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Investigation of remote sensing possibilities of the lower atmosphere in the microwave range and some aspects of statistical data use

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Abstract. An integral relation has been obtained between variations of the brightness temperature for ground-based microwave radiometry and meteorological parameters of the atmosphere which permits a general approach to the statement of inverse problems of thermal and humidity sensing in the microwave range.

Statistical estimations of accuracy for recovering low-altitude temperature and humidity profiles are given. Using the example of ammonia pollution of the atmosphere (over its radiation in the region of the inverse resonance A~ 1-25 cm) possibilities are illustrated of remote-sensing methods for the definition of constituents of an industrial origin.

Problems are considered for the use of remote-sensing data in real-time monitoring of the astronomical refraction and the electrical path length of the atmosphere in the radio range.

1. Introduction

Problems of remote sensing of the environment in the radio range are of a particular interest for specialists because of a possible use of the sensing results in meteorology, oceanology, hydrology and agronomy as well as for the real-time monitoring of atmospheric radio characteristics, etc. In the field of climate monitoring remote observations are used in different parts of the electromagnetic spectrum, and the possibility of conducting observations even in the presence of clouds and precipitation stimulates the development of effective means of obtaining information on the present state of the atmosphere and the surface in the radio range.

The present paper considers physical aspects of lower atmosphere remote sensing by ground-based microwave radiometry and the possibilities of remote-sensing methods are illustrated by results of both model statistical investigations and natural observations. In this respect we point out excellent works by Staelin (1969), Toong and Staelin (1970), Croom *et al* (1977), Basharinov and Kutuza (1968), Waters (1973), Westwater (1965), Westwater *et al* (1975), and West water and Grody (1980) and concentrate our attention on the general approach to the statement of inverse problems of remote sensing of the atmosphere in the radio range.

The basic problems of remote atmospheric sensing are problems in defining temperature and humidity height profiles from measurements of characteristics of descending radiation in resonance absorption regions of O_2 ($\lambda \sim 5$ mm) and H_2O ($\lambda \sim$ 1.35cm; 1.64mm). First, we present the results of solutions to these problems. In the following sections of the paper possibilities are considered for the remote sensing of atmospheric constituents of industrial origin (by an example of ammonia pollution detection) and methodic problems of real-time monitoring of radio-wave propagation characteristics in the troposphere.

2. The integral expression for variations of the brightness temperature

A relation between the atmospheric brightness temperatures T_B measured in the radio range and meteorological elements and their radio images (coefficients of radio-wave absorption and refraction) is expressed by the following relation which is obtained in the definite approximations from the solution of the radiation transfer equation†

$$T_B = \int_0^{H_1} T(l)\gamma(l) \exp\left[-\int_0^l \gamma(l')\, dl'\right] dl \tag{1}$$

where T is the temperature, γ is the absorption coefficient, an element of the ray path dl is expressed through the height element dh by the relation $d = dh[1 - (n_0r_0/nr)^2 \sin^2 \theta]^{-1/2}$, where n is the refraction index, $n_0 = n(h=0)$, r_0 is the Earth's radius $r = r_0 + h$, θ is the zenith angle of observation and H_1 is the level above which a contribution of the atmospheric radiation into the value T_B is unessential.

In remote sensing one has to observe not the atmospheric brightness temperatures but their variations, i.e. deviations from the average values. When setting and solving inverse problems, a problem of linearization of the initial integral relation occurs. Linearization is usually carried out when passing from absolute values of T_B to their variations δT_B. In principle, such a transition may be made by transformation of relation (1) both by power expansion of the weighting function with the use of functional derivatives (Zhevakin 1981), or Frechet derivatives, (Gurvich and Tume 1966) and by algebraic weighting functions transformations (Markina and Sumin 1981 a). Such methods of δT_B definition demand individual approaches to each of the problems (thermal, humidity sensing, etc). The general expression for variations of brightness temperatures is also obtained from the solution of the radiation transfer equation. Let us present a brief conclusion of this relation according to Markina *et al.* (1981).

