The methods of radioastronomy have been widely used for investigating the conditions under which radio waves are propagated in the Earth's atmosphere and they appear to provide the only means of measuring weak atmospheric absorption. These methods also have the advantage of being simple and convenient from the experimental point of view.

The first measurements of atmospheric absorption in the radio range, using a radio telescope, were made in 1946 by Dicke et al. [39]. These authors also suggested and used a method for determining the absorption in the atmosphere which was new in principle—the use of the atmosphere's own radio emission. This method was found to be very effective, and as a result of its use it became possible for the first time to separate the absorption in atmospheric water vapor from that in oxygen [26].

A considerable contribution to the further development of this method of investigating the absorption of radio waves in the atmosphere from its own radio emission was made by Zhevakin, Troitskii, and Tseitlin [25, 26]. They solved the transfer equation for radio emission in the atmosphere, calculated the effective path length, and found the connection between the color temperature of the atmosphere and the absorption coefficient, i.e., they constructed a model of the atmosphere which could form the basis of a valid interpretation of the experimental data relating to atmospheric radio emission.

Over the last ten years intensive work has been carried out at the Scientific Research Radiophysical Institute on the atmospheric absorption of radio waves (in the millimeter and decimeter ranges), using the methods of radioastronomy. The following survey discusses the state of the subject at the present time, and gives an analysis of the theoretical and experimental data relating to the molecular absorption of radio waves which have been obtained both here and abroad.

The absorption of radio waves by hydrometeors is outside the scope of this paper. All the calculations carried out below, as well as the methods of measurement and the experimental data refer to a troposphere free of hydrometeors.

THE THEORY OF THE MOLECULAR ABSORPTION OF RADIO WAVES IN THE ATMOSPHERE

In an atmosphere free from dust and hydrometeors, molecules having an electric or magnetic dipole moment are able to absorb radio waves; the most important of these are water vapor and oxygen molecules. The theory of molecular absorption in these gases was established by Van Vleck in 1947 [1, 2]. The first absorption measurements carried out in the centimeter range using radioastronomical methods showed good agreement with the theoretical predictions, and this formed the subsequent basis for determining the absorption coefficient for any wave from Van Vleck's formulas. However, the work done in 1962 at the Scientific Research Radiophysical Institute on the atmospheric absorption of decimeter waves showed serious divergence from the theory [3]. This gave rise to a reexamination of the theory of nonresonant absorption in particular. Certain theoretical considerations, which are given in [3], arose in connection with the reexamination.

The resonant part of the absorption by oxygen was analyzed again by Zhevakin and Naumov in [4] in which instead of the Van Vleck-Weisskopf line shape an expression obtained by solving a kinetic equation was used. It follows from these calculations that within the limits of the resonant lines a difference in the structural factor is unimportant. The frequencies of the absorption lines of oxygen $\nu K\pm$ were calculated by Mitzushima and Hill [5], and the precision frequency measurements carried out by Zimmerer and Mitzushima [6] showed close correspondence between theory and experiment.

For calculating the absorption coefficient we have the following expression:

$$\alpha (\text{dB} \cdot \text{km}^{-1}) = 2.52 \frac{P}{T^3} \sum_k \left( M_{K+} F_{K+} + M_{K-} F_{K-} \right) \times$$

$$\exp \left( -\frac{2.07(K+1)}{T} \right),$$

where $P$ is the pressure in mm Hg, $T$ the kinetic temperature (°K), $\nu$ the frequency (GHz), and

$$M_{K+} = \frac{K(2K+3)}{K}, \quad M_{K-} = \frac{(K+1)(2K-1)}{K}.$$
radio waves in the spectrum of molecular oxygen given by the transitions with $\Delta K = \pm 2$ was calculated in [8].

![Fig. 1. Over-all spectrum of the oxygen absorption in the millimeter to decimeter wave range. The broken lines indicate resonant absorption. The points represent experimental data.](image)

The absorption coefficient expressed in dB $\times$ km$^{-1}$ under normal atmospheric conditions is

$$x_{k}(\text{dB} \times \text{km}^{-1}) = 2.68 \times 10^{-4} \left( \frac{1}{k} \right)^{2} \times$$

$$\sum_{K} \frac{(1/\beta_{j, j})^{3} \exp[-0.0069K(K+1)]}{[(1/\beta_{j, j})^{2} - (1/\beta_{j, j})^{2} + 4(1/\beta_{j, j})^{2}(\Delta \nu)^{2}]}.$$

(3)

The line shape used in (3) was obtained by solving the kinetic equation

$$f(\nu_{j}, \nu, \nu') = \frac{\nu_{j, j}'}{\pi} \frac{4\Delta \nu}{(\nu_{j, j}' - \nu)^{2} + 4\Delta \nu^{2}},$$

(4)

and the values for the oscillatory forces were taken from [7]. The absorption spectrum for oxygen in accordance with (3) is given in Fig. 2. From the practical point of view the absorption in the lines 14.1 cm$^{-1}$, 16.2 cm$^{-1}$, 27.8 cm$^{-1}$, and 48.9 cm$^{-1}$ are of particular interest since they fall within the "transparency window" of water vapor.

