambda = 96.8\cdot 10^8 \frac{\nu_m^2}{(\nu_m^2+\omega^2)w_i}. \quad (4)$$

Let us substitute Eq. (4) into transfer equation (1):

$$\frac{dI_\lambda}{dz} = -(\alpha_\lambda + \mu_\lambda)I_\lambda = -\alpha_\lambda I_\lambda - \gamma_\lambda I_\lambda^2. \quad (5)$$

Integrating Eq. (5) with the boundary condition

$$I_\lambda(z=0) = I_\lambda^0, \quad (6)$$

write down the following expression for the laser radiation intensity

$$I_\lambda(z) = \frac{I_\lambda^0 e^{-\alpha_\lambda z}\alpha_\lambda}{\alpha_\lambda + \gamma_\lambda I_\lambda^0(1-e^{-\alpha_\lambda z})}. \quad (7)$$

At $\alpha_\lambda \to 0$, we obtain

$$I_\lambda(z) = \frac{I_\lambda^0}{1+I_\lambda^0\gamma z}. \quad (8)$$

The characteristic scale of the distance is $l = (I_\lambda^0\gamma)^{-1}$. For the CO_2 laser of $I_\lambda^0 = 10^{10}$ W/cm^2 $l = 4.7$ m at $I_\lambda^0 = 10^8$ W/cm^2 $l = 47$ m, i.e., the higher is the laser radiation intensity, the shorter is the distance the pulse passes, wasting energy for ionization.

Let us consider the transfer of UV radiation capable of producing the multiphoton ionization. The radiation transfer equation was derived[9] allowing for two-, three-, and four-photon ionizations, which, accounting for the radiation attenuation, is written as

$$\frac{dI_\lambda}{dz} = -\alpha_\lambda I_\lambda - \bar{\alpha}_\lambda I_\lambda^2 - \beta_\lambda I_\lambda^3 - \gamma_\lambda I_\lambda^4, \quad (9)$$

where $\bar{\alpha}_\lambda$, β_λ, γ_λ are the coefficients of two-, three-, and four-photon ionizations.

At $\lambda = 248$ nm ($\hbar\omega = 5$ eV), the three-photon ionization of O_2 and the four-photon ionization of N_2 are taken into account; the following values are used for the β_λ and γ_λ coefficients:

$$\beta_\lambda = 1.6\cdot 10^{-22}\ \text{cm}^3/\text{W}^2,\ \gamma_\lambda = 1.6\cdot 10^{-33}\ \text{cm}^5/\text{W}^3. \quad (10)$$

Consider some solutions of Eq. (9), assuming $\bar{\alpha}_\lambda = 0$. In this case, the transfer equation takes the form

$$\frac{dI_\lambda}{dz} = -\alpha_\lambda I_\lambda - \beta_\lambda I_\lambda^3 - \gamma_\lambda I_\lambda^4. \quad (11)$$

We also ignore the last term in Eq. (11), because the ratio of the second term to the third one is

$$\varepsilon = \frac{\beta_\lambda I_\lambda^3}{\gamma_\lambda I_\lambda^4} = \frac{\beta_\lambda}{\gamma_\lambda I_\lambda} = \frac{10^{11}}{I_\lambda}. \quad (12)$$

At $I_\lambda \cong 10^9$–10^{10} W/cm^2, $\varepsilon \gg 1$. The UV laser with a pulse of 200 fs = $2\cdot 10^{-13}$ s and energy of 0.2 mJ was considered in Ref. 9.

The solution of Eq. (11) at $\gamma_\lambda = 0$ is written as:

$$I_\lambda^2(z) = \frac{I_\lambda^{02}\alpha_\lambda e^{-2\alpha_\lambda z}}{\alpha_\lambda + \beta_\lambda I_\lambda^{02}(1-e^{-2\alpha_\lambda z})}. \quad (13)$$

Neglecting the radiation attenuation ($\alpha_\lambda = 0$), we obtain from Eq. (13) the equation

$$I_\lambda(z) = \frac{I_\lambda^0}{(1+I_\lambda^{02}\beta_\lambda z)^{1/2}}. \quad (14)$$

The magnitude of $z_* = (2I_\lambda^{02}\beta)^{-1}$ determines the scale of the length of the laser intensity decrease due to the three-photon ionization. At $I_\lambda^0 = 10^9$ W/cm^2 $z_* = 30$ m.

It is possible to derive the solution of Eq. (11) accounting for the four-photon ionization at $\alpha_\lambda = 0$ and $I_\lambda^0 \approx 10^{11}$ W/cm^2, which can be presented as

$$z = \frac{1}{2\beta_\lambda}\left(\frac{1}{I_\lambda^2} - \frac{1}{I_\lambda^{02}}\right) - \frac{\gamma_\lambda}{\beta_\lambda^2}\left(\frac{1}{I_\lambda} - \frac{1}{I_\lambda^0}\right) - \frac{\gamma_\lambda^2}{\beta_\lambda^3}\ln\frac{I_\lambda^0(\beta_\lambda + \gamma_\lambda I_\lambda)}{I_\lambda(\beta_\lambda + \gamma_\lambda I_\lambda^0)}. \quad (15)$$

Thus, as follows from the above estimates, it is possible to generate plasma channels in the atmosphere from 10 to 100 m. The ultralong propagation of the high-power ultrashort laser pulse at gas ionization is also reported in Ref. 10, where it is shown that the Ti:Sa laser femtosecond pulses with duration of 200 fs and energy of ≥ 3 mJ are capable of producing a plasma trace in the free air of 30 m length at 10^{16} cm^{-3} electron concentration in the channel.

Some calculations by Eq. (15), giving z dependence of I_λ, are presented in Table 2 ($I_\lambda^0 = 10^{11}$ W/cm^2).

Table 2. Dependence of I_λ on z at $I_\lambda^0 = 10^{11}$ W/cm^2

z, m	I_λ, W/cm^2
0.25	10^{10}
31	10^9
$3.1 \cdot 10^3$	10^8

It is advisable to supplement the solution of the considered problem with application of experimental methods for determining the radiation attenuation. In recent years, two alternative directions of the problem solving are developed: the one-position sensing based on traditional assumptions on the medium state, and the new one, based on the rigorous solution of the converted equation. In particular, the multiposition integrated method of lidar sensing of the inhomogeneous atmosphere has been suggested. The numerical investigation of the method information content, including the analysis of the results of cloud sensing[11] by the ruby laser (λ = 694.3 nm, pulse duration of 30 ns, pulse energy of 0.07–0.15 J) was carried out. Results of the one-position multi-beam sensing were used in modeling the many-position measurements. The method allows sensing at distances essentially exceeding the lidar range, which characteristics are presented above. For this purpose, a rigorous solution of the lidar equation has been found taking into account the background noise.[12]

Conclusion

Methods and equipment developed in the Research Center for Atmospheric Remote Sensing allow obtaining data on cloud parameters including thunderclouds in continuous regime with the use of laser methods and methods of microwave remote sensing of the atmosphere. Lasers can be also used for active impacts on thunderclouds to initiate lightnings in them.

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