An equation of the downward radiation transfer in the radio range (in Rayleigh-Jeans approximation) and in the absence of dense cloud (i.e. when scattering is neglected) is written in the form:

$$\frac{dI(s)}{ds} = -\gamma(s)I(s) + \frac{2k\nu^2}{c^2}\gamma(s)T(s), \qquad s<0 \tag{2}$$

where $I(s)$ is the radiation intensity at level s, v is the frequency of the electromagnetic radiation, c is the light velocity and k is the Boltzmann constant. The boundary condition for equation (2) has the form $I(-H_1) = I_r$ where I_r is the intensity of the cosmic background radiation. For a standard undisturbed atmosphere, which is characterized by average meteorological elements (temperature $\overline{T}$, specific humidity $\overline{q}$, etc.), equation (2) has the form:

$$\frac{d\overline{I}(s)}{ds} = -\overline{\gamma}(s)\overline{I}(s) + \frac{2k\nu^2}{c^2}\overline{\gamma}(s)\overline{T}(s) \tag{3}$$

with the boundary condition $\overline{I}(-H_1) = I_r$. In (3) $\overline{I}$ (s) and $\overline{\gamma}$ (s) are the radiation intensity and the absorption coefficient corresponding to average meteorological parameters.

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† In (1) a term which describes the attenuation of the cosmic background radiation by the atmosphere is omitted.

Subtracting equation (3) from equation (2) and adding and subtracting the term $\bar{\gamma}$ (s)*I*(s) in the right-hand side of the equation obtained we have the following equation for the intensity variations of the downward radiation:

$$\frac{d\delta I(s)}{ds} = -\bar{\gamma}(s)\delta I(s) - \delta\gamma(s)I(s) + \frac{2k\nu^2}{c^2}\,\delta[\gamma(s)T(s)] \tag{4}$$

with the boundary condition at the upper boundary of the atmosphere δ*l(* — H_1,) = 0. In the notations used $\delta I(s) = i(s) - \bar{I}(s)$, $\delta\gamma(s) = \gamma(s) - \bar{\gamma}(s)$ and $\delta[\gamma(s)T(s)] = \gamma(s)T(s) - \bar{\gamma}(s)\bar{T}(s)$.

The formulated problem is the Cauchy problem (the initial one) in one of the simple realizations (the initial differential equation is the one-dimensional linear equation of first order). From the general solution of this problem with the given boundary condition it follows:

$$\delta I(s) = -\int_s^{-H_1}\left\{\frac{2k\nu^2}{c^2}\,\delta[\gamma(t)T(t)] - \delta\gamma(t)I(t)\right\}\exp\left(\int_s^t \bar{\gamma}(t')\,dt'\right)dt \tag{5}$$

When passing from the radiation intensity to the atmospheric brightness temperature ($T_B(s)$) = ($c^2/2k\nu^2$)$I(s)$) we obtain:

$$\delta T_B(s) = -\int_s^{-H_1}\{\delta[\gamma(t)T(t)] - \delta\gamma(t)T_B(t)\}\exp\left(\int_s^t \bar{\gamma}(t')\,dt'\right)dt \tag{6}$$

where

$$T_B(t) = \int_t^{H_1} T(t')\gamma(t')\exp\left[-\int_t^{t'}\gamma(t'')\,dt''\right]dt'$$

For the case of ground-based remote sensing of the atmosphere (here the variable of integrating is again denoted by *s*) we have

$$\delta T_B \equiv \delta T_B(0) = -\int_0^{-H_1}\{\delta[\gamma(s)T(s)] - \delta\gamma(s)T_B(s)\}\exp\left(\int_0^s \delta(s')\,ds'\right)ds \tag{7}$$

Integrating in (7) along the path of the ray propagation from the Earth's surface ($l = -s$) and adding and subtracting the product $\bar{\gamma}(l)T(l)$ in braces we obtain:

$$\delta T_B = \int_0^{H_1}\{\delta T(l)\bar{\gamma}(l) + \delta\gamma(l)[T(l) - T_B(l)]\}\exp\left(-\int_0^l \bar{\gamma}(l')\,dl'\right)dl \tag{8}$$

Relation (8) is a new non-linear expression of the brightness temperature variation T_B measured on the Earth's surface through variations of the atmospheric characteristics δ*T(l)* and δγ(/). The present paper, based on equation (8), gives a general approach to the statement of inverse problems over the definition of the basic meteorological parameters of the atmosphere[t]. A similar equation for variations of the upward microwave radiation of the 'atmosphere-surface' system has been obtained in the paper by Markina and Sumin (1981 b).