The most important parameter in the theory of the molecular absorption of radio waves—the width of the line—depends on the pressure and the temperature, $\Delta \nu = \Delta \nu(P, T)$. The calculation of the line width obtained as a result of collisions leads to a temperature expression of the form $T^{\alpha}$ with the index taking the values $0.5 \leq \alpha \leq 1$, and a linear pressure relationship. In the case of oxygen the important mechanisms in broadening are the quadrupole–quadrupole ($\alpha = 0.75$) and rotational–resonant ($\alpha = 1$) interactions. Hence the index of the temperature relationship should fall within the limits $0.75 \leq \alpha \leq 1$. Hill and Gordy measured the widths of six lines for $K = 9$ at temperatures of 90° K and 300° K, and found that for each level $\alpha$ has a value which differs very little from the mean, $\alpha = 0.85$.

Direct measurement of the widths of oxygen lines is not possible at normal pressure because the individual lines are not resolved. For this reason experimental investigations were carried out at pressures of several millimeters of mercury, and in this way a linear relationship was found between the pressure and the width of a line. However, extrapolation of this linear relationship to normal pressure led to an overestimated half–width which is contrary to experimental data of the absorption of radio–waves in the atmosphere. Tolbert and Straiton [11] found from measurements of absorption at frequencies of 58–62 Gc in a chamber, and from the attenuation of solar radiation in the atmosphere at different heights, that the width depends nonlinearly on the pressure, and is given by

$$\Delta \nu = 1.9 \times 10^{-3} P \left( \frac{760}{760 + P} \right)^{0.9} \quad \text{(Gc)}.$$  (5)

Falcone [12], starting from the effective temperature of the radio emission of the atmosphere at frequencies of 15, 17, and 35 Gc, showed that the calculated color temperature of the sky agrees with experiment if

$$\Delta \nu = 3.146 \times 10^{-3} \frac{P}{73.85} \quad \text{(cm}^{-1}).$$  (6)

Under normal atmospheric conditions there is good agreement between the results from (5) and (6): $\Delta \nu = 0.024$ cm$^{-1}$ and $\Delta \nu = 0.025$ cm$^{-1}$, instead of $\Delta \nu = 0.02$ cm$^{-1}$ which was taken earlier in calculations. The width of the 118 Gc line was measured in a chamber in 100% oxygen [13] and was $\Delta \nu = 1.45$ Gc.

A reevaluation made in [15] for normal atmospheric conditions taking into account nonresonant absorption leads to the value $\Delta \nu = 1.3$ Gc. A possible mechanism for the nonresonant absorption in molecular oxygen was suggested in [14]: a detailed calculation based on this is given in [15]. The absorption mechanism is as follows: under normal conditions an oxygen molecule has a mean dipole moment $\mu$ which produces a magnetic field $H(R)$ at a distance $R$. Before the moment of impact a Zeeman splitting of levels takes place in the magnetic field which leads to a displacement of the transition frequency $\nu_{K}$, if the excitation is adiabatic: for transitions with $\Delta M = 0$,

$$\nu = \nu_{K} + \frac{1}{2 \hbar} (g_{j} - g_{j}) MBH;$$

for the transitions with $\Delta M = \pm 1$ or $\nu = \nu_{K} + \nu \Delta$,

$$\nu = \nu_{K} + \frac{1}{2 \hbar} [(g_{j} - g_{j}) M_{3} \pm g_{j}] BH.$$  (7)

The following notation is used here: $\hbar$ is Planck’s constant, $B$ the Bohr magneton, $g_{j}$ the molecular factor of spectroscopic splitting for the level $j$, and $M$ the magnetic quantum number.

Assuming that the collisions are direct and occur randomly, we can determine by means of the equation for the density matrix the mean magnetic moment of a system of two colliding molecules $\langle \mu \rangle$ and the corresponding absorption coefficient

$$x = -\frac{4 \pi}{c} \frac{\text{Re} \langle \mu \rangle F^{2}}{|F|^{2}},$$  (8)

where $F$ is the amplitude of the field.