In the problem of temperature sensing, which is considered at the slope of the O_2

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[t] A particular form of equation (8) (without the first addend in brackets) for the problem of humidity sensing of the atmosphere from space is obtained by an approximate method (by weighting function expansion of the problem in the vicinity of the average value of $\bar{\gamma}(l)$ in a paper by Schaerer and Wilheit (1979).

band (λ = 5 mm), the plane-stratified idealization of the atmosphere is used: *dl=sec*θ*dh;* and from (8) a relation is obtained as given by Westwater (1972). Westwater *et al.* (1975), Miner *et al.* (1972) and Ershov and Naumov (1974)

$$\delta T_B = \sec\theta \int^{H} \delta T(h)\bar{\gamma}(h)\exp[-\sec\theta \int^{h} \bar{\gamma}(h')dh']dh + I_T \qquad (9)$$

where the integral I_T is usually neglected in comparison with errors of radiometric measurements of T_B (or δT_B). In this respect the above papers, together with those of Aleshin *et al. (*1977), Sumin and Troitskij (1977) and Naumov *et al.* (1979), give a rather complete presentation on the possibilities of temperature sensing of the atmosphere in the microwave range. The characteristic errors of the temperature profile restoration from (9) by the method of statistical regularization, according to the last of the cited papers (Naumov *et al.* 1979), are given in table 1.

For the problem of humidity sensing, with the assumption that the height temperature profile is known *(6T(h)* = 0) and using the most informative regions of the spectrum (λ ~ 1-35 cm, λ ~ 1-64 mm) then:

$$\delta\gamma(h) = \delta\gamma_{H_2O}(h) = \delta q(h)\frac{\tilde{A}_\nu(h)}{\alpha+\beta q(h)} + \bar{q}(h)\left[\frac{\tilde{A}_\nu(h)}{\alpha+\beta q(h)} - \frac{\tilde{A}_\nu(h)}{\alpha+\beta\bar{q}(h)}\right] \qquad (10)$$

where $q(h)$ is the specific humidity of the atmosphere ($\delta q(h) = q(h) - \bar{q}(h)$; $\bar{q}(h)$ is the mean specific humidity). We have taken into account the curvature of the Earth and radio-wave refraction:

$$\delta T_B = \int_0^H \delta q(h)\frac{A_{\nu,\theta}(q(h),h)}{\alpha+\beta q(h)}[T(h) - T_B(q(h),h)]\exp\left[-\int_0^h \bar{\gamma}_\theta(h')\,dh'\right]dh + I_{q,T} \qquad (11)$$

$$I_{q,T} = \int_0^H \bar{q}(h)\left[\frac{A_{\nu,\theta}(q(h),h)}{\alpha+\beta q(h)} - \frac{A_{\nu,\theta}(\bar{q}(h),h)}{\alpha+\beta\bar{q}(h)}\right]\left[T(h) - T_B(q(h),h)\right]$$
$$\times \exp\left[-\int_0^h \bar{\gamma}_\theta(h')\,dh'\right]dh, \qquad T_B(q(h),h) \equiv T_B(h) \qquad (12)$$

In (11) and (12) we use a brief record for the coefficient of water vapour absorption (Van Vleck 1947, Zhevakin and Naumov 1963):

$$\gamma_{H_2O} = D(\nu,h)\rho(h) \qquad (13)$$

where *p(h)* is the absolute humidity. Since ρ is expressed by *q* by the relation $\rho = bq[(d + mq)T]^{-1}$', then

$$\gamma_{H_2O} = \frac{\tilde{A}_\nu(h)q(h)}{\alpha+\beta q(h)} \qquad (14)$$

Coefficients α and β are expressed, evidently, by values *b, d,* $D(\nu, h)$, *m* and *T.* In (11) and (12) we introduce the designations $\gamma_0(h)=\gamma(h)[1-(n_0r_0/nr)^2\sin^2\theta]^{-1/2}$ and $A_{\nu,q}(q(h),h) = \tilde{A}_\nu(h)[1-(n_0r_0/nr)^2\sin^2\theta]^{-1/2}$. Equation (11) is the non-linear integral equation. The most essential part of the non-linearity in the problem of humidity sensing is defined by the integral †

$$I_q = \int_0^H \delta\gamma_\theta(h)T_B(q(h),h)\exp\left[-\int_0^h \bar{\gamma}_\theta(h')\,dh'\right]dh \qquad (15)$$

† The value $A_{\nu q}(q(h),h)[\alpha. + \beta q(h)]^{-1}$ is weakly dependent on humidity.

Table 1. Mean seasonal values of the temperature $\bar{t}$ (^{0}C), r.m.s. deviations σ_T of the temperature from mean seasonal values, r.m.s. errors σ_T^{ext} statistically extrapolated over ground values of the temperature T_0, profiles T(P) and r.m.s. errors σ_T^r

central part of the European territory of the U.S.S.R.

	P = 950mbar		P = 880mbar		P = 700mbar		P=500mbar		P = 400mbar	
Value	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
$\bar{t}$ (°C)	-11.2	18.4	-10.6	13.1	-16.7	1.1	-31.1	-14.7	-42.0	-26.3
σ_T (degrees)	6.3	5.6	6.4	6.4	5.7	4.0	5.1	3.4	4.5	3.3
σ_T^{ext} (degrees)	2.3	1.6	3.7	2.2	4.4	2.5	4.4	2.4	4.0	2.4
σ_T^r (degrees)	1.1	0.3	1.4	0.7	1.7	1.5	2.4	1.8	3.1	2.4

In the resonance region of H_2O ($\lambda = 1.35$ cm) values of I_q are smaller than errors of the brightness-temperature measurements (δTr ~1-2K) in zenith sensing, but are comparable with them even for $\theta = 60°$ and exceed values of δT_r for $\theta > 75°$. With regard to the H_2O resonance at $\lambda = 1.64$ mm, here $I_q > \delta T_r$ even for the zenith direction of sensing.

The solution of equation (11) is obtained by an iterative process. As the first approximation to the solution, the profile q^{ext} *(h)* is statistically extrapolated over the known ground value q_0. At each *i*th step of iteration by the method of statistical regularization, a linear algebraic system is solved which has been derived from (11) when $q(h) = q_{i-1}(h)$. A review of methods for solving inverse problems is given, for example, in a monograph by Malkevich (1973). Two iterations are practically sufficient for the solution to the given problem. Figure 1 gives examples of humidity profile restoration at frequencies of ν_1 =21.5 GHz (sensing angles θ = 0 and 85^0) and ν_2 = 176GHz (θ = 0 and 60°) with modeling errors of radiometric measurements $\delta T_r \sim 1$ K. Results of statistical processing of numerical experiments on the restoration of profiles *q(h)* according to the given scheme are presented in table 2.

A choice of parameters (ν, θ) for atmospheric sensing in the given problem is made, taking into account the basic factors of the atmospheric radiation formation, including the degree of statistical dependence of the sensing conditions. Using frequency ν_2 for the remote sensing permits an increase in the accuracy of the humidity profile restoration at an interval of pressure $p \sim$ 900-1000 mbar, i.e. in low layers of the atmosphere. When restoring profiles *q(h)* at frequencies ν_1 and ν_2 one may build an optimal combined profile of the humidity from the results obtained.

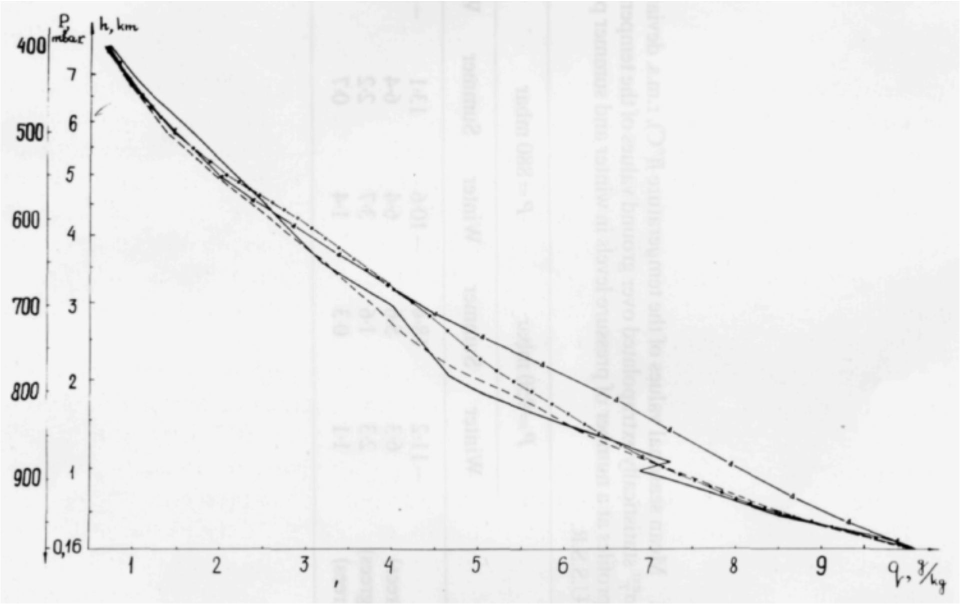

Figure 1. Comparison between restorated humidity profiles when modelling radiometric measurements of the atmospheric radiation at the frequency ν_1 = 21.5 GHz (dotted curve) and ν_2= 176 GHz (circles) and profiles obtained by aerological sensing of the atmosphere (solid curve) and by statistical extrapolation of surface values q_0 (triangles). The accuracy of radiometric measurements δT_r=1K (summer, the central part of the European territory of the U.S.S.R.).

Table 2. A comparison between relative variations of $\sigma_q / \bar{q}$ of the specific humidity and mean errors $\sigma_q^{ext} / \bar{q}$ for definition $q^{ext}(P)$ over statistically extrapolated profiles and mean relative errors $\sigma_q^r / \bar{q}$ the humidity profile restoration at a number of pressure levels from numerical experiments in summer conditions of the year in the central part of the European territory of the U.S.S.R.

Set	Sensing parameters		$\sigma_q^r / \bar{q}$ in per cent at levels P				
		δT_r(K)	950 mbar	880 mbar	700 mbar	500 mbar	400 mbar
I	ν_1 = 21.5 GHz	0.5	7.3	10.6	13.3	37.6	39.5
	$\theta = 0°$	2	7.7	11.4	16.7	50.6	51.2
11	ν_1=21.5 GHz	0.5	5.1	4.4	13	30.6	40
	θ = 0 and 85°	2	6.1	6.7	13.6	33.2	41.5
III	ν_2= 176GHz	0.5	2.2	5.1	15.2	34.8	44.7
	θ= *0* and 60-70°	2	4	9.9	18.8	45.4	49.6
IV	ν_1,ν_2 angles — see sets II and III	0.5	2.2	4.4	13	30.6	40
		2	4	6.7	13.6	33.2	41.2
Percentage mean relative of the specific humidity			22.1	21	34.3	54	52
Percentage mean relative errors $\sigma_q^{ext} / \bar{q}$			7.8	14	26	49	49.7
Mean seasonal value $\bar{q}$ (g/kg)			7.9	6.8	3.7	1.2	0.5

Comparison between the solution to the problem of sensing the temperature and humidity of the atmosphere and solutions to the same problems using the regression method gives:

$$\bar{\mathbf{X}}' = B^{-1}_{T_B T_B} B_{T_B X} \bar{\mathbf{T}}'_B \tag{16}$$

and testifies to the fact that the results of (9) and (16) for the problem of temperature sensing are close to one another, and an approach using (11) is preferable to the solution to the problem of humidity sensing. In (16) $\bar{X}'$ is the vector of deviation of the unknown meteoelement vertical profile (temperature or humidity) from the average values, $\mathbf{T'_B}$ is the vector of deviation of brightness temperatures from their average values (the generalized vector $\mathbf{T'_B}$ may include surface meteoparameters and nonlinear terms over Γ_B) and B_{TBTB} and B_{TBX} are the covariance matrixes. An effect of non-linear T_B terms on the accuracy of meteoelement restoration in (16) is manifested only in errors of radiometric measurements δT_r<0.1 K.

Experimental verification of the result obtained for temperature sensing was made by elevation angle radiometric sensing of the atmosphere at the frequency ν = 53-4 GHz (Ershov *et al.* 1975, Aleshin *et al.* 1977, Sumin and Troitskij 1977, Kuznetsova *el al.* 1979) for conditions close to optimal sensing ones. In this case, experimental errors of the temperature profile restoration are close to results given in table 1.

Remote sensing of the atmosphere humidity was made by one of the authors of this paper (V.M.P.) in 1979-1980 at the wavelength λ.= 1.3 cm, using the radiometer described in Plechkov (1968). Experimental conditions allowed measurements of the atmospheric radiation in the range of zenith angles *0*< 83°. An error of the brightness temperature measurements amounts to ~ 1-2 K. Results of restoration of humidity height profiles from the radiometric measurements proved to be close to results of variant 1 of the numerical experiment (see table 2). Results obtained confirm the adequacy of the radiometric experiment modelling over humidity sensing and underline perspectives of the given problem solution at complex sensing of the atmosphere in the resonance regions of H_2O at $\lambda = 1.35$cm and 1.64 mm.

3. Radiometric determination of the water vapour total mass

On the basis of equation (8) one may make generalized conclusions on the character of the relation between variations of the atmospheric brightness temperature in definite parts of the spectrum and the total mass of water vapour Q. Equation (8), taking into account (13) and for $\delta T(l) = 0$, has the form:

$$\delta T_B = \int_0^{H_1} \delta\rho(l) D(\nu, l)[T(l) - T_B(Q, l)] \exp\left(-\int_0^l \bar{\gamma}(l')\,dl'\right) dl \tag{17}$$

where $d\rho$ is the variation of the absolute humidity.

The minimal errors of the linear presentation $\delta T_B(\delta Q = \int_0^{H_1} \delta\rho(l)dl)$ are realized in a wide range of meteorological conditions close to $\lambda \sim 1.35$ cm when sensing at angles $\theta < 45°$. In this case the integral

$$I_Q = \int_0^{H_1} \delta\rho(l) D(\nu, l) T_B(Q, l) \exp\left(-\int_0^l \bar{\gamma}(l')\,dl'\right) dl \tag{18}$$

being the analog of the integral I_q (see (15)), is less than the error δT_r of measurement of the atmospheric brightness temperatures and thus, neglecting the value I_Q in comparison with δT_r and using the theorem on the mean, equation (17) may be written as:

$$\delta \tilde{T}_B + \delta T_r \simeq \bar{\psi}_\nu \cdot \delta Q \tag{19}$$

In (19) $\delta\tilde{T}_B$ is the measured value of the brightness temperature variations, $\bar{\psi}_\nu = \langle D(\nu, l)T(l)\exp(-\int_0^l \bar{\gamma}(l')dl') \rangle$. Equation (19) and the conditions when it is obtained illustrate the physical nature of the functional relations between variations δT_B and δQ. Condition (19) is fulfilled in the region of weak atmospheric absorption (the optical depth $\tau < 1$) and here $\delta T_B \sim \delta\tau$. Thus, the total mass of the water vapour in the absence of clouds may be defined from results of relative radiometric measurement oft at one wavelength (Naumov 1968).

Simplicity and reliability of the one-wave method of definition of the water vapour total mass over measurements of the vertical radio-wave absorption τ in the region $\lambda = 1.35$ cm permits us to obtain extensive data on peculiarities of the humidity propagation in the atmosphere for different zones of the Atlantic, on time and seasonal variations of the values Q and on the relation between the humidity content of the atmosphere and the synoptic conditions in the region of measurements at different geographic latitudes. These investigations were made onboard the scientific ocean ship *Akademik Kwchatov* at latitudes 47^0N-22^0 S. The basic results of the radiometric definition of Q according to the above methods were published by Plechkov *et al.* (1970), Mel'nikov et al (1974) and Plechkov and Romanov (1975,1977). A comparison of the accuracy of independent radiometric and aerological measurements of the total water vapour mass in the Earth's atmosphere was made by Ershov and Plechkov (1977) and shows that the r.m.s. error for definition of the humidity content over the aerological data amounts to ~ 11 per cent of the average value $\overline{Q}$ and the corresponding error of radiometric data proves to be equal to ~ 8 per cent of $\overline{Q}$. Alekseev *et al.* (1981) paid attention to the possibility of determining the total mass of water vapour according to the difference measurements of electrical path lengths of the radiation in the microwave and infrared ranges.

4. Atmospheric NH_3 pollution indication

Possibilities of the radiometric definition of atmosphere pollution by constituents of industrial origin are shown using an example of an increased NH_3 content. Natural radiometric investigations of the atmosphere brightness increase due to the presence of NH_3 in the background of the self-radiation of a pure atmosphere are made with an apparatus described in Plechkov (1968). Investigations were carried out in the region of the inverse resonance of ammonia centred at $\lambda \sim 1.25$ cm (frequencies $\nu \sim 24$-25 GHz) close to an ammonia source with space-localized (organized) NH_3 ejections (Naumov et al. 1980).

In natural conditions an increase of the atmospheric radiation brightness due to ammonia presence is accompanied by factors which complicate the interpretation of physical results. These factors are, in particular, the general increase of the atmospheric temperature in the region of ejection due to industrial thermal action (see, for example, tables 9.1 in Berlyand (1975)) as well as different degrees of humidity content of the ammonia ejections, and a difference of their temperatures associated with the ejection character (technological and ventilation ejections). However, estimation uncertainties in ammonia amount, due to approximate values of the listed interfering factors, are not larger than ~ 1.5. The general measurement accuracy of the atmospheric radiation brightness increase by multiple scanning of ejection regions and the pure atmosphere, which defines the sensitivity of the radiometric method, is estimated as 0.25 K, corresponding to the ammonia amount of ~ 30 LAC (limited admissible concentration) with the pollution depth layer $\Delta H \sim 100$ m or ~ 6 LAC for $\Delta H \cong 500$ m† . An example of a recording of the atmospheric radiation for a number of azimuthal scannings in the region of ammonia ejections is given in figure 2.

Using a two-frequency measurement of absorption on the surface trace at ~ 570 m by CO_2 laser a sensitivity of ~0.5 LAC NH_3 is achieved (Artemov *et al.* 1977), i.e. exceeds sensitivity by the radiometric method. However, the practical use of more sensitive laser methods is associated with some difficulty of measurement at low visibility. This drawback is practically absent in the radiometric method and this fact must be taken into account when choosing conditions of control of atmosphere pollution by different remote-sensing methods.

5. Refraction and electrical path length real-time monitoring

In conclusion we briefly consider the optimal use of downward radiation for the operative definition of atmospheric radio characteristics. In the papers by Gallop and Telford (1973,1975) and Schaper *et al.* (1970) the method used is considered for multiple regression of operative definition of the astronomical refraction at small elevation angles and the electrical path length of the atmosphere in the zenith direction

$$\bar{\mathbf{Z}}' = \bar{\mathbf{a}}^* \bar{\mathbf{T}}'_{\mathrm{B}} \qquad (20)$$

where **Z**' is the deviation vector of the unknown value from average values,
a = $[a_1,\ldots,a_m]$ is the *m*-component vector of regression coefficients, $\boldsymbol{T'}_{\mathbf{B}}$ is the *m*-component vector of data including arbitrary combinations of brightness temperature measurements (may include surface meteoparameters) and the asterisk represents matrix transposition. Regression coefficients are defined from the minimum r.m.s. error condition of prognosis according to equation (20) on the ensemble of *a priori*

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† The radiometric method sensitivity is expressed by the pollution depth layer $\Delta H \sim$ 500 m which is essential for comparison with possibilities of the laser method.

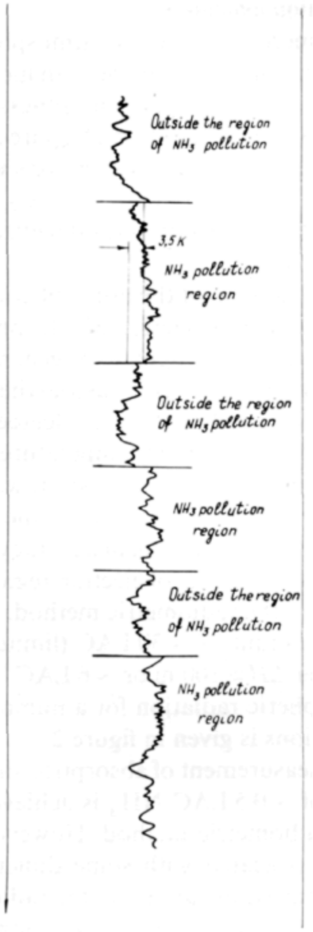

Figure 2. An example of variations of the atmospheric brightness temperature at the wavelength $\lambda = 1.25$ cm when sensing under the zenith angle $\theta = 85^0$ in the region of ammonia ejections.

meteorological statistics and have the form

$$\bar{a} = (\langle T_B' T_B'^* \rangle)^{-1} \langle T_B' Z' \rangle \tag{21}$$

We compare the definition of the astronomical refraction and the electrical path length of the atmosphere at small elevation angles $\phi = 1\text{-}5^0 (\theta = 85\text{-}89^0)$ by meteorological elements restored in the low atmosphere (temperature, pressure, humidity, see above) and according to equation (20). A comparison made shows the advantage of regression methods for the definition of refraction characteristics through the Earth's total atmosphere.

For astronomical refraction *R,* numerical modeling in this paper is made on the basis of real meteorological statistics, and in this approach correlation relations between separate meteorological elements are automatically taken into account. This fact improves the prognosis of the astronomical refraction for a spherically stratified atmosphere (Gaikovich 1980).

During recent investigations it has been discovered that for the most accurate prognosis of astronomical refraction *R(0)* it is necessary to measure the brightness temperature of the atmosphere T_B at $\nu_0 \cong 10$ GHz at the same angle θ. At this frequency the atmosphere is more transparent than in the absorption lines and the refraction leads to an increase of the ray path in both the lower and the upper layers of the atmosphere and, hence, to an increase of T_B. Such a character of the relation between *R(0)* and $T_B(\nu_0, \theta)$ remains in the presence of horizontal inhomogeneities, which raises hope that the method considered is effective in this case. For example, an r.m.s. error of refraction at an angle of 89° from measurements of $T_B(\nu_0 = 10\text{GHz}, \theta = 89°)$ amounts to ~ 12". The use of additional measurements of T_B in the regression relation (20) at 21.5 and 54 GHz in the zenith direction leads to an accuracy of definition $R(\theta = 89^0)$ up to ~ 5-10". Errors of measurement of the brightness temperature must be not worse than 0.5 K. When using equation (20) for processing of multichannel radiometric data, a strong dependence of regression coefficients a^* on the basis ensemble of meteoparameters should be taken into account.

In the approximation of plane stratified atmosphere the electrical path length $L = \int_0^{H_1} [n(l) - 1] dl$ has the form:

$$L = \sec\theta\left(0{\cdot}227P_0 + 0{\cdot}108Q + \frac{1{\cdot}729\times10^3}{\langle T\rangle}Q\right) \tag{22}$$

However, approximation (22) is sufficiently accurate only for θ≤60°. For θ>60° the approximation error of (22) exceeds 1 cm, at θ≅80° it is 30-35 cm and at θ≅85° it becomes more than 1 m. In (22) P_0 is the surface pressure in millibars, $<T>$ is the mean (over the height distribution of the absolute humidity) atmospheric temperature. Equation (20) for deviation L from average values is written in the form:

$$\bar{L}'(\theta) - 0{\cdot}227(P_0 - \langle P_0\rangle) = \bar{a}^*\bar{T}'_B(\nu, \theta) \tag{23}$$

With usual accuracies of absolute measurements of the atmospheric brightness temperature ($\delta T_r \cong$ 1-2 K) it is sufficient in (23) to use measured data at only one ν frequency (in the direction θ). Here, for definition of L at angles of θ≤70°, the sensing of the atmosphere can reasonably be made at the frequency ν = 21.5 or 23.5 GHz, i.e. at frequencies which are optimal for definition of the total mass of water vapour in the vertical column of the atmosphere.

Minimal errors in the definition of L at larger zenith angles may be expected at the decrease of the ν frequency of radiometric sensing of the atmosphere. Thus, r.m.s. error of L definition according to equation (23) for the zenith angle θ = 80° amounts to $\sigma_L \cong$ 4.5cm if radiometric sensing is made under the same angle at the frequency 21.5 GHz, but decreases down to the value $\sigma_L \sim 3$ cm for ν= 10 ÷ 19 GHz. Solutions to this problem for optimal (at each angle θ) ν frequencies are given in table 3.

Note that the theoretical coefficient of the correlation $r_{T_B L}^{theor}$, obtained in our paper between values $T_B(\nu = 20.6\text{ GHz}, \theta)$ and $L(\theta = 87.5°)$, is rather close to the corresponding experimental values $r_{T_B L}^{\exp er}$ defined by Decker *et al.* (1973) over the same measurements in 1971. The use of measurements of T_B in the regression relation (23) at frequencies 21.5 and 54 GHz in the zenith direction, together with measurements of T_B at ν = 10 GHz at the angle θ for $\delta T_B < 0.2$ K, permits, in principle, the decrease of the r.m.s. error of the definition of L (up to ~ 0.5 cm for θ = 80°). The results are given in table 3 and in the paper by Alekseev *et al.* (1981) [†].

[†] A part of the given set of frequencies is close to the frequencies defined (Schaper *et al.* 1970) for the solution of similar problems of remote sensing in the zenith direction.

Table 3. A comparison of r.m.s. errors of $L(\theta)$ [cm] definition in the central part of the European territory of the U.S.S.R. over the regression relation (23) by surface meteorological data (P_0, T_0, $<7_0$) and using results of remote-sensing data.

	θ (degrees)					
Method	10	30	45	60	80	89
Radiometric measurements $T_B(\nu,\theta)$	0.4	0.45	0.6	0.9	3	9
Radiometric measurements of the set $\{T_B(\nu,\theta)\}$	0.08	0.10	0.15	0.25	0.5	4
Using surface metorological data only	2.4	2.7	3.3	4.5	15	50

If we are interested in variations of $\Delta L(\theta)$ and not in its absolute value L (θ), then the problem of the operative definition of $\Delta L(\theta)$ is simplified, since variations of the atmospheric brightness temperatures may be really defined with an accuracy δT_r K.

6. Conclusions

The investigations reported here develop and supplement the results of remote-sensing studies of the Earth's atmosphere in the scientific periodicals and confirm the practical possibilities of decreasing uncertainties with the knowledge of meteorological elements of the lower atmosphere using remote sensing as well as confirming the validity of such measurements for operative monitoring of radio characteristics.

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